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Cost Estimation Model for Earthquake Damage Repair in New Zealand

A thesis presented in partial fulfilment of the requirements for
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Kahandawa Appuhamillage Ravindu Visal Dharmasena

Kahandawa

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Dedications

I dedicate this thesis to my parents, Dharmasena and Jayantha Kahandawa, and my sister, Parami Kahandawa, for their eternal care, love and continuous support for the success of my life and fulfilment of my soul.

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Abstract

Earthquakes are natural hazards that can devastate nations, their people and the surrounding built environments. Designing a suitable strategy for rapid recovery requires an accurate damage assessment process for the built environment. Loss estimation models were developed to predict the cost of repair, but these models were not used to estimate the costs of post-earthquake repair. This could be due to the fact that these probability-based models tend to provide less accurate outputs. In fact, there is no existing literature on post-earthquake repair cost estimation models that can rapidly produce repair cost estimates.

This research developed a post-earthquake cost estimation model for earthquake damage repair work (referred to as a cost of damage repair, earthquake estimation model or C-DREEM). The research used an exploratory sequential research design that used semi-structured interviews (N=19) with engineers, quantity surveyors and builders with experience in earthquake damage repair work as the primary data collection. Then a web-based survey questionnaire (N=310 distributed, N=92 received) of professionals with experience in cost estimation for earthquake damage repair work was the second data collection. The collected data was analysed using thematic analysis, descriptive statistics and non-parametric tests. Based on the findings in the literature, document review and research data analysis, a cost of damage repair earthquake estimation model (C-DREEM) was developed. The C-DREEM model was then validated through a focus group interview session with participants who had

experience in the cost estimation for earthquake damage repair work in New Zealand (N=9). Key findings identified from the research were: (i) 11 factors have a critical impact on the accuracy of cost estimation of earthquake damage repair work (CEEDRW) which includes consequential damage, initially unforeseen damage, and changes to the final repair state (ii) Use of a unit rate and lump sum amount methods were some of the most suitable ways incorporate these factors to CEEDRW; (iii) detailed damage evaluation reports are the most likely information sources post-earthquake for CEEDRW; and (iv) the standardised and automated cost estimation model, C-DREEM, developed by this research can improve both pre and post-earthquake CEEDRW process with include the benefits of sharing consequence functions and probable damage information with probability-based methods.

The key contribution to knowledge from this research is identifying the factors affecting CEEDRW, evaluating the significance, selecting methods to incorporate the factors into the costing process, and creating the C-DREEM costing process that combines the pre-and post-earthquake loss estimation processes. The research also supports the professional practice by providing: a standardised and automated cost estimation process; specifying the areas that should be improved, such as the damage reporting process; and a better cost control and monitoring process through standardised rates. Through the findings of the research, government and insurance companies: can standardise and improve the accuracy and speed CEEDRW process, and makes informed decisions to manage the impact of the eleven factors affecting CEEDRW identified by this research.

Keywords: Automation; Buildings; Cost estimation; Damage estimation; Earthquakes; New Zealand; Post-disaster; Reconstruction; Repair work

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List of Abbreviations

8D	Eight disciplines
ANN	Artificial neural networks
ANZSMM	Australian and New Zealand Standard Method of Measurement
ASCE	The American Society of Civil Engineers
ASMM	Australian Standard Method of Measurement
BOQ	Bills of quantities
CBR	Case-based reasoning
C-DREEM	Cost of damage repair, earthquake estimation model
CEEDRW	Cost estimation for earthquake damage repair work
CEQS	Canterbury earthquake sequence
DDE	Detailed damage evaluation
DMAIC	Define, measure, analyse, improve, control
DS	Damage states
DT	Decision tree

EQC	Earthquake Commission
EQR	Earthquake Recovery
ES	Expert systems
FEMA	Federal Emergency Management Agency
FLS	Fuzzy logic systems
FMEA	Failure mode and effects analysis
GIS	Geographic information system
HAZUS-MH	Hazards United States Multi-Hazard
JMA	Japan Meteorological Agency
LBP	licenced building practitioners
Lg	Love-guided
LNECLOSS	Laboratório Nacional de Engenharia Civil loss
MBIE	Ministry of Business Innovation and Employment
MDLA	MATLAB damage and loss analysis
MLR	Multiple linear regression
MMI	Modified Mercalli intensity scale
MSK	Medvedev-Sponheuer-Karnik
NZ	New Zealand

NZ\$	New Zealand dollars
NZS	New Zealand Standards
PACT	Performance Assessment Calculation Tool
PBEE	Performance-based earthquake engineering
PEER	Pacific Earthquake Engineering Research
PEQ	Post-earthquake
PEQ-CEEDRW	Post-earthquake cost estimation for earthquake damage repair work
PERT	Program evaluation and review technique
PGA	Peak ground acceleration
PGD	Peak ground displacement
PGV	Peak ground velocity
PSO	Particle swarm optimisation
P-waves	Primary waves
RBA	Level 2 Rapid Building Assessment
RBFNN	Radial basis function neural network
R _g	Rayleigh-guided
RICS	Royal Institution of Chartered Surveyors

SELENA	SEismic Loss Estimation using a logic tree Approach
SH	Shear horizontal
SLAT	Seismic Performance and Loss Assessment Tool
SLS	Serviceability limit state
SMM	Standard method of measurement
SP3	Seismic Performance Prediction Program
SSNS	Secondary structural and non-structural
SV	Shear vertical
S-waves	Secondary waves
TDE	Targeted damage evaluation
TRIZ	Teorija Rezhenija Izobretatelskih Zadach
T-waves	Tertiary waves
ULS	Ultimate limit state
UNISDR	United Nations International Strategy for Disaster Reduction
USA	United States of America
USGS	United States Geological Survey
WHO	World Health Organization

1

INTRODUCTION

1.1 Background

An earthquake can be defined as a “series of vibrations on the earth’s surface caused by the generation of elastic (seismic) waves due to a sudden rupture within the earth during the release of accumulated strain energy” (Shah, 2012, p. 96). The United Nations International Strategy for Disaster Reduction (UNISDR) (2009) puts earthquakes into the category of natural hazards. Earthquakes cause fatalities, injuries, and loss and damage to livelihoods, services, society and the environment (United Nations International Strategy for Disaster Reduction, 2009; Yaoxian, 1996). High-impact earthquakes cause destruction and damage to an excessive degree (Baocai, 1996). Between 1980 and 2018, significant earthquakes around the world caused over 822,499 fatalities and resulted in economic losses totalling more than US \$935 billion; these figures represent 56.1 percent of the fatalities and 25.6 percent of the monetary losses caused by all-natural hazards (Munich Re Group, 2019, 2020).

From 1990 to 1 June 2021, 475 earthquakes with a magnitude of 7.0 on the Richter scale occurred (USGS Earthquake Hazards Program, 2021c). New Zealand is one of the countries that has been repeatedly affected by seismic activity of such magnitude (Sun et al., 2021). According to historical data from New Zealand’s provider of

geological hazard information, GeoNet (2021c), in New Zealand, on average (from 1990 to 2019), one low-impact earthquake (with a magnitude between 4.0 and 4.9) has occurred every day, while high-impact earthquakes (with magnitudes above 7.0) have occurred every four years. The negative impact of these high-magnitude earthquakes extends to economic, social, psychological and political areas and requires swift rehabilitation and reconstruction (Yaoxian, 1996). The 2010 / 2011 Canterbury earthquakes in New Zealand created a loss of more than NZ\$40 billion to the community (Marquis et al., 2017). For the economic sector to recover after an earthquake, rebuilding or recovering earthquake-damaged buildings is essential. The economic success of the subsequent building rehabilitation processes can be determined, in part, by a review of the final construction costs.

Construction cost estimation is the process of predicting the total cost of a building project. Because building projects often involve significant costs, it is critical to make accurate predictions of construction costs (Lowe et al., 2006). Having accurate cost estimates of projects is also vital to any decision-making process (Alqahtani & Whyte, 2016). If the post-earthquake building is structurally stable at an individual property ownership level, owners make the repair or rebuild decisions based on the estimated repair cost (Applied Technology Council, 2018c). At a national level, rehabilitation cost estimates are used to develop country-wide recovery strategies (Neighbors et al., 2013). Therefore, cost estimates should be up to date and accurate so that they can be used with a degree of confidence.

Changes in complexity, uncertainties, size and time pressures of projects intensify the difficulty of producing accurate cost estimates for construction (Luo et al., 2017). This is particularly true in the context of an earthquake of strong magnitude, which can cause damage to a large range of buildings, other infrastructure and utilities. For

example, the 2011 Tohoku earthquake in Japan caused the partial and total destruction of 368,862 houses (Kazama & Noda, 2012); over 150,00 homes were damaged in the 2010–2011 Canterbury earthquake sequence in New Zealand (Potter et al., 2015). The rapid recovery of damaged buildings is a priority for the post-earthquake rehabilitation and reconstruction process (Yaoxian, 1996). Thus, the required time pressures related to repair work would be higher in these circumstances. Earthquakes occur at a low frequency and have a high impact. Complexity and uncertainty during the earthquake damage repair process is high due to factors such as longer construction rehabilitation time frames, the need to evaluate intangible variables and the requirement to fulfil multiple stakeholder values and expectations (Luo et al., 2017). Thus, the cost estimation process should address this heightened difficulty when producing accurate estimates.

1.2 Research justification

A review of the literature revealed the range of cost estimation models for earthquake damage currently available. Probability-based models have been developed to predict the building damage that can occur from earthquakes. Regional damage estimation tools include Hazards United States Multi-Hazards (HAZUS-MH) and Seismic Loss Estimation Using a Logic Tree Approach (SELENA). Building-specific damage estimation tools are also available and include the Seismic Performance Prediction Program (SP3), the Performance Assessment Calculation Tool (PACT) and the Seismic Performance and Loss Assessment Tool (SLAT) (Applied Technology Council, 2018c; Bradley, 2009; Department of Homeland Security & FEMA, 2003; Haselton & Baker, 2019; Molina et al., 2010).

Analysis of the literature revealed drawbacks to using each of these tools. These regional damage estimation tools used general parameters like building categories and floor areas that did not use specific building details to make damage cost estimations (Cook et al., 2017; Department of Homeland Security & FEMA, 2003). At the same time, many building-specific tools use the P-58 methodology, which exhibits the probable impact of significant earthquake forces using a statistical distribution (Hamburger et al., 2012). However, according to the literature on these models, the accuracy of cost estimates produced by these models is limited (Applied Technology Council, 2018d). Additionally, the models do not produce detailed cost breakdowns required for post-earthquake damage evaluation.

According to Wellington City Council (2017), traditional post-earthquake cost estimation methods are currently used to predict the costs associated with building repair. These conventional methods use bottom-up approaches, which break down unit rates into smaller fragments: materials, labour, plant and equipment, subcontracting, profit and overheads. Kirkham (2015) and Ashworth and Perera (2015) agree that the bottom-up method is the most suitable approach to estimating costs for refurbishment and repair work. However, estimates created by these models have not proven accurate. For example, in 2012, it was estimated that the repair cost for the Canterbury earthquake sequence would be NZ \$30 billion (Parker & Steenkamp, 2012). However, the predicted total cost had risen to NZ \$40 billion by 2016 (A. Wood et al., 2016). Loss estimation tools such as PACT are developed to predict earthquake damage repair work. However, literature has identified that (Applied Technology Council, 2018c; Department of Homeland Security & FEMA, 2003), predictions made by these models cannot be used for building-related decision-making processes due to their limitations related to accuracy and reliability. Therefore, as a country that is regularly impacted

by major earthquakes, New Zealand has a clear need for an accurate post-earthquake cost estimation model that can cater to the more significant number of buildings affected by such earthquakes.

1.3 Aim and objectives

The aim of this research is to develop a standardised and more accurate post-earthquake cost estimation model for earthquake damage repair work. The model intends to enhance the cost estimation practices used by practitioners in the construction industry by improving standardisation, accuracy and speed of producing cost estimates. The following objectives were considered:

1. To examine earthquake characteristics, damage to buildings, damage identification methods and cost estimation methods.
2. To examine current practices of cost estimation conducted after an earthquake in New Zealand in order to identify the processes used.
3. To identify the factors that have an impact on cost variations and examine the usage and significance of the identified factors and explore potential methods of incorporating them into a post-earthquake damage estimation process.
4. To develop and validate a model that incorporates the identified factors into a standardised earthquake damage cost estimation process and improves the accuracy and speed of such estimation.

In order to achieve these objectives, this research will focus only on the housing repair cost of earthquake-damaged buildings. Therefore, it excludes the cost of demolition and building it back better, retrofitting or building above code, repair costs related to

lifelines and waste management. However, the research considers the cost of removing damaged elements during repair work.

1.4 Research methodology overview

The research methodology sets out the research design and the assumptions of the research philosophy. This research project took the philosophical stance of pragmatism and used a sequentially mixed methodology. In pragmatism, the focus is on creating solutions using ‘what works’ for the problem (Creswell, 2018; Creswell & Tashakkori, 2007).

As noted above, the mixed research methodology involved qualitative and quantitative inquiry strategies. This combined approach combines the advantages of qualitative and quantitative methods and reduces the limitations associated with using each method exclusively (Creswell, 2018; Creswell & Poth, 2016; Greene & Hall, 2010). The research strategy adopted for this study was an exploratory sequential design in which the research was initiated with the use of a qualitative method to inquire and explore issues with professionals with experience in earthquake damage repair work. Subsequently, a quantitative approach was employed to validate the issues identified with the involvement of a broader population. The sections below outline the methods used for data collection and analysis.

1.4.1 Literature review

A comprehensive scholastic literature review was conducted to gain an in-depth understanding of issues related to the research. The literature was reviewed to gain insight into three areas: the characteristics of earthquakes; the damage caused by

earthquakes and damage identification methods used; and the methods used for damage estimation. Relevant literature was identified through the use of terminology that was identified during the publication review process. Related publications were identified through references and citations. Printed and electronic publications of books, thesis, journal papers, conference papers and government reports and publications from recognised organisations were used in the review. Google Scholar, the Massey University Library index and Scopus were also used to identify relevant literature. It is important to note that the search for and review of relevant publications was limited to those written in English. In addition to providing information about the three aforementioned areas, the literature review was used to identify any gaps in the research, refine the research objectives, understand the factors identified by the grounded theory method, identify tools and techniques that would be needed for the study and identify a suitable methodology for innovation required for the development of a new model.

1.4.2 Semi-structured interviews

Semi-structured interviews were conducted as the initial data collection method of the study, following Strauss's grounded theory (Thornberg & Dunne, 2019). The goal of the interviews was to gain an understanding of the current processes used for cost estimation of earthquake damage repair work, from initial to final stages after the Canterbury earthquake sequence (CEQS). Data analysis of these interviews provided additional sources of information used for cost estimation and revealed factors affecting the cost estimation of earthquake damage repair work. These semi-structured interviews were conducted with professionals who were involved in earthquake damage identification and cost estimation processes. Nineteen interviews were

conducted with quantity surveyors, engineers, engineering technicians and builders; interviewees worked in government, as consultants or in construction companies. The interview template covered three sections: background information, damage identification methods and cost estimation processes.

1.4.3 Survey questionnaire

The issues identified through the interviews were further investigated through a questionnaire survey. The questionnaire survey aimed to identify the factors that affect the repair costs of earthquake-damaged buildings and to collect opinions on how best to incorporate these factors into a cost estimation process. This quantitative survey questionnaire was conducted to capture the experiences and opinions of a broader number of professionals from around New Zealand. The questionnaire was distributed to 310 participants using the purposive sampling method, who had been identified using online directories and databases (e.g. LinkedIn and Master Builders). The data were collected using a cross-sectional online questionnaire. Participants who had experience in cost estimation in earthquake damage repair work were selected through a purposive sampling process.

1.4.4 Model development

In the attempt to develop a post-earthquake cost estimation model for earthquake damage repair work, the main aims of the model were to incorporate the factors affecting the cost estimation of earthquake damage repair work (CEEDRW) into a standard costing process and to improve the accuracy and speed of the process. To achieve this, first, the data collected from the qualitative data analysis was used to identify the factors affecting the CEEDRW and information sources used for cost

estimation. Then, the quantitative data from the survey questionnaire was used to identify the methods that could be used to incorporate the impact of key factors into the CEEDRW process. Next, innovative methods were employed to develop the concept design of the Cost of Damage Repair, Earthquake Estimation Model (C-DREEM) using Teorija Rezhnija Izobretatelskih Zadach (TRIZ) methodology. Based on the concept designs identified, as well as document analysis and professional input, the C-DREEM was developed. Once the model was developed, it was further improved through discussions with the model improvement team, which included professionals with experience in cost estimation. Each iteration of the model was evaluated by the model improvement team until the final output. The final iteration of the C-DREEM consists a three-sectors; identification, quantification, costing and summarisation. These steps were further divided into three sections each. The identification step includes considerations of pre-earthquake state, post-earthquake state and repair method. The quantification step addresses the assessment of repair work, duration and start date, and preliminaries. The costing and summarisation step involve: costing the total repair work, professional services and other costs; summarising total project costs; developing consequential functions; evaluating the outputs. The model also contains four interlinked pillars that work as system mechanics for the cost estimation process. These are the main principle, rate categorisation, repair method classification and the automation process.

1.4.5 Data analysis

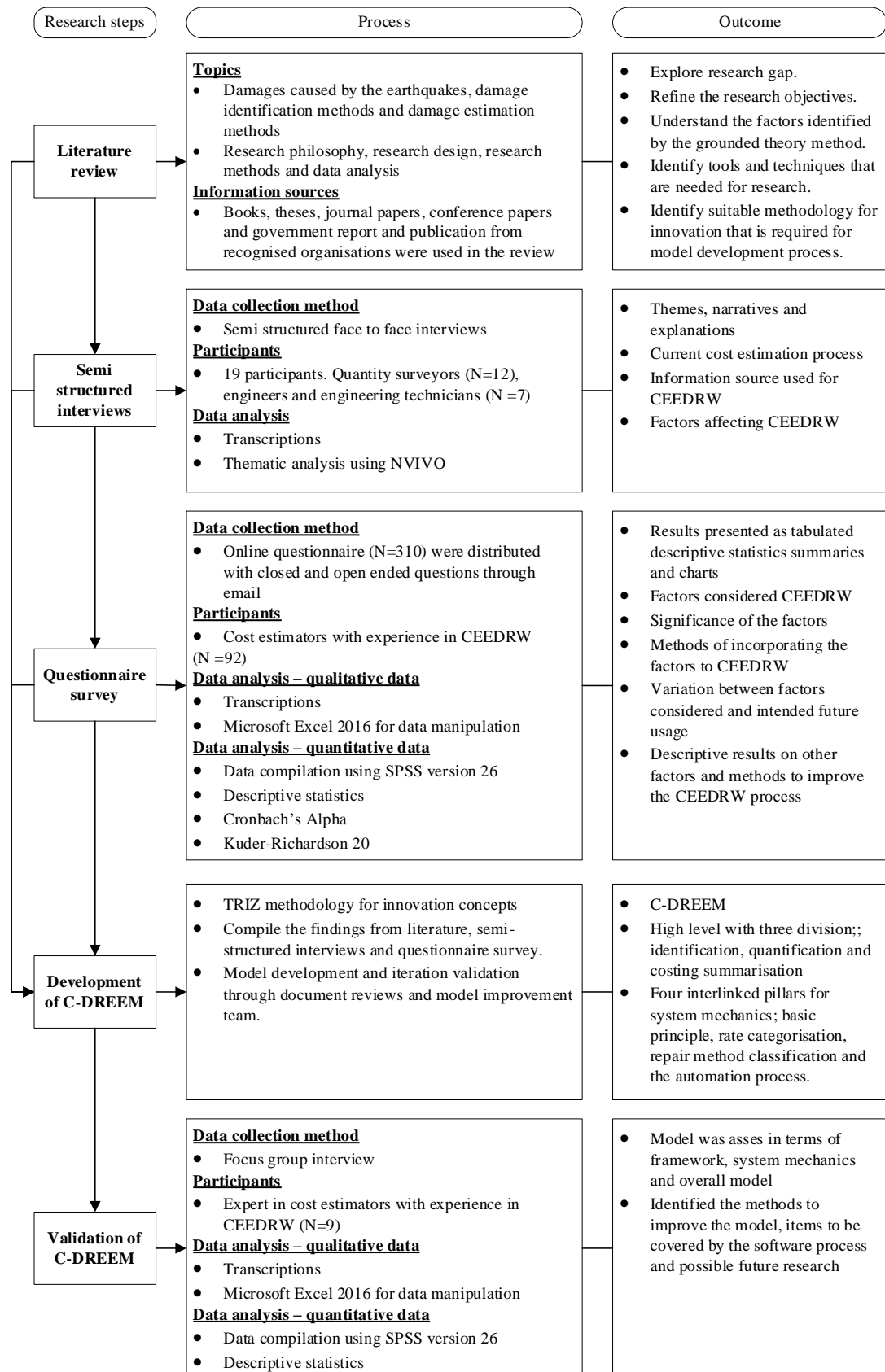
The data collected from the semi-structured interviews were analysed using the thematic analysis method. NVIVO computer software was used for the coding, grouping and category development process. The analysed data was then used to

identify the factors impacting the cost estimation process. The quantitative data of the surveys were analysed using the SPSS (Statistical Package for Social Science) software package (versions 26 and 27). Descriptive statistics were used to analyse the quantitative data. Qualitative results from the open-ended questions in the questionnaires were analysed manually using Microsoft Excel 2016. The steps, process and outcome outlined in the methodology are described in Figure 1.1.

1.4.6 Model validation

The model improvement team and cost estimators from the School of Built Environment, College of Sciences, at Massey University verified the validation process of the final model validation, which was conducted using a focus group interview of professionals. Nine experts in the field of cost estimation for earthquake damage repair in New Zealand, who had responded to the questionnaire, were selected as participants. These participants had not been involved in the model development or improvement process. Participants' opinions of models were collected through a survey questionnaire. The questionnaire posed questions about the main framework, the four pillars of system mechanics and the overall model. The steps, process and outcome outlined in the methodology are described in Figure 1.1.

Figure 1.1 - Research steps, process and outcome



1.5 Contribution to knowledge

The research explored the current processes of CEEDRW used after an earthquake in New Zealand. The outcome of this research is the development of a framework for an information processing system, C-DREEM, to improve the current cost estimation process in terms of standardisation, speed and accuracy.

The findings of the research contribute to the literature on developing a framework for cost estimation for earthquake damage repair work. First of all, the research identified eleven factors that had a significant impact on CEEDRW. Some of the previous studies identified the impact of these aforementioned factors on new construction. However, this is the first identifiable study that directly identifies the significance of these factors on CEEDRW. The study also identified methods that can be used to incorporate these factors to improve CEEDRW processes. These findings were supported by professionals with experience in CEEDRW.

The C-DREEM also provides a framework that can be used to standardise and automate key aspects of the cost estimation process. The model achieves these functions by using sets of standardised micro rates (rates which are smaller than standard rates) rather than ad-hoc or generalised rates that are used in repair work. The standardised rates allow the processes of item identification, quantity calculation and costing to also be standardised. These processes can improve the speed and accuracy of the CEEDRW process.

The research further improves the accuracy of the CEEDRW process through the integration of probability-based tools and the post-earthquake CEEDRW process. The findings from the research revealed that probability damage predictions could be used

to identify initially unforeseen damage, while consequence functions can be used to audit the outputs of post-earthquake CEEDRW processes. In turn, the audit of each post-earthquake CEEDRW process can update the consequence functions used in other pre-earthquake loss estimation tools.

For the practitioners in the industry, the C-DREEM can improve the accuracy and speed of the estimation of costs associated with earthquake damage repair work. The model also provides a blueprint that can be used to standardise the CEEDRW process. The model was developed and validated by cost estimators who have experience in earthquake damage repair work. Therefore, the model will be fit for its purpose with regard to independent certification.

1.6 Structure of the thesis

Chapter 1 - Introduction: This chapter provides an overview and guide to the research proposal. It begins with an introduction to the research, describing its importance. This chapter presents a summary of the proposal, stating background research justification, research aim and objectives, a summary of the research methodology and the key contributions of the study to subject knowledge.

Chapter 2 - Literature Review: This chapter provides a critical review of the literature relevant to the research. It focuses on the characteristics of earthquakes, earthquake damage, damage evaluation methods, cost estimation methods and problem-solving methodology.

Chapter 3 - Methodology: This chapter provides a descriptive overview of the research methodology. It describes literature related to research philosophies, philosophical assumptions, research methodology, research methods, research design

and the validity and reliability of the research. The chapter explains the adopted research design, which involved semi-structured interviews, data collection, a survey questionnaire, the C-DREEM development process and data analysis techniques. The final part of this chapter focuses on measures taken to ensure the reliability and validity of the research.

Chapter 4 - Interview Data Analysis: This chapter presents the semi-structured interview findings. The chapter covers the background information of the participants, the damage estimation process, information sources of cost estimation and factors affecting cost estimation.

Chapter 5 - Questionnaire Data Analysis: This chapter covers the findings obtained from the questionnaire data analysis. The chapter starts with the survey administration process. It outlines the background information, factors considered by current CEEDRW, the significance of the factors and a comparison between current and intended future use. Results are described that were obtained from the open-ended questions regarding factors and methods to improve the CEEDRW process.

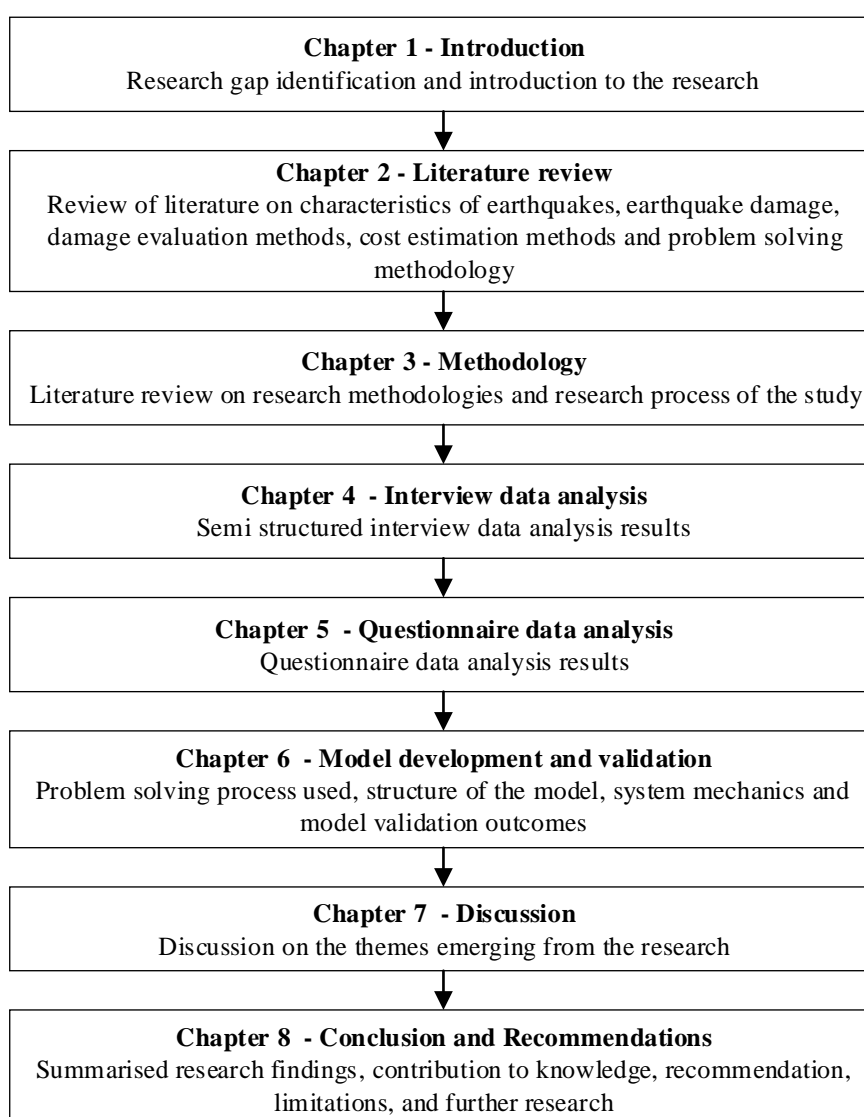
Chapter 6 - Model Development and Validation: This chapter presents the development and validation process of the C-DREEM. The chapter begins with a description of the current state of the CEEDRW process. This is followed by an explanation of the model development process, the aim of the C-DREEM and the structure of the C-DREEM. The results of the model validation process and measures suggested to improve the model conclude this chapter.

Chapter 7 - Discussion: This chapter presents the themes that emerged from the research in comparison with the literature.

Chapter 8 - Conclusion and Recommendations: This chapter summarises the research findings, achievements, specific contributions to knowledge, recommendations and research limitations, and proposes suggestions for possible further research.

Figure 1.2 summarises the structure of the thesis.

Figure 1.2 - Chapter breakdown of the thesis



2

LITERATURE REVIEW**2.1 Introduction**

This chapter focuses on the review of literature that examines the current characteristics of earthquakes, earthquake damage, damage identification methods and cost estimation methods. The section also includes a discussion about TRIZ (Teorija Rezhenjia Izobretatelskih Zadach) methodology that can be used to solve the problems associated with the gap in the research.

The first section of the chapter starts by defining an earthquake. Subsequently, the chapter presents an overview of earthquake characteristics in terms of causes, behaviour, impact, secondary impacts, frequency of occurrence, and measures for forecasting.

The second section of the chapter provides details on the specific types of damage caused by earthquakes to buildings. The chapter discusses the measures used for damage evaluation, levels of damage on different building elements, categorisation of damage, repair methods and damage detection measures.

The third section focuses on the cost estimation measures that can be used in the assessment of earthquake damage repair work. The section deliberates on items

included in project costs, standard methods used for cost estimation, literature related to factors identified through initial data collection and different types of cost estimation methods. The section also includes a comparison between cost estimation methods currently employed by probabilistic tools.

Finally, the chapter focuses on the TRIZ methodology, its characteristics and the process used to solve the problems identified by the research.

2.2 Earthquakes

Earthquakes are a natural hazard affecting most people around the world. Earthquakes can be explained as earth shakings and vibrations caused by the movement of the earth's crust (SMS Tsunami Warning, 2021; USGS Earthquake Hazards Program, 2021b). The World Health Organization (WHO) (World Health Organization, 2021) simplifies the definition of earthquakes as “the shaking of the earth caused by waves moving on and below the earth's surface and causing: surface faulting, tremors, vibration, liquefaction, landslides, aftershocks and/or tsunamis”. The damage caused by an earthquake can be intensified due to its timing, the number of aftershocks and the intensity of each aftershock (World Health Organization, 2021).

The United Nations International Strategy for Disaster Reduction (UNISDR) (2009, pp. 20–21) places an earthquake into the category of ‘natural hazard’, which is defined as a “natural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage”. As a natural hazard, an earthquake can cause damage to economies as well as human life and severely impede socioeconomic development, job creation and poverty reduction measures in society (Silva et al.,

2017). When a community's capabilities and resources cannot cope with a natural hazard, it is called a 'disaster' (United Nations General Assembly, 2016). Therefore, it is essential to understand the characteristics of earthquakes, the resultant impacts and the repair methods required to address such damage.

The occurrence of an earthquake can be due to tectonic movement, human actions, the breakage and sudden movement of ice, or volcanic activity (Jia, 2017c; USGS Earthquake Hazards Program, 2021b). Earthquakes create seismic waves of different types with different velocities along various paths that can affect human-made structures, such as buildings, in populated areas (Bachmann, 2003). The impact of the earthquake depends on the characteristics of each earthquake, for example, its cause, origin, magnitude, intensity, and the seismic waves generated.

2.3 Causes of earthquakes

Volcanic activity is one cause of earthquakes. Normally, most earthquakes generated by volcanic activity are small (Jia, 2017c). However, Bolt (2001) states that some large earthquakes can be related to volcanic activities. Furthermore, earthquakes can also set off volcanic activity. The 1960 Chilean earthquake, the largest recorded earthquake in the world, had a magnitude of 9.5 and created a huge volcanic eruption 48 hours after the actual quake (Lara et al., 2004). This event indicates that earthquakes and volcanic activity are sometimes interrelated, in which case, the devastation caused can be multiplied (Bolt, 2001; Hill et al., 2002).

Human actions and glaciers also generate earthquakes (Jia, 2017c). Human activities, such as the extraction of fossil fuels, underground mining, the disposal of hydraulic fracturing waste, the construction of large reservoirs and rock blasting, have caused

earthquakes around the world (Bolt, 2001; Jia, 2017c). Ice-induced earthquakes are typically triggered by polar glacier melting (Ekstrom, 2003). According to Ekstrom, Nettles and Abers (2003), glacial earthquakes occur when a large mass of ice is displaced over a relatively small distance.

The majority of the most damaging earthquakes result from the movement of tectonic plates (Bolt, 2001). Significant earthquakes, such as the 2010–2011 Canterbury earthquake series in New Zealand (with its ongoing tremors), the Wenchuan earthquake in China in 2008 and the Indian Ocean earthquake and tsunami of 2004, were all caused by tectonic movement in fault areas (Ammon et al., 2005; Gledhill et al., 2011; Li et al., 2008). The devastating results of tectonic earthquakes demand that we have a more explicit understanding of such occurrences.

2.3.1 Tectonic earthquakes

The earth's outer layer is a bulky and stable rocky shell called the 'lithosphere'. This section of the earth's crust and mantle consists of 15 major tectonic plates. The boundaries between these plates, which are also known as 'plate boundary zones', are categorised into four groups according to their movements, as shown in Table 2.1.

Table 2.1 - Types of plate boundary zones (Bolt, 2001; World Health Organization, 2021)

Plate boundary zone	Movement type
Transform faults	Plates move horizontally
Convergent boundaries	Plates move towards each other; one plate moves under the other
Divergent boundaries	Plates move away from each other and create a new plate area
Unknown	The movement of plates is unknown.

The movement between plates in their boundary zones causes tectonic plate earthquakes, which are also known as 'plate edge earthquakes' (Bolt, 2001; Jia, 2017c;

Simkin et al., 2006; USGS Earthquake Hazards Program, 2021b). The movement of plate edge boundaries has caused large shallow earthquakes in regions such as Chile, New Zealand, Peru, the Philippines, Indonesia, Japan, the eastern Caribbean, the south of Mexico, the Alpine-Himalayan belt, Taiwan, the south of Alaska, the Aleutians and Kuriles Islands (Bolt, 2001). Because New Zealand is constantly affected by tectonic earthquakes, this research is primarily focused on this type of earthquake.

2.3.2 Origin of an earthquake

Tectonic earthquakes do not originate from a single location, as they are caused due to ruptures along a length of one or more faults (Jia, 2017a). However, a single point of origin, which is known as the hypocentre, is typically identified as a reference point for a tectonic earthquake (Beroza & Kanamori, 2007). Earthquakes are categorised according to the depth of their hypocentre. They are categorised as ‘shallow focus’ if their depth is less than 50km; those with an ‘intermediate focus’ have a depth of between 50km and 300km, and ‘deep focus’ earthquakes have a depth below 300 km (Bai et al., 2017).

Past data shows that shallow earthquakes account for most of the damage caused globally. Bolt (2001) claims that 75 percent of the total energy released from recorded earthquakes is from shallow earthquakes. In New Zealand, the significant earthquakes experienced in the last decade have all been shallow earthquakes. Three significant earthquakes – Darfield, Canterbury, in 2010, Christchurch in 2011 and Kaikoura in 2016 – have all had shallow hypocentres, as shown in Table 2.2.

Table 2.2 - Magnitude and hypocentre of depth of significant earthquakes in the world (Adopted from GeoNet, 2021a; USGS Earthquake Hazards Program, 2021a; X. Wang et al., 2013; Z. Wang et al., 2015)

Country or Region	Area	Year	Magnitude	Depth of hypocentre
New Zealand	Kaikōura	2016	7.8	15 km
Japan	Kumamoto	2016	9.1	29 km
Nepal	Khudi	2015	9.1	29 km
China	Yunnan	2014	6.2	12 km
China	Lushan	2013	7.0	14 km
Italy	Emilia-Romagna	2012	9.1	30 km
Japan	Sendai	2011	9.1	29 km
New Zealand	Christchurch	2011	7.2	11 km
Chile	Santiago	2010	8.8	23 km
Haiti	Port-au-Prince	2010	7.0	13 km
New Zealand	Canterbury	2010	6.2	5 km
China	Wenchuan	2008	8.0	20 km
Japan	Honashu	2004	6.6	16 km
South Asia	Sumatra	2004	9.1	30 km

2.3.3 Seismic waves

The most significant damage caused by earthquakes results from the generation of seismic waves. Seismic waves have two primary locations of occurrence, the hypocentre and the epicentre. The actual location of the origin point of the seismic wave in the earth is known as the ‘hypocentre’ or ‘earthquake focus’. The projected point of this hypocentre on the ground surface is called the ‘epicentre’ (Bolt, 2001; Jia, 2017c). The generated earthquake waves can be divided into two main categories according to their direction of travel: ‘body waves’ and ‘surface waves’ (Kusky, 2008). Body waves travel from the hypocentre. When they travel through the earth to its surface, body waves generate surface waves, which travel along the earth’s surface. If

the earth medium has layers in it, the third type of wave is generated from body waves; these are called ‘guided waves’ (Jia, 2017a; Kusky, 2008).

Body waves consist of primary waves (P-waves) and secondary waves (S-waves), which are also called ‘shear waves’ or ‘transverse waves’ (Kusky, 2008). P-waves are the first to arrive at a location and create a push-pull motion of particles. In the 2011 Tohoku earthquake in Japan, P-waves ranged in speed from 1600 meters per second to 1800 meters per second in the earth’s upper sedimentary layer, to 7700 meters per second to 7900 meters per second in the oceanic upper mantle (Nakahigashi et al., 2012). P-waves normally create less damage to buildings, however, if the building is near a tectonic plate rupture, these waves can create significant damage to it (Jia, 2017a). S-waves travel more slowly than P-waves, with speeds of around 3.5 kilometres per hour, and have a higher amplitude than P-waves. S-waves also differ from P-waves in that they transmit energy through shear action. As a result, such waves do not travel through a liquid, and the resulting movement of particles is perpendicular to the direction of the motion (Jia, 2017a; Kusky, 2008). This perpendicular action of particles occurs across shear horizontal (SH) and shear vertical (SV) plains, thus creating horizontal and side-to-side motions (Jia, 2017a).

Surface waves travel in paths parallel to the earth’s surface and are created when P-waves and S-waves interact with the earth’s surface. They consist of two types, Love waves and Rayleigh waves. Rayleigh waves are a combination of P-waves with push-and-pull motions and S-waves with vertical perpendicular (SV) actions (Takaji Kokusho, 2017). This combination of waves creates a motion similar to ocean waves. Love waves contain only the horizontal movement of S-waves creating a ‘zig-zag’ motion on the ground. Surface waves travel more slowly than body waves, and will create peak ground acceleration only if the epicentre is at a distance, for example,

where the ground may be more than twice the thickness of the earth's crust (Jia, 2017a).

Guided waves are a type of body wave that travels through a medium channel of layers in the earth, such as through an area with coal seams. These waves are Love-guided waves (Lg), Rayleigh-guided waves (Rg) and tertiary waves (T-waves). Lg and Rg waves are high-frequency waves (Jia, 2017a). T-waves, which are considered as acoustic signals from an earthquake, can be observed in coastal zones where earthquakes occur in underwater regions (J. Lee et al., 2019). This form of the wave travels between 700m to 1300m below the sea surface in channels at speeds of around 1500 meters per second (Jia, 2017a).

2.3.4 Magnitude, intensity and peak ground motions

The terms 'magnitude' and 'intensity' refer to measurements which can be used to estimate or determine the size and impact of earthquake waves (Jia, 2017a). Magnitude, which is measured using seismograms, is an effective measurement of the maximum amplitude of the waves produced by the earthquake (Beroza & Kanamori, 2007). There are many scales by which magnitude is reported: the Richter scale, surface wave magnitude, body-wave magnitude and moment magnitude (Richter, 1935; Scawthorn & Chen, 2003). The Richter scale is a globally recognised measure of the size of an earthquake. Due to instrumental characteristics, the Richter scale can measure earthquakes with an epicentre located within 600 km (Jia, 2017a). Body wave magnitude and surface wave magnitude, as the names suggest, are measures of the size of the body waves and surface waves generated by an earthquake, respectively. Strong earthquakes, those above 6.5 magnitude, are measured using the moment magnitude method, which uses seismic moments generated during the rupture of faults (USGS

Earthquake Hazards Program, 2021b). A comparison of these magnitude-measuring tools is given in Table 2.3.

Table 2.3 - Comparison of earthquake magnitude-measuring parameters (Jia, 2017a)

Item	Richter magnitude	Body wave magnitude	Surface wave magnitude	Moment magnitude
Wave type measured	S- and Le-waves and higher-order surface waves	P-waves	Rayleigh waves	Physical modelling of faults rather than measuring ground motions
Applicable earthquake focal depth	Mostly shallow However can be used for deep	Deep	Less than 70 km	Shallow and deep
Applicable epicentre distance	Less than 600 km	Not available	More than 1000 km	Not available
Measurable magnitude	Less than 6.5	Less than 7.5	Less than 6 - 8	Used for earthquakes with moment magnitude >3.5
Measured wave amplitude period (in seconds)	0.8s	1–5s	3–20s	Not available

An earthquake's intensity is determined based on the severity of its impact on a specific site (Scawthorn & Chen, 2003). Intensity is a qualitative measure based on the human response, damage caused to structural and non-structural components and effects on the environment, such as the movement of furniture (Jia, 2017a). The most common intensity-measuring methods are the Modified Mercalli Intensity Scale (MMI), the Medvedev-Sponheuer-Karnik (MSK) scale, the Japan Meteorological Agency (JMA) intensity scale, and the Chinese Seismic Intensity scale (Jia, 2017a; Shabestari & Yamazaki, 2001; Yuan, 2008). The MMI scale, with twelve steps indicating the effect of the earthquake, is the most used method (H. O. Wood & Neumann, 1931). Due to the subjective nature of intensity, different countries have

their own intensity scale. New Zealand's GNS Science (2021b) and GeoNet (2021b) have provided the steps and descriptions of intensity as shown in Table 2.4.

Table 2.4 - Definition of different categories of MMI (GeoNet, 2021b; GNS Science, 2021b)

MMI	Category	Impact and description
I	Imperceptible	Very few people barely sense it
II	Scarcely felt	People at rest in houses and upper floors feel it.
III	Weak	Light vibration is felt indoors. The slight swinging of hanging objects might occur.
IV	Largely observed	Typically observed as a slight jolt indoors. It might wake light sleepers. Creaking of walls. Rattling glassware, crockery, doors or windows.
V	Strong	Felt by almost everyone indoors. Generally felt by people outdoors. Most sleeping people are awakened, and a few people are alarmed. Movement overturns and shifts small objects. Knocks down pictures from walls. Breaks some glassware and crockery. It might swing open or shut any loosely secured doors.
VI	Slightly damaging	All people feel it. Alarms people and animals, making many run outside. Causes difficulty walking. Overturns and shifts furniture and appliances on smooth surfaces. Breaks glassware and crockery. Objects fall from walls and shelves. Damage to buildings may be slight and non-structural.
VII	Damaging	Widespread alarm. People experience difficulty standing. Overturns and shifts furniture and appliances. Damages fragile or unsecured objects substantially. Damages a few weak buildings.
VIII	Heavily damaging	Alarms may approach panic levels. Damages a few buildings. Destroys some weak buildings.
IX	Destructive	Damages some buildings. Destroys many weak buildings.
X	Very destructive	Damages many buildings. Destroys most weak buildings.
XI	Devastating	Damages most buildings. Destroys many buildings.
XII	Completely devastating	Damages all buildings. Destroys most buildings.

Measuring peak ground motions provides a more direct method to assess and report the impact of earthquakes on a given site (Jia, 2017a). Peak ground motions are primarily reported in terms of acceleration, velocity and displacement. Peak ground acceleration (PGA) is the maximum amplitude of recorded acceleration while the earthquake is shaking, measured in three directions, two horizontal and one vertical (Scawthorn & Chen, 2003). The 2016 Kaikōura earthquake in New Zealand recorded a PGA of three times the acceleration due to gravity (Wotherspoon et al., 2017). Two

less commonly used measures are Peak Ground Velocity (PGV), which measures the largest speed of shaking at a given point during an earthquake, and Peak Ground Displacement (PGD), which measures the distance moved by an initial point to its final point of rest after an earthquake (Beer et al., 2015).

Many studies have been conducted to find a correlation between intensity and peak ground motions. However, the relationship between peak ground motion and reported intensity varies with building construction, improvements in buildings through time and past experiences of earthquakes by the population (Caprio et al., 2015; Pailoplee, 2012; Wald et al., 1999).

Finally, parameters like the duration of the ground motion and the pattern of ground motion arrival at a location are also measured to record the impact of an earthquake on a location (Jia, 2017a). Information records of such ground motions are referred to as 'seismographs' or 'time histories' (Scawthorn & Chen, 2003).

2.3.5 Aftershocks and foreshocks

When most moderate and significant earthquakes occur, the main quake is followed by smaller quakes which originate from the same area and last for months after the primary earthquake (Bolt, 2001). These are called aftershocks. According to GNS Science (2021a), more than 15,000 aftershocks have occurred since the Darfield quake in September 2010, which was the initial major earthquake in the Canterbury earthquake sequence. Foreshocks are earthquakes that happen before the main earthquake. A foreshock with a magnitude above three on the Richter scale, was recorded a few days before the first primary earthquake in the Canterbury earthquake sequence (GeoNet, 2021d). Earthquakes cannot be considered, therefore, as a single

tremor but as a series of events. The sequence of events related to the foreshocks, main shocks and aftershocks that occurred in Canterbury in 2010 and 2011 have been labelled the ‘Canterbury earthquake sequence’ (CEQS) (Christophersen et al., 2013). The impacts of aftershocks, in general, are noticeable as they are able to increase the damage caused by the main tremor and create new damage (Dhakal, 2010).

2.3.6 Earthquake-induced hazards

Losses associated with earthquakes can result from a number of factors other than the main shaking caused by earthquake waves. These factors are called ‘earthquake-induced hazards’, and include soil liquefaction, landslides, tsunamis, fires, seiches and surface faulting (Applied Technology Council, 2018c; Bachmann, 2003; Jia, 2017b). Earthquake-induced hazards are recognised for their potential to cause major damage.

2.3.6.1 Soil liquefaction

One form of post-earthquake ground condition, soil liquefaction, occurs when soil loses its rigidity and behaves like a liquid. This leads to shear deformation of the soil (Beroza & Kanamori, 2007). Liquefaction results in the loss of the bearing capacity of the soil, ground surface settlement and soil displacement on slopes (Jia, 2017b). Soil liquefaction is observed in certain types of liquefiable sediments like sand and mud (Kusky, 2008).

Liquefaction causes significant damage to buildings. Over US \$1 billion worth of damage was estimated to have been the result of a 1964 earthquake in Japan; most of this was damage to buildings caused by liquefaction (Jefferies & Been, 2016). In the 2008 Wenchuan earthquake in China, newly developed buildings on reclaimed land

along the Minjiang river were severely damaged or destroyed due to cracking and unequal settlement associated with soil liquefaction (Huang & Jiang, 2010). Most liquefaction damage occurs near a rupturing fault, but during a 1964 earthquake in Alaska, significant liquefaction-related damage was observed 100 km away from the epicentre (Bartlett, 2021; Beroza & Kanamori, 2007). In New Zealand, unprecedented damage from liquefaction was observed in the CEQS (Orense et al., 2011) and, most recently, in the 2016 Kaikōura earthquake (Cubrinovski et al., 2017). According to Orense et al. (2011), aftershocks associated with the Canterbury earthquake sequence also caused substantial liquefaction damage to buildings.

2.3.6.2 Landslides

Many things can trigger landslides. One such thing is an earthquake (Malamud et al., 2004). Waves created by earthquakes can sometimes produce landslides that cause damage exceeding that which is created by ground shaking and fault rupture (Jia, 2017b). According to a study that analysed forty landslides, earthquake-induced landslides can be categorised as ‘disrupted slides’, ‘coherent slides’ and ‘lateral spreads and flows’ (Keefer, 1984). Disrupted landslides consist of falling and bouncing boulders and rock fragments. The sliding or rotation of complete rocks or blocks of soil and the slow flow of earth are considered characteristic of a ‘coherent slide’. If a landslide has a fluid-like motion, it is considered to fall into the category of ‘lateral spreads and flows’. According to Keefer (2002), a disrupted slide can be caused by lower intensity ground shakings. The minimum shake intensity of an earthquake recorded to have set off a disrupted landslide was MI IV (Keefer, 2002).

Earthquake-induced landslides have been documented since 1789 BCE (Before the Common Era) and have caused significant casualties and considerable economic

losses (Keefer, 2002). In 1970, an earthquake in Peru set into motion a massive avalanche from the peak of Mount Huascarán, which travelled at a speed of 320 km per hour 15 km down the mountain and buried 18,000 people (Bolt, 2001). Earthquake-induced landslides were also witnessed in New Zealand after both the CEQS (G. Dellow et al., 2011) and the 2016 Kaikōura earthquake (S. Dellow et al., 2017).

2.3.6.3 Tsunamis

Tsunamis are gravity-driven waves created at sea locally or at a distance from land due to a substantial displacement of the ocean floor. These waves may be created by large earthquakes, exploding volcanos or major submarine slides (S. N. Ward, 2011). Massive tsunamis generated by the 1896 Honshu earthquake in Japan, the 2004 earthquake in Sumatra and the 2011 Tohoku earthquake in Japan caused more than 26,000 (Bolt, 2001), 220,060 (Munich Re Group, 2020) and 15,889 (Uehara & Yan, 2017) fatalities, respectively. Clearly, the impact of a tsunami can be massive. Coastal engineering methods like breakwaters and early warning systems such as the Seismic Sea Wave Warning System are used internationally to mitigate problems associated with tsunamis (Bolt, 2001).

2.3.6.4 Fires

Earthquake-induced fires cause damage in addition to those caused by the earthquake itself. This is due to factors such as fires occurring simultaneously in many places, damage to building fire suppression systems, restricted access to damaged areas and a high demand for fire personnel for other services (S. Lee et al., 2008). Significant casualties and damage from earthquake-induced fires were observed in earthquakes in San Francisco (1906), Loma Prieta (1989) and Northridge, California (1994), Tokyo

(1923) and Kobe (1995), Japan, and Marmara, Turkey (1999) (Mousavi et al., 2008). More than 293 fires were recorded after an earthquake in Tohoku, Japan, in 2011 (Elhami Khorasani & Garlock, 2017). Modern engineering has reduced the severity of major fires in earthquake scenarios, however, they remain a serious concern.

2.3.6.5 Seiches

Seiches are standing waves generated by earthquakes in closed bodies of water, such as ponds, reservoirs, bays, lakes, harbours and swimming pools (McGarr, 2020; Suzuki, 2012). Seiches are extremely rare but were reported to have occurred during earthquakes in Lisbon (1755), Alaska (1964) and Denali (2002) (Canitano et al., 2017). During the 2011 Tohoku earthquake, seismic waves triggered seiches of one metre in height in Lake Saiko, a body of water about 300–500 km away from the earthquake region (Suzuki, 2012).

2.3.6.6 Surface faulting

Surface faulting is the “displacement that reaches the earth’s surface during slips along a fault” (USGS Earthquake Hazards Program, 2021b) as a result of cracks opening up. When compared with earthquake shaking damage, Bolt (2001) states that, while surface faulting damage is rare, it can be frightening and extreme local damage can occur. Such damage was seen after earthquakes in Borah Peak (1983), Wenchuan (2008) and Darfield (2010) where average rupture zones of 0.8 m, 4–5 m and 2.5 m were recorded with 2.7 m, 6.5 m and 5.3 m extremes, respectively (Crone & Machette, 1984; Quigley et al., 2012; Xu et al., 2009). According to Bonilla (1988), surface faulting can be caused by earthquakes with magnitudes of five or six and can damage buildings.

2.3.7 Impact of earthquakes on countries

The behaviour of an earthquake is different in each situation. When considering earthquakes in general, average quakes last around 10–20 seconds (Bachmann, 2003). An example of a longer-lasting earthquake is one that occurred in 2004 off the west coast of the northern Sumatra islands, which had a magnitude of 9.1 on the Richter scale and lasted over 10 minutes (USGS Earthquake Hazards Program, 2021a; Walsh et al., 2016). This earthquake and the subsequent tsunami created the highest overall monetary loss associated with an earthquake up to that point in time; losses totalled US\$ 9.5 billion (Munich Re Group, 2019).

The magnitude of an earthquake, rather than its duration, is the primary measure of its power. The greatest magnitude for an earthquake was recorded during an earthquake in Chile in 1960 which had a magnitude of 9.5 (USGS Earthquake Hazards Program, 2021a). A more recent earthquake, which by far exceeded the costs associated with the event in Sumatra, resulted in losses of over US\$ 210 billion (excluding costs associated with the Fukushima power plant) and 15,889 fatalities (Krausmann & Cruz, 2013; Uehara & Yan, 2017). This devastating event was the 2011 earthquake and tsunami in Sendai, Japan. The 2010 earthquake in Haiti caused 316,000 fatalities, the largest number of deaths associated with an earthquake in recent years (DesRoches et al., 2011). A list of major historical earthquakes and their impact on human life and damage is detailed in the following Table 2.5.

Table 2.5 - Financial losses and fatalities from significant earthquakes occurring from 1985 to 2016 (DesRoches et al., 2011; Jia, 2017b; Munich Re Group, 2017)

Country	Location	Year	Loss (USD billion)	Loss-adjusted for inflation	Loss (% GNP)	Fatalities
Japan	Kumamoto	2016	32	32	0.59	205
Khudi	Nepal	2015	4.8	4.8	N/A	8,868
China	Yunnan	2014	5	5	0.03	617
China	Lushan	2013	6.8	6.6	0.04	196
Italy	Emilia-Romagna	2012	16	14	0.75	18
Japan	Sendai	2011	210-	162	3.8–5.4	15,880
New Zealand	Christchurch	2011	15	22.1	10	1
Chile	Santiago	2010	30	27.7	19	520
Haiti	Port-au-Prince	2010	8	7.4	121	316,000
New Zealand	Canterbury	2010	10	10.5	5.3	0
China	Wenchuan	2008	85	107	1.8	86,445
Japan	Honashu	2004	28	15.1	N/A	46
South Asia	Sumatra	2004	15	9.5	N/A	220,060
Japan	Kobe	1995	100	89.8	2.0	6,430
Iran	Manjil	1990	7.1	13	7.2	40,000
USSR	Armenia	1988	14	28.4	3	25,004
EL Salvador	San Salvador	1986	1.5	3.3	31	1,000
Greece	Kalamata	1986	0.8	2	2	20
Mexico	Mexico City	1985	4	8.1	3	9,500

When the different costs and damage arising from all major earthquakes from 1980 to 2018 are added together, the accumulated totals show that earthquakes have caused over 822,499 fatalities and an economic loss of over US\$ 9135 billion globally (Munich Re Group, 2020).

Clearly, as a natural hazard, an earthquake can have a significant impact on our social, economic and environmental well-being. The impact of earthquakes, in general, can be better illustrated when they are compared with other natural hazards. One such comparison between 1980 and 2018 demonstrated that 56 percent of fatalities and 25.6

percent of the monetary losses associated with natural hazards were due to geophysical events such as earthquakes and volcanoes (Munich Re Group, 2020).

2.3.8 Frequency of earthquakes

An earthquake is a high-impact risk. Thus, it is essential to understand the frequency with which earthquakes occur. As indicated by data for earthquake occurrence from 1990 to 2019, there were, on average, 1,665 earthquakes a year, among which, 14 significant earthquakes of above 7.0 magnitude on the Richter scale caused most of the damage. Further, between 1990 and 2019, 30 earthquakes recorded a magnitude of 8.0 or above on the Richter scale (USGS Earthquake Hazards Program, 2021d). This data is summarised in Table 2.6.

Table 2.6 - Occurrence of earthquakes worldwide from 1990 to 2019 (USGS Earthquake Hazards Program, 2021d)

Size	Magnitude (Richter scale)	Total number of earthquakes	The average number of earthquakes per year
Great	8.0 and above	30	1
Major	7.0-7.9	425	14.2
Strong	6.0-6.9	4108	136.9
Moderate	5.0-5.9	45409	1513.6
Total		49972	1665.7

2.3.9 Unpredictability of earthquakes

Given that earthquakes occur relatively frequently and that each carries a significant risk of high impact, it is essential to be able to forecast future earthquakes. However, earthquakes, are harder to predict than other natural hazards because they often occur without warning (Jia, 2017c). Even though Geller (1997, p. 443) concluded that the

‘occurrence of individual earthquake is unpredictable’, some are attempting to understand and predict earthquake occurrence using precursor signals. These precursor signals which arise prior to the earthquakes include water level changes (Roeloffs et al., 1997), changes in water geochemistry which include radon and halogen gas emissions (Padron et al., 2013; Tsunogai & Wakita, 1995), variation in seismic velocities (Whitcomb et al., 1973), thermal anomalies on the earth’s surface (Tronin et al., 2002) and the concentration of ions in the ionosphere (Jia, 2017b). In addition to these signals, unusual behaviour is often observed in animals before an earthquake event; this can also be used to forecast earthquakes (Bhargava et al., 2009). Research has been conducted on the behaviour of animals to assess their reactions to magnetic field variations, humidity changes, ground tilting and electric currents associated with earthquakes (Bhargava et al., 2009; Hayakawa, 2013; Kirschvink, 2000).

Studies of such precursor signals are still being explored, and a final forecasting method is yet to be implemented. If such a method is developed, the number of fatalities and injuries and the destruction of valuable items can be reduced, but damage to buildings cannot be avoided. Thus, earthquake mitigation methods are needed to reduce earthquake damage or earthquake-induced damage.

2.3.10 Unique characteristics of earthquakes compared to other natural hazards

Based on the characteristic of earthquakes, we can create a comparison between earthquakes and other natural hazards to understand their impact. According to Munich Re Group (2020), Geophysical events, which include earthquakes and volcanic activities, only account for 8.7 percent of the total number of natural loss events that occurred from 1980 to 2018. However, geophysical events account for 49.1 and 19.7

percent of the total fatalities and monetary losses caused by natural loss events, respectively.

Earthquakes also occur in a matter of seconds, similar to lighting, but other disaster takes longer (Alexander, 2018). For example, tornado, floods, and hail hit in minutes; windstorms, hurricanes, and snowstorms fall in hours; droughts happen in months; and expansive soil and some volcanic eruptions takes years (Alexander, 2018). Alexander (2018) expresses that forewarning time available for disasters and earthquakes, similar to lighting, might have seconds forewarning while tsunamis and floods have minutes and windstorms, hurricanes, and snowstorms can have hours. This illustrates that loss-causing earthquake events occur less frequently but can occur suddenly with high impact without much forewarning.

2.4 Earthquake damage and damage evaluation process

As described in the previous section, earthquakes can cause substantial damage to buildings and produce induced hazards. A major portion of the damage caused to buildings results from ground shakings (Beroza & Kanamori, 2007). Therefore, its essential to understand how the shaking associated with an earthquake causes damage to buildings.

Ground shaking from global or local failures may cause damage to foundations, structures, and the surroundings of buildings. Localised damage to building components will affect a limited area of a given building, whereas global damage will affect the stability of the overall building (Wellington City Council, 2017). At the beginning of an earthquake, shaking is transferred to the foundations and then to the superstructure. In a building with a weak foundation, the connection between

foundation and structure will be damaged. However, in a building with a strong foundation, the shaking energy will be shifted upwards, creating damage to the superstructure. When the overall building structure is strong and integrated with its foundation, it can withstand the most severe earthquakes (Jia, 2017b). In addition to being vulnerable to ground shaking, buildings can also be damaged by earthquake-induced hazards such as fires, landslides, tsunamis and soil liquefaction, as explained in Section 2.3.6.

Depending on the earthquake, the environment, the building structure and its elements, damage to a given building will vary. An earthquake building evaluation will allow for an approximate estimation of the extent of damage and costs associated with a given earthquake event.

2.4.1 Damage evaluation methods

After an earthquake, building evaluations are conducted to evaluate the damage to buildings. Building evaluations are used to assess the safety for occupancy and to provide a detailed identification and evaluation of the damaged building elements (Nakano et al., 2004). Therefore, damage evaluations become an information source for final project cost estimations. Building evaluations can be divided into ‘initial evaluations’ and ‘detailed evaluations’. Damage evaluation specified here focus only evaluate the damage and specify how the building elements are affected by the earthquake. This does not contain repair cost or damage repair methods.

In a post-earthquake scenario, building damage can be evaluated initially using rapid evaluation methods (Ministry of Business Innovation and Employment, 2015). In the United States of America, the ‘ATC-20-1 Field Manual: Post-earthquake Safety

Evaluation of Building’ (Applied Technology Council, 2015) has been adopted as an evaluation manual. Based on the ATC-20-1, the Level 2 Rapid Assessment Method was developed for use in New Zealand (Ministry of Business Innovation and Employment, 2015). Both of these initial evaluation methods categorise buildings into two groups: ‘simple residential’ and ‘complex residential / non-residential’. During an initial building evaluation, complex residential and non-residential buildings are further subdivided into seven types according to the building structure (Ministry of Business Innovation and Employment, 2015; R. P. Gallagher Associates & Applied Technology Council, 2005). A comparison of how these seven types of buildings are categorised in NZ and the USA is shown in Table 2.7.

Table 2.7 - Building type comparison (Applied Technology Council, 2015; Ministry of Business Innovation and Employment, 2015)

Building categorisation in New Zealand	Building categorisation in the USA
Timber-framed structures (1)	Wood frame (A)
Reinforced concrete or masonry wall construction (2)	Reinforced masonry (B)
Reinforced concrete frame construction (3)	Concrete frame (C)
Precast concrete tilt-up structures (4)	Tilt-up concrete (D)
Suspended concrete floors (5)	-
Steel frame structures (6)	Steel frame (E)
Unreinforced masonry (URM) structures (7)	Unreinforced masonry (F)
-	Other (G)

According to the literature, the initial evaluation method used most recently in New Zealand, the Level 2 Rapid Building Assessment (RBA), involved the visual inspection of a building for earthquake damage in order to determine the safety of occupancy (Ministry of Business Innovation and Employment, 2015). The evaluations described only gave a general idea of the damage to the building.

Studies reveal that, generally, after the RBA of the building, Interim Use Evaluation (IUE), Targeted Damage Evaluation (TDE) or Detailed Damage Evaluation (DDE) were conducted (Wellington City Council, 2017). In cases in which TDE was used, the primary purpose of the TDE was to qualitatively evaluate and ensure the safety of buildings (Ministry of Business Innovation and Employment, 2015; Wellington City Council, 2017). This method identified and evaluated hotspots in buildings where damage would be most likely to occur and cause critical building failures (Brunsdon et al., 2017). These hotspots were identified by analysing buildings with similar characteristics. Therefore, TDE was only conducted on buildings with the required profiles. RBA and TDE were less likely to result in detailed accounts of all the damage to a building that required repairs, however, these methods were able to indicate damage that had occurred in the initial stages. In cases in which DDE was used, this method was employed to specify the damage to a building in a qualitative and quantitative manner (Brunsdon et al., 2017). The process of damage evaluation of non-residential buildings is expressed in the targeted building assessment guide used to assess the Kaikōura earthquake of 2016 (Wellington City Council, 2017). For this event, the RBA assessment was followed by a TDE and a DDE. By combining these evaluation methods, the levels of damage were better able to be identified.

2.4.2 Level of damage to different building elements

An earthquake can do different levels of damage to a variety of building elements. According to The Ministry of Business Innovation and Employment (MBIE) (2017), damaged building elements can be categorised into two main groups, structural and non-structural. Primary damage evaluation methods like TDE tend to focus on structural damage because such damage can affect the stability and safety of the

building (Ministry of Business Innovation and Employment, 2015; Wellington City Council, 2017). However, when estimating the overall associated repair costs of a building, both structural and non-structural damage must be taken into consideration (Taghavi & Miranda, 2003).

2.4.2.1 Structural damage

‘Structural elements’, which are also referred to as ‘primary structural elements’, can be defined as elements that transfer gravitational and lateral loads of the building to the ground (Ministry of Business Innovation and Employment et al., 2017). MBIE’s (2015) RBA and the Applied Technology Council’s (2005) ATC-20-1 Field Manual specify the elements that must be observed in order to assess primary structural damage and offer examples for each element. These elements are foundations, roofs and floors, gravity systems, lateral systems, diaphragms and horizontal bracing, precast connections and ‘other’ (Applied Technology Council, 2015).

A review of the literature revealed that different types of damage were observed in reinforced concrete framed buildings. For example, the following information in Table 2.8 confirms what was observed during the Canterbury earthquake sequence (CEQS).

Table 2.8 - Damage to structural elements observed in buildings associated with the CEQS (American Society of Civil Engineers, 2007; Ministry of Business Innovation and Employment, 2015; Ministry of Business Innovation and Employment et al., 2017)

Element type	Damage
Column	Columns out of plumb or leaning storey(s)
	Shear failure of columns (ex-axial shear failure)
	Deformation or buckling of column reinforcement
	Cracking and spalling with or without reinforcement exposure (ex-torsion cracks)

Element type	Damage
	Decrease in strength of columns (Decrease in the flexure capacity (stress at bending failure) of plastic hinges, moment capacity and gravity bearing capacity)
Non-ductile columns	Lack of capacity to hold the load from displacement drift
	Loss of gravity-bearing capacity
Column-beam joints	Diagonal cracking of column-beam joints
	Shear damage or failure
Beams	Cracking and spalling of end regions of beams (horizontal cracks and openings)
	Deformation of beams
	Compression and shear damage
	Single cracks with decreased strength in the element
	Internal tension failure of reinforcement
Floor	Tearing of floor diaphragms and differential settlement
Cladding	Raking of cladding
	Damaged cladding connections
Infill walls	Cracking and spalling of concrete
	Reduction in tensile strength
	Crushing and buckling in the boundary regions
	Local lateral instability and focused compression on regions

2.4.2.2 Secondary structural and non-structural (SSNS) damage

‘Secondary structural elements’ are structural elements that are not part of the primary structure but are used to transfer the inertial and gravity loads (Ministry of Business Innovation and Employment et al., 2017). These include stairs, curtain wall framing systems, support to significant building services items and precast concrete panels. ‘Non-structural elements’ are items that do not form part of the primary or secondary structure (Ministry of Business Innovation and Employment et al., 2017). Examples are partitions, exterior cladding, ceilings, mechanical components, building contents and electrical components. According to Ferner et al. (2016), 70 percent of the value of a building can be attributed to its non-structural components. According to the

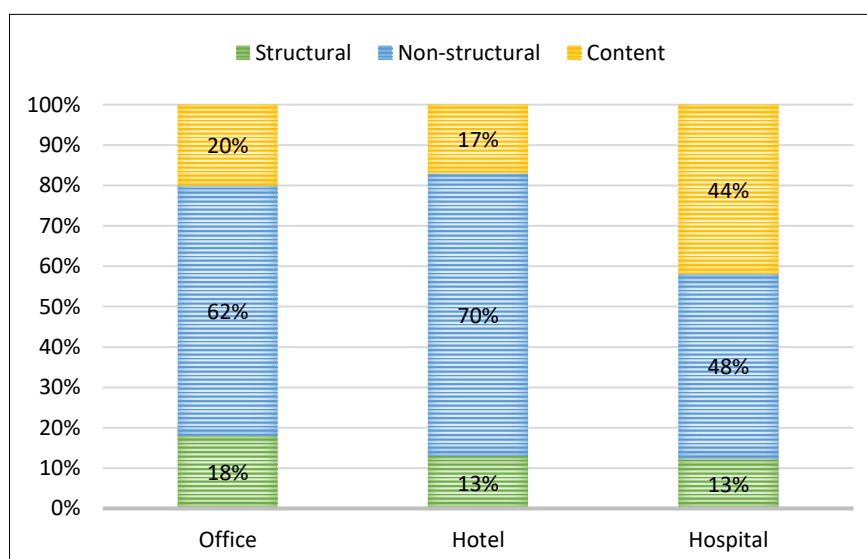
American approach, the following items in Table 2.9 can be categorised as secondary and non-structural components (American Society of Civil Engineers, 2007).

Table 2.9 - Categorisation and elements of SSNS (Almufti & Willford, 2013; source - American Society of Civil Engineers, 2007; Applied Technology Council, 2018d; Ministry of Business Innovation and Employment et al., 2017)

Category	Element
Secondary structural components	Precast concrete panels
	Curtain wall framing systems
	Stairs and fire escapes
	Significant building service items
	Heavy internal partitions
	Large building ornaments
Non-structural - architectural components	Cladding
	Glazing
	Light partitions
	Ceilings
	Light parapets and ornaments
	Canopies and marquees
	Doors
Non-structural - mechanical components	Elevators
	Heating, ventilation and air conditioning equipment
	Manufacturing equipment
	Ducts
	Piping
	Fire sprinkler and fire alarm systems
	Emergency lighting
	Electrical distribution equipment
	Light fixtures
	Plumbing
Non-structural - contents	Computer systems
	Desktop equipment
	File cabinets
	Bookshelves
	Hazardous material
	Art objects

Modern buildings are designed to withstand structural damage caused by earthquakes. Although structural damage from earthquakes is mostly found in older buildings, non-structural damage can be observed in all types of buildings (Dhakal et al., 2011, 2016; Whittaker & Soong, 2003). Taghavi and Miranda (2003), in their investigation of offices, hotels and hospitals, demonstrated that, comparing costs associated with the repair of structural components, non-structural components and contents, the repair of non-structural elements required the majority of the expenditure for all types of buildings (refer Figure 2.1).

Figure 2.1 - Cost breakdown of building elements (Taghavi & Miranda, 2003)



Non-structural elements have also accounted for most of the damage caused according to studies of other earthquakes. For example, 50 percent of the damage recorded in the Northridge earthquake of 1994 was non-structural damage (Whittaker & Soong, 2003). Significant non-structural damage was also observed in earthquakes in 2010 in Christchurch, Chile and Baja, California, as well as in the 2011 Tohoku earthquake (Pantoli et al., 2016). A loss of several billion dollars can be attributed to the damage

to non-structural building elements from earthquakes that occurred in 2010 (Fierro et al., 2011).

An experimental study on the seismic performance of multi-storey buildings revealed that non-structural elements accounted for 74 percent and 87 percent of repair costs at the ultimate limit state (ULS) and serviceability limit state (SLS), respectively (Del Gobbo et al., 2017).

Research has shown that partitions represented a major proportion of the non-structural elements damaged during the CEQS (Dhakal et al., 2016). According to the Canterbury Earthquakes Royal Commission (EQC) (2012), during the CEQS, damage to partitions caused failures in other elements like ceilings (Canterbury Earthquakes Royal Commission, 2012). Furthermore, Canterbury Earthquakes Royal Commission (2012) emphasised that partition damage could block building exit routes. Damage to masonry and gypsum partitions was also common in the 2010 Chile earthquake (Miranda et al., 2012). Additionally, an experimental study of damage to building elements further revealed that partition damage significantly contributed to overall repair costs (Del Gobbo et al., 2017).

An experimental study conducted in Japan on light partition boards identified that the repair cost of light partition damage can be the same as the initial cost of partition installation under two percent radian and increase to up to twice the initial cost at eight percent radian (T. Lee et al., 2007). According to the Applied Technology Council (2018a), 27 percent of the total loss from different building components created by a 6.5 magnitude earthquake can be attributed to damage to interior wall partitions.

Due to the high number of fabricated components in non-residential buildings and the importance of non-structural components in all buildings, this study will use the

damage repair of partitions as an example for building the model. In order to assess the damage to non-structural partition elements, the characteristics of these elements should be understood.

2.4.2.3 Damage to partitions

Partitions are non-load bearing interior components that divide a space vertically (American Society of Civil Engineers, 2007). The American Society of Civil Engineers (2007) divides partitions into three types, heavy, lightweight and glazed. ‘Heavy partitions’ usually consist of clay brick or block masonry. Masonry partitions can be reinforced or unreinforced, solid or hollow. The hollow types can be filled, partially filled or unfilled (Ministry of Business Innovation and Employment et al., 2017). ‘Lightweight partitions’ have two main components, inner studs and a surface layer. Inner studs are typically constructed of steel and wood. The surface layer is made with materials like lath and plaster, wood boards, gypsum boards and other surfacing materials (American Society of Civil Engineers, 2007). The American Society of Civil Engineers (2007) states that glazed and movable partitions are also used in buildings. Glazed partitions span from the floor to the ceiling, the underside of the floor or the roof.

The damage that can occur to these components varies according to factors such as earthquake size, building type and fixing methods. According to previous studies, damage observed to these non-structural partition elements included fractures at openings, deformations, joint cracks, falling to ground, racking and cracks at corners (Applied Technology Council, 1998a, 1998b, 1998c, 2018d; Bradley, 2009; T. Lee et al., 2007).

Due to the variation and overlap of these forms of damage and the resulting difficulty estimating associated repair or rebuild costs, any assessment of damage to partitions will require a standardised range of damage categories.

2.4.3 Damage categorisation and repair methods

Damage to each element is unique to each situation, therefore it is crucial to find a way to categorise damage according to severity and impact. Damage states (DS) have been used to categorise different types of damage to structural and non-structural elements depending on the potential repair action, repair cost, repair time, casualties or risk for building occupancy (Applied Technology Council, 2018c; Bradley, 2009; Taghavi & Miranda, 2003). Damage estimation tools like the Performance Assessment Calculation Tool (PACT) and the Seismic Loss Assessment Tool (SLAT) use DS in their calculations. The following DS are based on changes in repair cost and repair time only, as expressed in Table 2.10.

Table 2.10 - Damage states and repair methods of heavy and lightweight partitions (Applied Technology Council, 1998a, 1998b, 1998c, 2018d; Bradley, 2009)

Element	Damage state (DS)	Unit of measure	Damage occurred	Damage repair method
Heavy Partitions	DS1	m ²	Small cracks, width less than 1/16", with no spalling.	Treat cosmetically using either wallpaper or drywall taping, organic polymers materials or sealer with paint can be used to hide the damage. Repoint the mortar at joints. Inject of epoxy or grout to the cracked area.
	DS2		Extensive cracks, width less than 3/16", with spalling. Vertical cracks in the toe region are detected.	Remove and patch the spalled area with loose concrete. Inject epoxy or grout into the cracked area. Replace rebar if wall reinforcement is damaged.

Element	Damage state (DS)	Unit of measure	Damage occurred	Damage repair method
	DS3		Reinforcement of wall fractured. Crack width more than ¼". Crushing and spalling of the areas. Buckled.	Remove and replace the wall.
Lightweight Partitions	DS1	m2	Cracked surface layer.	Tape, sand, and paint.
	DS2		Major cracks, buckling of wallboards at corners of walls.	Replace wallboard panels, and then tape, sand and paint.
	DS3		Stud failure, sill plate splitting and failure, wall panel failure.	Replace entire partition walls.

2.4.4 Building damage and damage detection methods

Many methods are used to detect damage to structural and non-structural components in a building. Damage detection methods use technologies such as acoustics, ultrasonic scanners, eddy-current monitors, magnetic fields and radiography, and, for global damage detection, vibration-based damage identification methods (Doebbling et al., 1998). For structural damage detection, the Applied Technology Council (1998a) has established guidelines for the use of different inspection methods for different types of damage. These inspection types fall into the categories of ‘non-destructive’ and ‘intrusive’. The non-destructive inspection types include visual inspection, tapping on the wall with dense objects, use of rebound hammers, cover meters to detect reinforcement bars and ultrasonic pulse velocity meters to detect the current state of the building (Applied Technology Council, 1998a, 1998c). Alternatively, intrusive tests cause damage to building elements during inspections. Some of these methods are summarised in Table 2.11 below.

Table 2.11 - Damage detection methods (Applied Technology Council, 1998a, 1998c)

Type	Method	Usage
Non-destructive	Visual inspection	Visual inspection is used for detection. For cracks, spalls, delamination, lateral displacement, buckling and fractures.
	Sounding	Tapping with a solid object is used for detection. Used to identify voids, delamination. Used to verify if cells in block walls are grouted.
	Rebound hammer	Calibrated hammer impact on the surface is used for detection. Used to test the compressive strength of concrete. Used to compare with the required strength.
	Rebar detector	Low-frequency magnetic waves are used for detection. Used to detect the location and size of the reinforcement in concrete or masonry walls. Can also be used to detect the clear cover of the reinforcement.
	Ultrasonic pulse velocity	The travel time of ultrasonic waves are used for detection. Used to measure the relative strength of masonry or concrete. Used to detect the presence of cracking or delamination.
	Impact echo	The energy pulse generated from an impact on the surface is used for detection. This method detects the thickness and discontinuities within a concrete or masonry wall, such as voids, cracks and delamination.
	Spectral analysis of surface waves	The propagation velocity of different surface wavelengths is used for detection. Used to detect the thickness of the material, size, and location of discontinuities in the wall, such as delamination, large cracks and voids.
	Radiography	X-rays are used for detection. Used to locate reinforcing bars and other discontinuities.
	Penetrating Radar	Electromagnetic waves are used for detection. Used to locate reinforcement bars, cracks, voids, and delamination.
Intrusive	Removal of selected material	A portion of concrete or masonry is removed and visually observed for detection. Used to determine the method of construction and identify hidden damage, such as the buckling of rebar. (Performed alongside non-destructive tests.)
	Petrographic evaluation	A microscope analysis is used for detection. Used for microscopic evaluation of concrete or masonry sample. Used to determine the cause of cracking and the mix design of concrete or mortar.
	Material testing	Removed sample is tested for compressive, tensile strength. Used mainly for concrete, masonry, and steel.
	In-place testing - shear test	A hydraulic ram is used for detection. Used to test the shear strength of existing mortar walls. Used mainly for unreinforced walls.

In the context of damage evaluation using RBA, TDE or DDE, visual inspection is the primary method of evaluation, followed by non-destructive methods. If suggested as a result of the TDE or DDE, intrusive methods are employed to investigate further

(Wellington City Council, 2017). Post-earthquake damage cost and time estimation models should utilise reports from RBA, TDE and DDE based their sequence. The initial model should account for the likelihood that unexpected aspects of the damage will be discovered in future evaluations.

2.5 Cost estimation

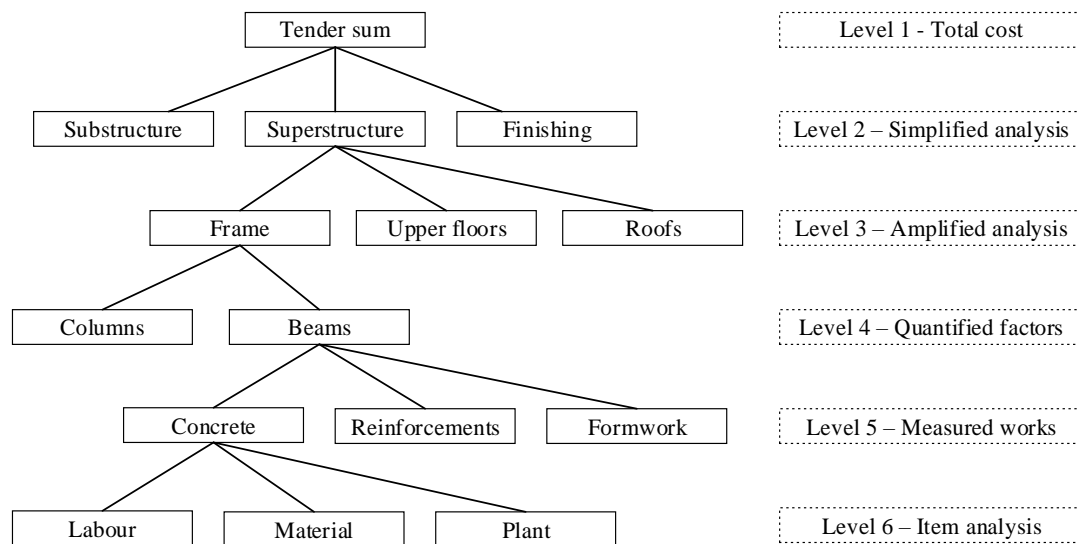
Accurate cost estimation is one measure of the success of a project. Under-estimation of costs will cause cost overruns, and over-estimation is likely to result in waste and inefficiency (Kazaz et al., 2016; Leung et al., 2007; Walker, 1995). The literature indicates that any definition of ‘cost’ depends on the context in which it is estimated. The term ‘cost’, in the construction industry, is unique to construction, where the meaning changes depending on the party to which it refers. From the contractor’s point of view, ‘cost’ is the total expenditure associated with the project, including overheads. For the client, ‘project cost’ is the price that should be paid to the building contractor (Ashworth & Perera, 2015). The project cost referenced in this research is the construction project cost to the client for earthquake damage repair work. The total cost of a project is the cumulation of different cost items, which should be identified during the cost estimation process.

2.5.1 Breakdown of project cost

A combination of many ingredients makes up the final cost of a construction project. Ashworth and Perera (2015) expressed a hierarchical framework of cost data, in which the final project cost is called the ‘tender sum’. Within this framework, the total cost can be divided into primary elements such as substructure, superstructure and

finish(es). Cost can be further broken into five levels of analysis, as shown in Figure 2.2. When preparing detailed cost estimation methods such as bills of quantities (BOQ), total cost can be derived from the cost estimate associated with each item.

Figure 2.2 - Breakdown of the project cost (Ashworth & Perera, 2015)

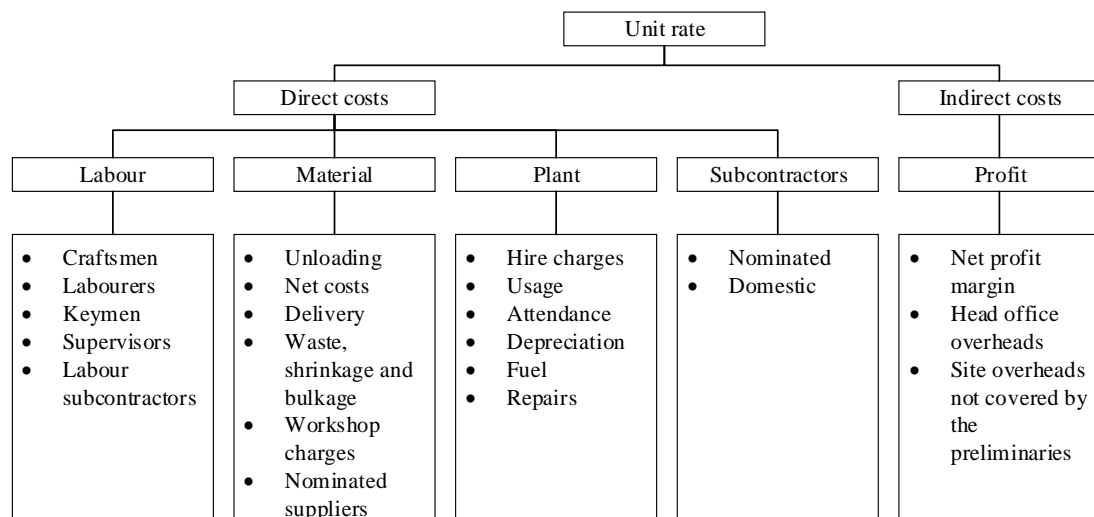


The cost of construction can be separated again into three main sections: direct costs, indirect costs and mark-ups. Direct costs are costs that can be directly and physically attributed to defined economic activity (Carr, 1989). For example, all permanent construction work items are direct costs. Direct costs include the resource costs for labour, material, plant and subcontracted work. Direct costs are generally calculated using unit rates that take into consideration all the resource requirements for a work activity (Brook, 2017).

Costs that cannot be linked to specific construction work activity are considered as indirect costs (Carr, 1989). An example of such indirect costs can be supervision and the cost of hiring a tower crane. Indirect costs are calculated using the preliminaries and profit percentages. Preliminaries consist of the indirect fixed or time-related costs of the project (Flanagan & Jewell, 2018) and can be built into the estimate using unit

rates. Any remaining indirect costs, or project costs that were not covered by the preliminaries and the inclusion of head office overheads, would be determined by the inclusion of the mark-up percentage. The mark-up can include profit, contractor's overhead, project overhead and contingencies (Edyta Plebankiewicz & Leśniak, 2013), and can be included in the total project cost as either a percentage increase on all rates, a percentage increase on selected rates, a percentage increase on the total project cost, a preliminary item or a lump sum amount (Buchan et al., 2003). The breakdown of a unit rate is depicted in Figure 2.3, using functions expressed by Ashworth and Perera (2015) and Kirkman (2015).

Figure 2.3 - Breakdown of a unit rate



With correct initial details, direct costs, indirect costs and mark-ups can be used to provide an initial estimate of the total cost of a project, however, there are cost items that cannot be predicted accurately in the initial stages. According to the literature, provisional sums, prime costs and daywork sections are typically used to cover expected uncertainties in a cost estimate. Costs that cannot be defined directly, such as contingencies and undefined work items, are included under provisional sums (NZIQS et al., 2018). Prime costs of items are used to specify the estimated cost of the work of

nominated subcontract work, suppliers and materials (Brook, 2017). Incidental works in a project are calculated as daywork, which includes all labour, material and plant rates and is measured using different methods (Ashworth & Perera, 2015).

Other than the above, the cost of professional services, inflation, government taxes and levies are also typically considered when estimating costs. The cost of professional services refers to payments that are made to consultants of the project, which would include the engineers, quantity surveyors and legal advisers. The cost of building consents, government levies and taxes can be included under the preliminaries if paid by the main contractors or considered separately (Brook, 2017). Consideration of price fluctuations covers any changes to the costs of the resources during construction periods (Flanagan & Jewell, 2018). Price inflations can be: attributed to the costs of all items, calculated in a separate section, given in a separate section, included as an item in provisional sums or not included at all (Brook, 2017; Flanagan & Jewell, 2018). A typical BOQ also includes a preamble section to express the measurement and pricing rules of each section of the cost estimate (Buchan et al., 2003). This preamble section will define the standard method of measurement (SMM) used for the cost estimation process and outline any deviations from the standard method and the specific measurement rules applicable (NZIQS et al., 2018).

2.5.1.1 Costs related to earthquake damage repair work

The cost of earthquake damage repair work can include many types of costs. This can include demolishing a building, building a new building, retrofitting a building to make it better than before, repairing a building to the before earthquake state, and repairing civil structures and lifelines. However, these areas require wider research scope that this research cannot cover. Therefore, research only focuses on building repair costs

and excludes total building demolition, retrofitting the building to make it better and rebuilding new buildings for demolished ones.

2.5.2 Standard methods of measurement

Standard methods of measurement have been developed using a bottom-up approach to quantify project costs accurately. These standards are unique to each country as well as to each institution. Table 2.12 shows some of the standards related to the New Zealand construction industry.

Table 2.12 - Standard Methods of Measurement relevant for New Zealand

Standard Method of Measurement	Country of origin
Standard Method of Measurement (SMM7)	Royal Institute of Chartered Surveyors (RICS)
New Rules of Measurement (NRM)	Royal Institute of Chartered Surveyors (RICS)
New Zealand Standards - Standard Method of Measurement for Building Works (NZS 4202:1995)	Standards New Zealand
Australian and New Zealand Standard Method of Measurement (ANZSMM) (2018)	Australian Institute of Quantity Surveyors, New Zealand Institute of Quantity Surveyors (Inc.), Master Builders Australia Limited and Registered Master Builders Association of NZ (Inc.)
Australian Standard Method of Measurement (ASMM) 6th edition	Australian Institute of Quantity Surveyors and Master Builders Australia Limited

SMMs have long been used in the construction industry for many reasons. SMMs provide a set of instructions for preparing BOQ that explains what must be covered by each item (NZIQS et al., 2018; Royal Institution of Chartered Surveyors, 2009). Ashworth and Perera (2015) explain that the use of a standardised method of measurement will provide accuracy, transparency and consistency, prevent misinterpretations and allow for the development of standard cost systems. Akbar et al. (2015) further noted that an SMM should be used in pre-and post-tendering stages as a guide, legal document and benchmark for project control. A cost estimation model

that adheres to an SMM will ensure greater accuracy and consistency of the model. Data from construction projects can be directly included in such a model if the project's BOQ adheres to the guidelines mentioned in an SMM. It also allows transforming data from different SMM formats to the required model. Therefore, cost estimation models should be based on an SMM.

Jafarzadeh, Ingham and Wilkinson (2014) developed a model for estimating seismic retrofitting costs, based on data from tender documents in Iran. Their model focused on the basic costs of construction, due to the variability associated with nine specific mark-up items they identified. The items they included in the mark-up were dynamic factors that were considered to affect a construction project. It could be argued that, if guidelines of an SMM were followed, some of these variables could be quantified by including them in unit cost, as illustrated in Table 2.13. Wherever they are located within an estimated cost, these factors are most likely to result in cost variations, so they need to be predicted accurately for better cost estimation.

Table 2.13 - How the use of an SMM can redistribute mark-up items into mark-up and unit cost

Location of coverage	Item
Included in mark-up	Contingency
	Labour and material price fluctuation
	Project complexity
Included in unit cost	Geographical location
	Number of storeys
	Height of building
	Renovation of mechanical and electrical components
	Preparation of a construction site
	Overhead

2.5.3 Factors affecting cost estimation

Various factors that affect the variation between the initial cost estimation and the money spent to complete the project are not covered by SMM. These factors are related to global social, economic, political, cultural, technological and environmental factors as well as factors related to the construction organisations themselves (Baloi & Price, 2003). Being able to identify the impact of these factors in the event of an earthquake will improve the accuracy of cost estimations for earthquake damage repair. An accurate cost estimation model should incorporate these factors.

Baloi and Price (2003) categorised the factors affecting cost variations in construction as organisation-specific, global and acts of God. Organization-specific variables are factors that can be controlled by the contractor; these include variables such as material delivery and quality. Global risks are factors that are somewhat out of the control of contractors, are not included in cost estimates and can have a significant impact on cost. Acts of God include risks of high impact and low probability. Even though acts of God cannot be modelled, organisation-specific and global risks should be incorporated into any cost estimation model in the pursuit of an accurate cost estimate. Non-consideration of such factors is one of the reasons for cost overruns (Memon et al., 2010).

A great deal of research has gone into identifying other variables that influence cost variations in construction projects (Frimpong et al., 2003; Kim et al., 2018; Memon et al., 2010; Olawale & Sun, 2010; Rahman et al., 2013). Factors affecting cost estimation are one of the reasons for the discrepancy between the cost estimates and final cost (Y. M. Cheng, 2014). Some of the highly-rated factors are summarised in the following Table 2.14. The variation in highly impactful factors affecting cost

estimation in different research instances shows that these factors should be re-evaluated for different types of projects.

Table 2.14 - Factors affecting traditional cost estimation

No	Factors affecting cost estimations	References
01	Ability and capacity of the management team	(Y. M. Cheng, 2014; Ekung et al., 2021; Ibrahim & Elshwadfy, 2021; Mahamid, 2015; Sayed et al., 2020)
02	Accuracy of the cost estimation process and BOQ	(Britto et al., 2013; Enshassi et al., 2005; Ibrahim & Elshwadfy, 2021; C. Ji et al., 2014; Sayed et al., 2020)
03	Amount of work to be done by the specialists	(Enshassi et al., 2005)
04	Capability and capacity of the consultants/estimators	(Britto et al., 2013; Ekung et al., 2021; Enshassi et al., 2005; Ibrahim & Elshwadfy, 2021; C. Ji et al., 2014; Sayed et al., 2020)
05	Capability and capacity of the contractor	(Y. M. Cheng, 2014; Enshassi et al., 2005; Mahamid, 2015)
06	Changes in government regulations	(Ekung et al., 2021)
07	Clear and detailed project documentation	(Britto et al., 2013; Y. M. Cheng, 2014; Ekung et al., 2021; Enshassi et al., 2005; Ibrahim & Elshwadfy, 2021; C. Ji et al., 2014)
08	Completeness and quality of cost data	(Britto et al., 2013; Ekung et al., 2021; Ibrahim & Elshwadfy, 2021)
09	Contract disputes	(Y. M. Cheng, 2014)
10	Contract type	(Britto et al., 2013; Elfaki et al., 2014)
11	Experience with similar projects	(Y. M. Cheng, 2014; Ibrahim & Elshwadfy, 2021; Mahamid, 2015)
12	Financial capability of the contractor	(Enshassi et al., 2005; Ibrahim & Elshwadfy, 2021; Mahamid, 2015)
13	Financial capability of the owner	(Akintoye, 2000; Britto et al., 2013; Enshassi et al., 2005; C. Ji et al., 2014; Mahamid, 2015)
14	Ground and site conditions	(Akintoye, 2000; Elfaki et al., 2014; Sayed et al., 2020)
15	Items that required lead time	(Enshassi et al., 2005)
16	Lack of inter organisation synergy	(Ekung et al., 2021)
17	Likely scope changes	(Y. M. Cheng, 2014; Ekung et al., 2021; Elfaki et al., 2014; Enshassi et al., 2005; C. Ji et al., 2014)
18	Method of construction and construction technique	(Akintoye, 2000; Enshassi et al., 2005)
19	Price fluctuations	(Y. M. Cheng, 2014; Ekung et al., 2021; Enshassi et al., 2005; Mahamid, 2015; Sayed et al., 2020)

No	Factors affecting cost estimations	References
20	Project duration	(Ekung et al., 2021; Elfaki et al., 2014; Enshassi et al., 2005; Ibrahim & Elshwadfy, 2021)
21	Project location	(Akintoye, 2000; Enshassi et al., 2005)
22	Project scope and complexity of design and construction	(Akintoye, 2000; Ekung et al., 2021; Elfaki et al., 2014; Enshassi et al., 2005; Ibrahim & Elshwadfy, 2021; C. Ji et al., 2014)
23	Quality of assumptions used in preparing the estimate	(Ibrahim & Elshwadfy, 2021)
24	Quality, prices, and availability of resources	(Akintoye, 2000; Britto et al., 2013; Y. M. Cheng, 2014; Elfaki et al., 2014; Enshassi et al., 2005; Ibrahim & Elshwadfy, 2021)
25	Tendering method and competition	(Britto et al., 2013; Ekung et al., 2021; Elfaki et al., 2014; Enshassi et al., 2005; C. Ji et al., 2014; Mahamid, 2015)
26	The political and economic situation	(Akintoye, 2000; Ekung et al., 2021; Enshassi et al., 2005; Mahamid, 2015)
27	Time allowed for the estimation / tendering period	(Akintoye, 2000; Ekung et al., 2021; C. Ji et al., 2014)
28	Type of client	(Akintoye, 2000; Britto et al., 2013; Elfaki et al., 2014; Enshassi et al., 2005)

2.5.4 The discrepancy between earthquake loss estimations and final cost incurred

Even though the earthquake damage repair projects considered the impact of the aforementioned factors affecting traditional cost estimates, deviations between the cost estimations and final repair cost can be identified. For example, after the 2011 Tohoku earthquake, property damage was estimated as 16.9 trillion yen or 210 billion USD (International Bank for Reconstruction and Development, 2012). However, the final economic loss incurred due to the earthquake increased up to 360 billion USD (Alton et al., 2017). Similarly, initial direct economic estimates after the 2008 Wenchuan earthquake were estimated at around 100 billion USD (Yuan, 2008), but the total impact on the economy increased to 124 billion USD in 2012 (Wu et al., 2012). In New Zealand, as mentioned above, initially estimated the repair cost for the 2010 -

2011 Canterbury earthquake sequence also increased from NZ \$30 billion in 2012 (Parker & Steenkamp, 2012) to NZ \$40 billion by 2016 (A. Wood et al., 2016). These results show the need for a better cost estimation process for earthquake damage repair work. Within that perspective, it is imperative to understand the cost estimation methods in order to improve the costing processes.

2.5.5 Cost estimation methods

A variety of cost estimation methods use available information to assess the total cost of conducting construction work activities on a project within a specified period (S. H. Ji et al., 2019). In practice, developing a BOQ is the most typical method of creating a detailed cost estimation (Cartlidge, 2017); it can also be quite accurate. However, there are also other methods, including expert systems (ES), artificial neural networks (ANNs), case-based reasoning (CBR), fuzzy logic systems (FLS), simulations, statistical regression approaches, decision tree (DT), radial basis function neural network (RBFNN), and particle swarm optimisation (PSO) (Tayefeh Hashemi et al., 2020; Yu, 2006).

Cost estimation methods can be divided into those which take qualitative and quantitative approaches. ES and heuristic rules are examples of qualitative methods that use an estimator's knowledge of the project and cost-influencing factors to develop a cost estimate (Tayefeh Hashemi et al., 2020). ES can be identified as a type of applied artificial intelligence, in which the knowledge and expertise of the person are transferred to a computer system (S. Liao, 2005). The transformed data can be used for referencing, human consultations, creating solutions and explaining the logic behind predictions. Therefore, an ES can support decision-making and problem-solving. According to Idrus et al. (2011), expert systems are used when the statistical

data is limited and expert knowledge, experience and intuition are the only measures that can be used, even when these are vague and not defined properly. Heuristic methods or rules of thumb are mental shortcuts that can be used to simplify complex decision-making processes (H. K. Baker & Nofsingerr, 2011). In construction, heuristic measures are used to solve socially and technically uncertain problems, mitigate coordination problems, simplify novel solutions, and achieve justifiable solutions within limited time and cost constraints (Beamish & Biggart, 2012).

Quantitative methods of cost estimation use historical data to develop cost estimates through quantitative tools and techniques (Layer et al., 2002). Such quantitative methods can be divided into parametric, analogical and analytical methods. Parametric cost estimation methods use a number of parametric attributes of a project to estimate project costs without considering smaller details (Duverlie & Castelain, 1999). Example parameters can be volume and mass (Tayefeh Hashemi et al., 2020). Linear regression and multiple linear regression (MLR) are additional examples of parameters used to develop construction cost estimation models (Swei et al., 2017).

Analogical methods use functional and geometric past projects that are similar to estimate the cost of the current project (Duverlie & Castelain, 1999). Analogical methods have a less complex estimation process. Ratio estimation and the three-quarters rule are examples of analogical methods used for cost estimation. The ratio estimation method uses a linear relationship between the final cost and the features of a project (Layer et al., 2002). For example, the percentage costs of electrical services are predicted in relation to the projected total cost, based on a project of a similar type and scale. The three-quarters rule compares an aspect of the proposed project against historical projects; examples of aspects considered are size, the number of units, speed or complexity of the required outcome (Rad, 2002). One example would be the number

of beds in a hospital or hotel. Case-based reasoning (CBR) is also considered to represent an analogical method by which problem-solving methods used for historical problems are used for new problems that have similarities (Duverlie & Castelain, 1999; Keung et al., 2008; Leśniak & Zima, 2018). Such analogical methods are used in the initial stages of a cost estimation process.

Analytical methods deconstruct the activities required to achieve the total compound cost (Duverlie & Castelain, 1999). Analytical methods define cost in terms of the resources related to each construction activity and use a bottom-up method to cumulate the cost. This creates more accurate results (Tayefeh Hashemi et al., 2020). Building up a bill of quantities from a work breakdown method is a process that also uses analytical methods (Layer et al., 2002). A disadvantage of analytical methods is that they require a great deal of information and are extremely time-consuming to use (Caputo & Pelagagge, 2008). To address these drawbacks, newer analytical methods have been developed using ANN (Matel et al., 2019) and CBR (An et al., 2007).

Recently, methods have been developed that combine the aforementioned approaches to include all the positive characteristics of each. Linear regression plus neural networks, MLR plus factor analysis, MLR plus principal component analysis, MLR plus stepwise, and MLR plus case-based reasoning are some examples of these hybrid construction cost estimation models (Swei et al., 2017).

In the context of earthquake repair damage, the bottom-up method can be used to generate the actual cost of construction by breaking down unit rates, as expressed in Figure 2.3. Kirkham (2015) and Ashworth and Perera (2015) agree that the bottom-up method is the most suitable method for estimating costs of refurbishment and repair work. The downside of using the bottom-up method is that each work item must be

developed, and this requires a great deal of time and effort (Ahmad, 2011). However, if a database is developed that can use this method, and is maintained and updated, it can be used to produce cost estimates quickly and accurately.

2.5.6 Current cost estimation models for earthquake damage repair work

Currently, several loss estimation tools are used to estimate probable earthquake damage repair costs. Examples of loss estimation tools are the previously mentioned HAZUS-MH, PACT, SP3 and SLAT, as well as Matlab Damage and Loss Analysis (MDLA), and the loss estimation tool developed by Laboratório Nacional de Engenharia Civil, Portugal, named LNECLOSS (Molina et al., 2010). In the context of USA and New Zealand, HAZUS-MH, PACT, SLAT and SP3 are important tools in use. These tools, some of which will be described and compared in more detail in the following sections, can be categorised into two groups: building damage prediction tools and regional damage prediction tools.

2.5.6.1 HAZUS

HAZUS is one of the tools developed for regional damage evaluation and estimation using Geographic Information System (GIS) information. HAZUS was developed by Whitman et al. (1997) and the Federal Emergency Management Agency (FEMA). HAZUS classifies buildings that will be impacted by a hazard, based on their function. These categories are utility lifelines, building stock, transportation lifelines and essential facilities with a high potential for loss (Department of Homeland Security & FEMA, 2003). Building stock is divided into agricultural, government, housing, educational, religious, industrial and commercial buildings (Department of Homeland Security & FEMA, 2003). The purpose of the HAZUS model is to reduce the risks,

guide preventive actions and support emergency retrieval and response procedures. The HAZUS model can be used to estimate the casualties, monetary losses, economic losses and indirect losses from earthquake-induced hazards like debris, fire, floods and toxic contamination. The model also can be expanded to estimate the effect of tsunamis, seiches, surface faults and dam failures (Department of Homeland Security & FEMA, 2003).

HAZUS can also be used to predict the losses associated with a specific building. Parameters like floor area, the existence of garage(s), structure type, damage level, building category, building location, potential earthquake forces on a location and standard rates from costs databases are used to develop floor-area-based rates. (Department of Homeland Security & FEMA, 2003). Department of Homeland Security and FEMA (2003) has acknowledged that there might be a large variation between the HAZUS estimate and the actual loss. Variations could have arisen particularly from the use of building category, floor area, probability-based loss estimation and rates from standard cost databases as parameters.

2.5.6.2 FEMA P-58 methodology and PACT, SLAT and SP3 tools

The FEMA P-58 methodology is a performance-based earthquake engineering (PBEE) framework developed by the Applied Technology Council in the USA to produce building-specific estimates (Applied Technology Council, 2018c). It is based on the work of Porter, Kiremidjian and LeGrue (2001) and a PBEE framework. The PBEE framework used for FEMA P-58 was developed by Pacific Earthquake Engineering Research (PEER) (Applied Technology Council, 2018c). FEMA P-58 methodology generates its loss estimations utilising an assembly-based seismic vulnerability method.

FEMA P-58 methodology uses a number of parameters to predict probable damage to buildings: peak floor velocity, storey drift ratio, peak floor acceleration and residual building drift (Alani & Khosrowshahi, 2007). The method estimates the likelihood of different damage state occurrences in building elements due to the impact of the earthquake. Damage states define damage severity levels of each element. The likelihood of achieving each damage state according to different earthquake scenarios is estimated using past earthquake data and experimental data. The relationship between the earthquake forces and damage states are included in fragility curves. The identified damage states are then linked to predicted repair costs using consequence functions (Applied Technology Council, 2018d).

FEMA P-58 methodology is the basis for PACT, SLAT and SP3 tools (Applied Technology Council, 2018b, 2018c; Haselton & Baker, 2019). PACT and SP3 were developed for the USA, while SLAT was developed using data from New Zealand. SLAT only provides monetary loss estimations (Bradley, 2009). However, casualties, building usability and downtime and repair costs can also be predicted by SP3 and PACT. The new version of PACT also includes the ability to predict the environmental impact of repair work (Applied Technology Council, 2018c).

FEMA P-58 methodology has been further improved through building information modelling (BIM) concepts that use element visualisation, damage visualisation, repair activity sequencing and productivity sequencing (Almufti & Willford, 2013; Charalambos et al., 2014). There is also research into the use of 3D laser scanning for damage analysis (Jiao et al., 2019).

2.5.6.3 HAZUS vs FEMA P-58

To consider HAZUS and the FEMA P-58 methodology as post-earthquake cost estimation models, the approaches need to be compared and evaluated. On the surface, both methods provide reliable cost estimates according to their intended purpose. A closer high-level evaluation focused on the cost estimation process at the post-earthquake stage revealed key differences. A summary of these differences is depicted in Table 2.15, which was developed using findings from Bradley (2009), Haselton and Baker (2019) and an analysis of the research data.

Table 2.15 - Differences between HAZUS and P-58 methodology

Characteristics	HAZUS	P-58 methodology (PACT, SLAT, SP3)
Main measurement method	Single rate approximate estimation - floor area method with minor updates	Multiple rate approximate estimations - elemental cost estimation method with minor updates
Information source	Historical data and judgement	High-performance simulations and results built into fragility curves and consequence functions
Output of cost	A single rate	A detailed breakdown of elemental repair costs
Consideration of earthquake-induced hazards	Yes. It can produce damage estimation for inundation, fire, and release of toxic materials and debris. It also has the capability to incorporate liquefaction, landslides, surface fault rupture, tsunamis, seiches or dam failure.	Yes. It also has the capability to incorporate aftershocks.
Unit of measurement for cost estimation	Gross floor area, building type and damage state	Item, m, m2 and m3, depending on the element, building type and damage state
Source of cost data	General cost databases	General cost databases
Capability to incorporate new methods	Yes	No

The HAZUS method was developed for regional damage estimation using historical data and judgements for estimations. It uses generic parameters like building category-based floor area for estimations. Alternatively, the P-58 methodology focuses on each specific building element and creates an element-wise detailed estimate using past data, experimental data and Monte Carlo simulations (Applied Technology Council, 2018c; Department of Homeland Security & FEMA, 2003). A study comparing HAZUS and P-58 methodology identified that both methods produce similar results (Cook et al., 2017), and further demonstrated that building-specific details like component anchorage details, the building height, building plan and earthquake-resilient design were captured by the P-58 methodology.

It is important to note that the HAZUS method has been found to be able to consider earthquake-induced hazards which are not covered to the same extent by P-58 models. Additionally, according to the Department of Homeland Security and FEMA (2003), the HAZUS model has the ability to include input from other models with different estimation methodologies. Therefore, HAZUS has the upper hand when considering all earthquake-related damage upgradability. However, when considering the base concept, the P-58 methodology produces building-specific and element-based cost estimates, which are more useful in a post-earthquake CEEDRW process. Therefore, PACT, SLAT and SP3 must be further considered, particularly within the New Zealand context.

2.5.6.4 Comparison of PACT, SLAT and SP3

In order to identify the most suitable P-58 methodology-based tool for New Zealand, PACT, SLAT and SP3 were compared using details from the Applied Technology Council (2018d, 2018a), Bradley (2009), and Haselton Baker Risk Group (2020) (refer

to Table 2.16). As previously mentioned, SLAT is an NZ-focused model. Therefore, the data in SLAT can be used most directly for post-earthquake cost estimation modelling in New Zealand. It must be noted that less than 50 fragility curves and consequence functions were included in SLAT (Bradley, 2009). Alternatively, the SP3 and PACT models contain over 700 fragility curves and consequence functions. Even though the consequence functions might not be applicable for the NZ context, the fragility curves developed for PACT and SP3 could be used for post-earthquake CEEDRW models in New Zealand (Applied Technology Council, 2018d; Haselton & Baker, 2019).

These two models have other advantages worth considering. PACT offers free access, a standard classification system and transparent functions, and includes detailed cost breakdowns and multiple building element categories (Applied Technology Council, 2018c, 2018d). SP3 is a commercial-based model that, while it might not have the ability to share its internal content, it incorporates the following into its estimates: repair activity sequencing, effects from aftershocks, time required to achieve different repair levels (re-occupancy, functional recovery and full recovery) and impeding time estimation (factors that prevent start of work). SP3 can also automate the calculations of population, content and non-structural components (Haselton Baker Risk Group, 2020).

Table 2.16 - Differences between currently-available PACT, SLAT and SP3 (Applied Technology Council, 2018d, 2018b; Haselton Baker Risk Group, 2020)

Characteristics	PACT	SP3	SLAT
Standard number of fragility curves	Over 764	Over 700	Less than 50
Inbuilt data suitability	For the USA	For the USA	For New Zealand

Characteristics	PACT	SP3	SLAT
Software availability	.exe program and spreadsheet	Commercially available Cloud computing capability	Web interface
Operational support	Clear and detailed user manuals. Inbuilt functions can be identified through the spreadsheets provided.	User manuals published for PACT, with demos, user support, and tutorials.	Web interface provides black box method data processing systems. Users need additional knowledge to understand and use the system.
Classification system	Uses a standard NISTIR 6389 classification system.	Uses a standard NISTIR 6389 classification system.	Uses a simple and unique classification system.
Types of structures	Buildings	Buildings	Buildings and bridges
Ability to update consequence functions	The user can update the consequence functions, and detailed breakdowns are provided	The user can update the consequence functions, and detailed breakdowns are provided	Cannot be updated by the user
Facilitates repair work sequencing	No	Yes	No
Outputs re-occupancy, functional recovery and full recovery time estimations	No	Yes	No
Incorporates impeding factors	No	Yes, but not to calculate the impact on cost.	No
Incorporates the effects of aftershocks	Manual input	Yes	No
Updatable according to the changes in the cost	Yes	Yes	No
Incorporates price fluctuations	No	No	No
Upgradable according to need	Yes	No	No
Considers the environmental impact of the repair work	Yes	No	No
Considers restrictions during repair work	No	No	No

In the context of the development of post-earthquake cost estimation, the SP3 model offers better coverage of the factors related to earthquake damage. However, due to its proprietary nature, SP3 might not be able to be used as a post-earthquake CEEDRW

(PEQ-CEEDRW) model. The PACT tool has a more transparent data structure. Therefore, this model can be considered. Furthermore, the operation of the SP3 model is based on the PACT process. Therefore, all functions related to SP3 can be included within a PACT-based model.

2.5.7 Drawbacks of the current models and the need for the research

However, further analysis of the PACT and SP3 tools revealed drawbacks for their use in the development of a PEQ-CEEDRW model. One weakness of the PACT tool is that it generates one-off results. PEQ-CEEDRW requires detailed cost breakdowns to make the estimates transparent. However, analysis of the PACT and SP3 reports revealed that these models do not provide reports with the required level of detail (Applied Technology Council, 2018d; Haselton Baker Risk Group, 2020).

A further disadvantage of using the P-58 methodology is that project-based costs like preliminaries are assigned to each unit rate rather than to the overall project (Applied Technology Council, 2018d). Overall project-based costs should be calculated separately. There can be over-or underestimations of the cost items if project-based cost items are divided and included within individual rates. Therefore, there is a need for a cost estimation model that caters to post-earthquake conditions and requirements.

2.6 Problem-solving methodologies

Problem-solving is a process of overcoming unwanted situations and removing difficulties (Marin-Garcia et al., 2020). Many problem-solving strategies have been developed to help process, and product developers, organisations, quality engineers and project teams solve complications and create new solutions. Failure mode and

effects analysis (FMEA), the Deming Cycle, the eight-discipline methodology (8D), Six Sigma, and TRIZ methodology are some of the aforementioned problem-solving strategies. Each of these problem-solving methodologies is used in a different context to achieve specific outcomes.

Some problem-solving strategies take a heuristic approach, which focuses on user experience and judgement, rather than identifying the most optimal result, to develop a good solution to a problem (Silver, 2004). The heuristic method is typically used in time-constrained situations, and the FMEA process is a good example. FMEA is used to identify and eliminate potential errors in a process or system to increase the dependability of that process or system (Liu et al., 2013). The process identifies and prioritises potential failures in a system based on severity, occurrence and the probability of not being detected (Liu et al., 2019).

Another strategy, the Deming Cycle, focuses on improving the quality and efficiency of a process through the following phases: plan, do, check and act (PDCA) (Isniah et al., 2020). The 8D strategy focuses on the continuity of an existing process and on identifying and removing the root causes of a problem (Broday & Andrade Júnior, 2013). The 8D strategy also incorporates the PDCA cycle in its eight-step process (Koncz & Pokorádi, 2018). Similarly, the Six Sigma strategy provides a six-step guide to improve the quality of a process and reduce costs by reducing defects and minimising process variations. Six Sigma takes users through a process cycle to define, measure, analyse, improve, and control (DMAIC) the problem (Sharma et al., 2020). Finally, the TRIZ method is used to create innovative solutions to complex problems through systematic analysis (Sheu et al., 2020).

2.6.1 Problem-solving methodologies best suited for innovation for this research

A suitable problem-solving methodology for innovation should identify the problems in a system and support the development of solutions in a systematic manner. However, some of the above-mentioned methods have their drawbacks for use in innovative problem-solving. For example, the heuristic method focuses only on developing a suitable solution rather than an optimal one, and the FMEA process is more focused on the identification of potential problems than on problem resolution. In addition, most problem-solving methodologies use a trial and error method to develop solutions (Savransky, 2000). As an example, the DMAIC and PDCA cycle-based methods like 8D, the Deming cycle and Six Sigma, do not provide suggestions for problem resolution through innovation.

However, when compared to other problem-solving methodologies, TRIZ methodology, the ‘Theory of Inventive Problem Solving’, provides a rigorous systematic process to solve problems through innovation (Sharma et al., 2020). TRIZ was developed by Genrich Altshuller, who analysed 40,000 patents and identified basic patterns of innovation (Kalevi et al., 2018). TRIZ methodology introduces a contradiction matrix and 40 innovation principles which summarise these patterns and help identify the most suitable method for problem-solving for a given context. Additionally, the TRIZ methodology offers an arsenal of problem resolution tools, including function (and object) analysis, ideal final result, resource analysis and solution evaluation (Ilevbare et al., 2013; Kalevi et al., 2018). Therefore, as a knowledge-based innovation generation system, TRIZ methodology can be considered to surpass other methods that only provide a set of guidelines for problem-solving (Savransky, 2000). TRIZ can also incorporate other problem-solving methodologies

like Six Sigma into its strategy. Worldwide usage of TRIZ for innovative purposes has been observed in different industries, including the construction sector (S. Cheng et al., 2006; Ding et al., 2017; Renev & Chechurin, 2016). Hence, the TRIZ methodology was selected as a suitable method for this study, which seeks to solve a complex problem through an innovative solution.

2.7 Summary

An earthquake is an unpredictable natural hazard that can cause extensive damage to social, economic, and environmental wellbeing. Apart from the damage caused by primary earthquake waves, damage also results from aftershocks and earthquake-induced hazards. Due to the unpredictability of earthquakes, earthquake damage risk must be accepted and mitigated. New Zealand is in a region where tectonic earthquakes are frequent, and as such, requires new methods to assess the damage caused by earthquakes in order to respond to them more cost-effectively.

Damage to a building, after an earthquake event, is largely assessed using rapid and detailed evaluation methods. These evaluation methods categorise damage into structural and non-structural components. Currently, thanks to modern engineering methods, the incidence of structural damage to a building following an earthquake is reducing. Non-structural components in a building are likely to be damaged in the event of an earthquake regardless of whether the structure is critically damaged or not. Damage to partitions can be categorised into damage states (DS) depending on the expected method of repair, which can then be used to estimate the repair cost.

Due to the qualitative nature of many of the evaluation methods reviewed, the identification and quantification of earthquake damage is largely objective and can

result in uncertainty. A repair time and cost estimation model should account for these uncertainties and be built in such a way as to address a wide variety of circumstances.

When examining issues related to the cost estimation of earthquake damage repair work, damage caused by earthquakes and their induced hazards were closely examined. The review, which focused on damage to buildings, also identified that earthquakes could cause damage to different types of structural elements, of which partition damage is significant. It further clarified damage state categories (based on the building element, the severity of damage and damage repair method) and the ways that damage can be identified (through visual inspections or other identification methods).

In the context of current loss estimation tools, PACT, SLAT, SP3 and HAZUS tools generate earthquake-related loss estimations through performance-based probability estimates. PACT, SLAT and SP3 tools are based on a P-58 methodology, while HAZUS runs on GIS-based data. When HAZUS and P-58 were compared in this study, the P-58 methodology was deemed to be more suitable for post-earthquake cost estimations as they can produce more detailed building-specific cost estimates. Considering the functionality of PACT, SP3 and SLAT which were based on the P-58 methodology, this study found SP3 tools more capable of achieving more accurate cost estimations than the others. However, due to its proprietary nature and content, the PACT model was considered to be the most suitable model on which to base the development of a PEQ-CEEDRW model. However, the PACT tool does not provide the required level of cost breakdowns and does not meet requirements related to cost estimation earthquake repair work. Therefore, the review identified the need to develop a new cost estimation model for earthquake damage repair work. This development process will require that innovative tools and methods be created.

The chapter also identified categories of project costs and demonstrated how these can be properly identified and described through standard methods of measurement (SMM). The review further identified existing cost estimation methods used for earthquake-based cost estimation and their drawbacks. The review was not able to identify an existing post-earthquake cost estimation model that captured all the factors affecting CEEDRW; this forms the research gap targeted by this study. The review also identified that the TRIZ methodology could be used as a tool to begin developing a post-earthquake cost estimation model to address the research gap.

3

METHODOLOGY**3.1 Introduction**

This chapter describes the process used to conduct the research in order to achieve the aims and related objectives of the study. The first sections of the chapter provide a background of the current knowledge on philosophical stances, research methodologies and research methods. This literature review of methodology is used to identify and select the most suitable method for the research.

Succeeding sections discuss the adoption of a suitable philosophical stance and an appropriate research method and design. These sections further explain the data collection methods and analysis used in the research: semi-structured interviews, a survey questionnaire, model development and validation. Each data collection method is described in terms of its process design, sampling method, sample size and administration process. The data analysis techniques used for qualitative and quantitative data analysis are also described as are, finally, the measures employed to maintain the reliability and validity of the research process.

3.2 Research philosophy

Research is undertaken to produce new acceptable knowledge for human society. Research can be defined as systematic, organised, information-centred, objective scientific inquiry into a specific problem with the aim of creating a resolution or finding answers (Gray, 2018). The systematic nature of the research process contributes knowledge to the world through a path that is acceptable. An acceptable research process and related outputs should be testable, replicable, objective, able to be generalised, purposive, precise, rigorous and parsimonious (Sekaran & Bougie, 2016). Any acceptable method of research inquiry can take a particular path, thus leading to the debate around research methodologies.

The term ‘research methodology’ can be defined as a broad method to specify the process of systematic inquiry involved in defining research questions and acquiring results (Teddlie & Tashakkori, 2009). According to Teddlie and Tashakkori (2009), research methodology includes: how the reality is perceived, preferred methods of research design, logical sampling processes, data collection techniques, data analysis techniques, procedures for interpreting results, criteria for quality valuation and design criteria for improvement. In simpler terms, methodology refers to the specific process of the research. In some instances, the terms ‘research methodology’ and ‘research method’ can be misinterpreted and wrongly used interchangeably (Saunders et al., 2019). However, unlike methodology, research methods refer to procedures and strategies used to implement the research design. These include sampling, data collection, data analysis and result inference (Teddlie & Tashakkori, 2009). According to Creswell (2018), research methodology is defined in terms of three main

components: the philosophical stance held by the researcher, the research strategies of inquiry and the methods of data collection.

According to the research onion concept, understanding the philosophical stance of the research is the first step to take in developing the study (Saunders et al., 2019). Easterby-Smith, Thorpe and Jackson (2015) identified four reasons for understanding the philosophical issue of a study: first, to have a clear sense of the researcher's role in research methods by understanding the core epistemological issues; second, to recognise suitable and unsuitable research designs; third, to clearly identify research design in terms of the type of required evidence, methods of data collection, data interpretation process and how the results will provide substantial answers to the research questions; and, finally, to create designs that are new to the researcher. The philosophical stance for a specific study is decided by the nature of reality (ontology), the required knowledge (epistemology) and the researcher's set of beliefs and assumptions about the world (axiology) (Saunders et al., 2019).

Ontology is an area of philosophy that asks what reality is and sets out basic classifications of reality (Neuman, 2014). Epistemology refers to the methods used to obtain valid and acceptable knowledge and ways to communicate knowledge to others (Saunders et al., 2019). Axiology refers to the role of the researcher in the research, based on the researcher's values, ethics and scope of the research (Creswell & Clark, 2018; Lincoln et al., 2018). Although there are many research philosophies and methodologies, the researcher's view also plays a significant role in the credibility of the output (Lincoln et al., 2018).

When considering possible philosophical assumptions, one can begin by examining two extremes: positivism and constructivism (Gage, 1989; Teddlie & Tashakkori,

2009). These stances can reflect and shape one's view on ontology, epistemology and axiology. Through an ontological positivist viewpoint, the world has one truth that can be measured, calculated and identified (Lincoln et al., 2018). Positivism considers that objects, procedures and social phenomena exist apart from the individuals who interact with them and that there is only one reality experienced by all (Bryman & Bell, 2011). Epistemologically, positivists use scientific rigour to extract data that is not impacted by society or researched objects (Lincoln et al., 2018). In a positivist stance, researchers believe that social entities and actors are independent. Therefore, axiologically, positivist researchers keep themselves detached from their values and beliefs in order to observe in an unbiased and value-free way (Saunders et al., 2019).

Alternatively, ontological constructivism, which is known as nominalism, considers multiple realities and does not regard any reality as being separate from the people who constructed it (Saunders et al., 2019). This results in each person experiencing a different reality. In epistemological constructivism, knowledge is shaped by the interactions between the object under investigation and the researcher with whom the object is interconnected (Lincoln et al., 2018). Axiologically, the researcher who takes a constructivist stance accepts that their research is value-laden, and that research bias is proportional to their involvement. In such a case, the researcher's opinion is included in the data collection process as their own interpretation, in combination with those of the participants (Creswell & Poth, 2016).

The views of constructivism and positivism sit at two ends of a spectrum. According to Biesta (2010), taking constructivist or positivist stances on ontology, epistemology and axiology allows for the development of different methods of observing reality and results in different outcomes. Biesta (2010) argues that neither constructivism nor positivism alone can provide a holistic account of any phenomena. Hence,

implementing mixed methods research designs that use a combination of these two approaches can lead to the collection of diverse views of a phenomenon (Creswell & Clark, 2018; A. S. Lee, 1991).

Campbell and Fiske (1959) are credited as the initial users of a mixed-methods approach for validation purposes. 'Mixed methods research' can be defined as research conducted using a combination of qualitative and quantitative approaches to increase the breadth and depth of understanding and collaboration (Johnson et al., 2007). According to the literature, a mixed methods approach does not have a specific stance in terms of ontology, epistemology and axiology, and can therefore change based on research design and include multiple perspectives (Biesta, 2010; Creswell & Tashakkori, 2007).

Mixed methods research is primarily associated with the philosophical stance of 'pragmatism', due to its logical nature (Johnson et al., 2007). A researcher taking a pragmatic stance examines 'what works' in order to understand and find solutions to research problems (Creswell, 2018). Pragmatists understand that phenomena can be interpreted in different ways and have more than one reality (Saunders et al., 2019). There are many debates about the philosophical underpinnings of pragmatism in relation to constructivism and positivism, in that pragmatism does not accept the making of a singular choice (Lincoln et al., 2018). A researcher taking a pragmatic approach can use mixed or multiple methods that are relevant to the research problem, taking into consideration the characteristics of each method (Creswell & Clark, 2018).

Ontologically, pragmatism considers reality as complex, external, rich and created out of the practical consequences of ideas, experiences, practices and flux of processes (Saunders et al., 2019). Epistemologically, pragmatism considers knowledge to be

both objective and subjective based on the specific context and in consideration of the consequence of the research problem (Saunders et al., 2019; Teddlie & Tashakkori, 2009). Axiologically, researchers who rely on pragmatism take both biased and unbiased approaches (Creswell & Clark, 2018).

The following characteristics of pragmatism can be identified based on the studies of Creswell (2018), Creswell and Poth (2016), Greene and Hall (2010) and Teddlie and Tashakkori (2009):

- Pragmatism rejects the traditional binary selection offered by traditional dualism (constructivism vs positivism) and uses a neutral path whereby knowledge is a function of organism-environment transactions.
- Pragmatism users draw assumptions from both constructivism and positivism for research.
- The researchers have the own freedom to look into many approaches and select the most suitable research procedure(s) and technique(s).
- Pragmatists do not view the world as having a single view. Therefore, pragmatists collect and analyse data collected using multiple approaches (quantitative and qualitative) and do not use just one method.
- Truth, from a pragmatist approach, is based on the situation and not based on constructivist or positivist views.
- A pragmatist considers the intended consequences of the research by looking into the ‘what’ and ‘how’ of the research. Based on the intended purpose of the research, a pragmatic researcher must employ rationale reasoning to combine quantitative and qualitative data.

- Pragmatism considers social, cultural, political, historical and other views and endorses shared values of democracy, freedom, progress and equality.
- Pragmatists agree that reality can be singular and external to the mind while also being included in the mind. Pragmatists believe truth is generated from experience and that absolute truth will be comprehended at the end of the world.
- Pragmatism considers knowledge to be constructed and based on the reality of worldly experience.
- Pragmatism offers the mixed methods researcher the use of multiple methods, different assumptions, diverse worldviews, and a variety of data collection and analysis techniques.

The researcher will determine the most suitable philosophical stance and research method for a study depending on assumptions regarding the nature of reality, the nature of knowledge and the best methods of obtaining that knowledge (Saunders et al., 2019).

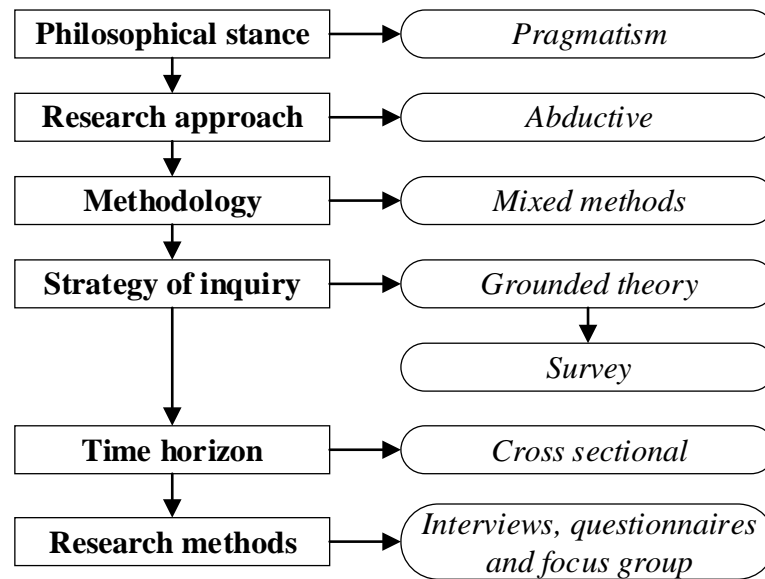
3.2.1 Research philosophy used for this research

A consideration of all of the philosophical stances mentioned above led to the development of the research process for this study, which also considered the objectives, characteristics of the study and its subject, and the ontological and epistemological assumptions on which the research aim is based.

The study aimed to develop a cost estimation model for earthquake damage repair work that could generate a final project cost that could be considered as an objective output. Professional cost estimators have formulated previous cost estimation

approaches according to their opinions and experiences; such cost estimation approaches have also been based on details and environmental conditions associated with a given project. Therefore, on one hand, the reality of cost is based upon the damage done to the building elements, the repair methods to be used and the cost of resources, all facts to justify taking a positivist ontological approach. On the other hand, the cost can also be ontologically constructivist, since estimated costs are based on calculations conducted by professionals based on their experience, their assumptions regarding unknowns and an agreement of estimated cost or rates between client and builder. This study aimed to consider both sides in order to achieve the research aim. Traditional philosophical stances require the researcher to take either a subjective or an objective stance with regard to ontology and epistemology. However, as described in the previous section 3.2, a pragmatic philosophical stance supports viewing reality from both positivist and constructivist perspectives. Additionally, because pragmatism is oriented toward solving a problem, pragmatism was chosen as the philosophical stance from which to holistically view the current situation with respect to cost estimations for post-earthquake damage repair and create a solution. Once a philosophical stance is taken, the research approach can be decided, which is detailed in Figure 3.1.

Figure 3.1 - Research design based on levels identified by Saunders et al. (2019)



3.3 Research approach

A ‘research approach’ is defined as the connection of philosophical assumptions and specific research methods for data acquisition and analysis (Creswell, 2018). Research approaches can be divided into three categories: quantitative, qualitative and mixed. Each research approach is described in the following sections.

3.3.1 The qualitative approach

A qualitative approach is selected by researchers who favour constructivism and an inductive method of inquiry. Inductive research focuses on creating new theoretical patterns from observed data (Saunders et al., 2019). A qualitative approach supports an exploratory method of inquiry by creating untested new conclusions (Teddlie & Tashakkori, 2009). This method examines individual and group meaning in order to generalise a social and human problem (Creswell, 2018). A qualitative method of inquiry is used to understand the causes of a complex phenomenon by considering the

context of individual participants and developing a theory using a flexible style of reporting (Saunders et al., 2019).

Creswell and Poth (2016) have outlined eight phases of qualitative research: identifying the research assumptions and philosophical stance; determining the research problem from the relevant literature; creating exploratory research questions; collecting the data; analysing the data; representing the data; discussing and comparing the findings; and applying validation strategies. In qualitative research, the researcher will be considered as the primary instrument (Merriam & Tisdell, 2016). The strategies of inquiry used in a qualitative induction approach are grounded theory, ethnography, case study, phenomenology and narrative (Creswell, 2018).

3.3.2 Quantitative approach

On the other side of the spectrum, a quantitative approach is chosen by researchers that favour positivism. A quantitative approach supports a deductive inquiry method focused on confirming, refuting or modifying a hypothesis (Gray, 2018). Hypotheses are statements containing two or more concepts that are used to explain a relationship between variables. The variables are measured using instruments in order to create a statistical analysis which can lead to a standardised output (Creswell, 2018). By identifying specific characteristics in the results, the researcher can better understand the data (Saunders et al., 2019). Hypotheses create a focus for the research process and will be proven right or wrong based on the results gained from collected data.

When using a quantitative approach, a researcher can take the following steps: select the theory of investigation, create hypotheses; design the research to measure the hypotheses; collect data; analyse the data; accept or reject the hypothesis; and modify

the theory if the hypothesis is rejected (Gray, 2018). Unlike qualitative methods, quantitative methods rely on the instrument of measure rather than on the researcher. Predetermined data, closed questions, and numeric data are used as the strategies of inquiry in a quantitative approach (Creswell, 2018). The advantages and disadvantages of each method were identified and shown in Table 3.1.

Table 3.1 - Comparison of qualitative and quantitative approaches (Biesta, 2010; Creswell, 2018; Niglas, 2010; Saunders et al., 2019; Yilmaz, 2013)

Area	Quantitative	Qualitative
Assumptions	Reality is single, perceptible, and divided into smaller segments.	Realities are numerous, built on individual perception, and have overall views.
	Researchers and phenomena are independent	Researchers and phenomena are bound and interactive.
	Value-neutral	Value-involved
	Variables can be recognised, and relationships can be measured.	Variables and relationships are difficult to measure due to their complexity.
	The main focus is on the research process.	The main focus is on the data.
Purposes	For predictions	For interpretation
	Explanatory	Exploratory
	To understand the causes and effects of an event	To understand the meaning of an event
	To generalise from general to specific	To generalise from specific to general
Approach	Instrument-based closed questions	Open-ended questions
	Predetermined method	Emerging method
	Begins with assumptions and hypotheses	It ends with hypotheses or theories
	Manipulation and control	Emergence and portrayal
	Uses formal, structured instruments	The researcher is the instrument
	Experimentation and intervention	Naturalism or non-intervention
	Deduction	Induction
	Statistical analysis	Thematic analysis
	Probability sample	Purposive sample
	Seeks consensus and standards	Seeks variety and complexity
	Reduces data to numerical indices	Makes minor use of numerical indices
	Uses abstract language in the write-up	Uses descriptive language in the write-up

Area	Quantitative	Qualitative
Researcher role	Detached	Attached
	Objective understanding	Empathic understanding
	Third-person view	First-person view

3.3.3 Mixed methods approach

A mixed-methods approach combines both qualitative and quantitative approaches into one method as an abductive technique. Morse (2016) defines ‘mixed method’ as a single approach to research that incorporates two or more methodological strategies and uses secondary methods to understand a part of the phenomena that cannot be understood by the first method. Using a mixed-methods approach, the researcher collects data to identify patterns and generate a new or modified theory, which is then tested with new data (Cameron & Price, 2009). The abductive method can also be used to generalise data (Saunders et al., 2019).

The level of the mixture can change based on the requirements. The sequence and dominance of each method are major considerations of mixed methods design (Easterby-Smith et al., 2015). ‘Dominance’ refers to the method (qualitative or quantitative) that has the most significant impact on the research. In some instances, methods are equally dominant. ‘Sequence’ refers to the order in which each method is employed.

Another thing to consider is the level of mixing or interactions (Nastasi et al., 2010). ‘Level of mixing’ refers to any integration of the methods, in other words, whether the chosen methods are fully or partially integrated. Using the three considerations mentioned above, Leech and Onwuegbuzie (2009) created eight typical mixed-

methods topologies, in which the dominant method can be either qualitative or quantitative:

1. Partly integrated concurrent equal rank designs
2. Partly integrated concurrent dominant rank designs
3. Partly integrated sequential equal rank designs
4. Partly integrated sequential dominant rank designs
5. Fully integrated concurrent equal rank designs
6. Fully integrated concurrent dominant rank designs
7. Fully integrated sequential equal rank designs
8. Fully integrated sequential dominant rank designs

There can, in fact, be many further variations of mixed methods design. Based on the occurrence of the method, the main designs of mixed-method approaches can be identified as convergent, exploratory sequential and explanatory sequential (Creswell & Clark, 2018). The convergent design incorporates the use of parallel qualitative and quantitative data collection to compare or triangulate data. The exploratory sequential design employs qualitative data collection and analysis followed by quantitative data collection and analysis. Explanatory sequential design starts with quantitative data collection and analysis, followed by qualitative data collection and analysis. Researchers can also develop multi-phase designs having more than two data collection and analysis stages (Saunders et al., 2019).

In complex designs, the mixed design can be achieved at different stages of the research process. Teddlie and Tashakkori (2009) have identified four stages: the conceptualization stage, the experiential methodological stage, the experiential analytical stage, and the inferential stage. Nastasi et al. (2010) further divided these stages based on the specific location at which they might occur in the research process: philosophical stance; research question; sampling; data collection; data analysis; interpretation; presentation; and application. Therefore, the methods can be mixed at different stages and the location at which they might occur to achieve the research objectives.

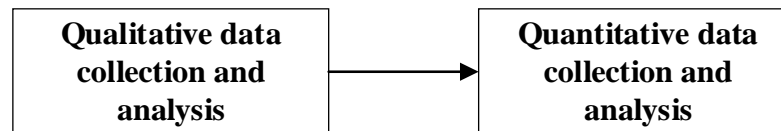
The combination of quantitative and qualitative methods can clearly provide much more to research than using a single method. However, there are drawbacks to mixed methods research. According to Doyle et al. (2009), some of the drawbacks of mixed methods are the need for additional research teams when using concurrent research designs, additional resources, additional time requirements and the knowledge of both quantitative and qualitative methods. Additionally, Easterby-Smith et al. (2015) added that mixed methods studies are difficult to replicate, demand that research designs be more competent overall and are only useful when designed correctly.

3.3.4 The research approach adopted by the research

Based on this pragmatic philosophy, the study utilises an abductive approach that combines quantitative and qualitative research approaches to minimise the drawbacks of using one or the other method alone. Exploratory sequential design, which uses qualitative data collection and analysis followed by quantitative data collection and analysis (refer to Figure 3.2) (Creswell & Clark, 2018), was selected as suitable for the research. The qualitative part of the research was conducted first to identify and

explore in detail a range of factors from the different perspectives of people related to the study. The factors identified were then verified and narrowed down through a quantitative approach to identify the key issues.

Figure 3.2 - Exploratory sequential design used in the research



According to the typology put forward by Leech and Onwuegbuzie (2009), this study utilises a partly integrated sequential dominant rank design, in which the dominant method is the qualitative approach. The qualitative approach was considered as the core and the dominant approach in the research design for this study since it is the factors impacting cost estimation identified through qualitative semi-structured interviews that drives the rest of the research. With reference to Nastasi et al. (2010), the stages used to ‘mix’ the qualitative and quantitative data followed this order: data analysis, interpretation and application. As such, the research design of this study is based on the partial mixing of qualitative and quantitative approaches.

Based on the research question(s) and assumption(s), the researcher can choose to take the qualitative, quantitative or mixed methods approach that best suit the research. The research approach chosen will be then used to determine the appropriate research method.

3.4 Research design and strategy of inquiry

‘Research design’ refers to the methodological process by which researchers find the solutions to the research question(s) or research problem(s) (Fellows & Liu, 2015).

Research design designates the abilities, assumptions, process, data collection and data analysis used in a study (Denzin & Lincoln, 2018). Denzin and Lincoln (2018) state that the research design of a given study connects the philosophical stance of the researcher(s) to the research method(s) used to collect and analyse data.

Research design details are essential to reach a valid result. Research design details include timeframe, researcher interference, research setting, the population of the research and research strategy (Sekaran & Bougie, 2016). The timeframe can be considered longitudinally and cross-sectionally. Longitudinal studies examine and gather data over multiple time points to observe changes in events, people or social relations over time, while cross-sectional data analyses data associated with one point in time (Neuman, 2014). Researcher interference can be correlational or causal (Sekaran & Bougie, 2016). Correlational studies are characterised by low researcher involvement in the study; the researcher observes the phenomena in their natural context. Causal studies are characterised by the manipulation of the variables by the researcher in order to identify the cause and effect relationships in a study. Partially related to interference, the research setting refers to the study environment, which can be natural or contrived (artificial) (Saunders et al., 2019). The population of a research describes the level of data aggregation and establishes the unit of analysis. This can be individual or involve multiple main groups, categorised by gender, department, organisation, industry or nation (Sekaran & Bougie, 2016).

‘Research strategy’ is defined and categorised in different ways in the literature. According to Sekaran and Bougie (2016), experiments, survey research, observations, case studies, grounded theory and action research can be used as categories for research design. Creswell (2014) has categorised the strategies into, simply, qualitative, quantitative, and mixed methods. Creswell (2018) deemed surveys and

experiments to represent quantitative methods while considering narrative research, phenomenology, grounded theory, ethnographies and case studies to represent qualitative methods. Mixed methods designs were identified as combinations of qualitative and quantitative methods. Eight research strategy designs have been identified by Saunders et al. (2019): experiment, survey, documentary research, case study, ethnography, action research, grounded theory and narrative inquiry. Depending on the research requirements, a suitable method can be selected.

A particular type of research design is used in a particular situation. There are four qualitative approaches: ethnography, grounded theory, narrative inquiry and action research. Ethnography seeks the cultural perspectives of study participants through observations and interviews (Creswell, 2018; Gray, 2018). Grounded theory is a systematic process that aims to create theories using the data as evidence. Grounded theory research is usually conducted through interviews or observations (Neuman, 2014). The narrative inquiry seeks to maintain a narrator's story in terms of the chronological connection and sequencing of the events to increase the researcher's understanding and inform the subsequent analysis (Saunders et al., 2019). Narrative inquiry employs in-depth interviews, informal interviews, observations, biographies, diaries and documentation for data collection. Action research considers knowledge as a form of power to create social-political change or achieve a social-political value-oriented goal which can be measurable (Neuman, 2014). As a qualitative method, action research primarily draws on either single or multiple case studies (Gray, 2018).

Research design associated with quantitative methods involves the use of surveys and experiments. A traditional quantitative survey method uses a questionnaire to efficiently collect data from a large number of people (Denzin & Lincoln, 2018). Such a survey can be used to get feedback, analyse human preferences or behaviour and

identify relationships between variables. In some instances, based on the data collected, surveys can be used in qualitative settings. As a quantitative data collection method, experiments are used to observe changes in relationships between variables by changing the conditions in one group and comparing the results with a control group (Neuman, 2014). Maximum control over the variables is achieved in experiments that are conducted in laboratory settings which contain control groups. If the experiments are conducted in the field, the variable control is minimal, so field experiments are generally identified as quasi-experiments (Fellows & Liu, 2015).

Two methods can be used, depending on how they are structured, in both qualitative or quantitative approaches: case studies and document research. Case studies collect data from a variety of sources to gain an in-depth understanding of a program, event, process activity or person(s) (Creswell, 2018). While case studies collect data from interviews, observations and document analysis, there is no precise method for such data collection (Denzin & Lincoln, 2018). Document research involves the use of secondary data acquired from databases and past research and the analysis of this data to create new findings (Saunders et al., 2019). This method can be incorporated into other methods, such as grounded theory and case studies. Observations are traditionally considered as a part of the research method. This is described further in section 3.5.

3.4.1 Selection of strategies of inquiry

Following the determination of the research methodology, strategies of inquiry were selected for the study. The qualitative stage of the study sought to explore and understand how variations arose between cost estimation and final cost calculations for earthquake damage repair work. For the qualitative approach, documentary

research, case studies, ethnography, action research, grounded theory and narrative inquiry were considered as possible strategies. Using only document research for this project was not appropriate, as such research requires an in-depth analysis of people's opinions that, in this case, were not given (Saunders et al., 2019). Action research focuses on changing processes and human behaviour rather than understanding and accepting an existing process (Sekaran & Bougie, 2016), and this study did not aim to change processes/behaviour. Ethnography investigates social and cultural human behaviour rather than phenomena, and narrative inquiry focuses on the stories of individuals (Easterby-Smith et al., 2015). While these strategies can capture the subjective views of individuals, neither caters to the main focus of this study. A case study method was also not suitable as case studies aim to understand the dynamics of a particular case (Gray, 2018; Saunders et al., 2019), and this study seeks to develop a tool that can address a range of circumstances. The grounded theory focuses on developing theories from the data collected and resists the influence of other aspects (Neuman, 2014), so it was the best fit for this study.

Within the grounded theory, there are three main methodological genres; Glaser's traditional grounded theory, evolved grounded theory developed by Strauss and the constructivist grounded theory that originated with Charmaz (Chun Tie et al., 2019). Glaser's grounded theory does not evaluate literature before data collection as it can create preconceptions that do not suit the data (Thornberg & Dunne, 2019). However, Strauss and Corbin (1990) stated that a literature review would add a rich background to the data collection that you are going to do, as long as it does not hinder the data collection process. Alternatively, the constructivist grounded theory states that data interpretation is based on the researcher's view of the world (Chun Tie et al., 2019). This research takes the stance of Strauss and Corbin (1990) and does an initial

literature review but does not hinder the data interpretations based on the literature review. Ultimately, appropriate data collection techniques can be selected based on the chosen research design which is further detailed in the following section.

3.5 Research methods

‘Research methods’ or ‘data collection techniques’ refer to actual data types, data collection methods, ethical considerations, sampling techniques, data recording methods, data storage procedures and the handling of practical issues (Creswell & Poth, 2016). Data collection methods used in research include interviews, questionnaires, observations, secondary data-based research, simulations and document analysis (Creswell, 2018). A suitable research method can be selected based on the purpose of the research, data availability, resource availability and skill of the researcher (Kumar, 2019).

3.5.1 Interviews

Interviews are conversations between two to more people during which the interviewer asks questions and listens attentively to the response from the participant(s) (Saunders et al., 2019). According to Gray (2018), interviews are used to: gather personal knowledge, values, attitudes and preferences on phenomena; identify variables and their relationships to test hypotheses; or in conjunction with other data collection techniques. The advantages of interviews have been proposed as follows (Kumar, 2019):

- Suitable for sensitive or complex situations
- Useful for the collection of in-depth information

- Can address and explain issues or questions in detail
- It can be administered to a wider audience and include those who might otherwise be excluded, such as illiterate, elderly, young and handicapped people.
- Can collect additional information from observations and non-verbal reactions.

Disadvantages of interviews include that they often cost more, can be time-consuming, and those interactions may influence the quality of data, the interviewer can influence the quality of data, and the researcher may be biased (Kumar, 2019; Saunders et al., 2019).

Interviews can be conducted face to face, by telephone or via virtual means and can be structured, semi-structured or unstructured. Structured interviews have rigid content and include multiple questions (Fellows & Liu, 2015). The rigid practice of research interviews involves closed questions, are one-way in terms of communication, are pre-designed process and maintain structured communication processes (including tone and word) (Kumar, 2019). Structured interviews are normally associated with quantitative data collection and require the researcher to remain detached.

In contrast to structured interviews, unstructured interviews gather qualitative data and do not have a predetermined structure. Unstructured interviews involve a two-way communication path and open-ended questions (Gray, 2018). In unstructured interviews, participants are given the opportunity to talk freely about a phenomenon, experience or beliefs. Questions can be used to probe the participant's account to gain further insight into the explanations. The interview questions are based on the data emerging from an interview and not on a researcher's predetermined perspectives (Saunders et al., 2019).

Semi-structured interviews combine qualities of both structured and unstructured interviews (Fellows & Liu, 2015). Semi-structured interviews are used in qualitative data collection (Gray, 2018) and involve a set of pre-designed themes and questions that the interviewer can remove, change or add to based on the experience of each interview (Saunders et al., 2019).

The themes or questions can arise from previous data collection, the literature, preliminary interviews or the researcher's own knowledge (Bryman & Bell, 2011). Semi-structured interviews can be used inductively, to create new themes from the data collected, or deductively, to verify pre-identified themes (Saunders et al., 2019). Additionally, themes and questions can be identified through initial interviews and verified in subsequent interviews, combining both inductive and deductive approaches (Kumar, 2019).

Interviews are normally conducted one-to-one. However, group interviews can be held with more than one participant at a time, multiple interviewers, or a combination of both (Gray, 2018). Multiple interviewers are normally used in instances in which one researcher conducts the interview while the other takes notes or facilitates the process. Group interviews are used to reduce the cost of interviews or for convenience (Sekaran & Bougie, 2016). A group interview can also take the form of a focus group interview, in which participants are encouraged to discuss a phenomenon and provide opinions (Hodder, 2003). In this case, rather than acting as a direct interviewer, the researcher plays the role of a facilitator (Saunders et al., 2019).

3.5.2 Questionnaire

A questionnaire is a research tool through which participants are asked to respond to a standard set of questions in an objective manner (Gray, 2018). A questionnaire can be administered through telephone messages, telephone calls, face-to-face interviews, direct delivery, postal mail, web-based email, or phone and web applications. The suitability of questionnaire administration can be based on the respondent type, the importance of each person's response, the likelihood that distorted responses will be collected, sample size, response rate, type of questions and number of questions (Saunders et al., 2019).

According to Kumar (2019) and Gray (2018), advantages of questionnaires include: respondent anonymity, a large potential sample number of respondents, low cost, reduced time consumption, increased data inflow, speed of data coding, simplicity of analysis and lack of respondent bias. However, questionnaires can have drawbacks, such as: low response rates, self-selecting bias created by respondents choosing not to respond, the inability to clarify issues, the non-availability of spontaneous responses and the chance that a single question will influence another (Kumar, 2019).

3.5.3 Observations

'Observation' is a selective, purposeful and a systematic way of looking, recording, analysing and understanding actions, behaviours or events (Kumar, 2019). An observation process can be conducted in the following four ways (Saunders et al., 2019; Sekaran & Bougie, 2016):

- Observing in a particular environment, whether natural environment (e.g. playground or workplace) or controlled (e.g. laboratory)
- Observing first-hand through active participation or as a passive participant or external observer
- Observing predetermined events in a structured manner or observing surroundings and events without a plan in an unstructured way
- Observing in such a way that participants are unaware (researcher is concealed) or aware (researcher is known) of the study

Methods of observation can be combined based on the aim(s) of the research. Observations can be used in cases in which the behaviour of the individuals, event or phenomenon cannot be objectively understood by individual perception and cannot be measured directly (Gray, 2018). It is important to note that observers are not impartial, interpretations can vary, observations can be incomplete, and the behaviour of the individual being observed can be influenced (due to awareness) (Kumar, 2019).

3.5.4 Secondary data

‘Secondary data’ is data which is collected for other reasons, and generally takes the form of bulletins, publications, published data and unpublished data (Saunders et al., 2019). This secondary data can come from governmental or semi-governmental publications, earlier research, personal records or the mass media (Kumar, 2019), and can be in the form of surveys and documents from multiple sources (Saunders et al., 2019). Surveys can contain census, and or regular surveys, while documents contain text, audio or both. Document analysis involves the systematic analysis of printed and audio material that is used in socially organised ways to create meaning and new

knowledge. Document analysis can involve the examination of text, images, audio video or cultural artefacts. Document analysis is a low-cost, inconspicuous, and nonreactive means of collecting supplementary data that should be used with other methods (Bowen, 2009).

3.6 Data collection process used for this research

At the time that this study commenced, there were no known post-earthquake cost estimation models. The researcher's aim was to identify factors affecting cost estimation by analysing current cost estimation processes. Therefore, the research used grounded theory as the initial strategy of inquiry to create theories around what factors had an influence on post-earthquake cost estimation. The grounded theory process was used to identify these factors by analysing participants' responses to semi-structured interview questions about damage identification, damage evaluation and cost estimation methods used in the CEQS.

Once the factors related to cost estimation processes in the context of the CEQS were identified, a quantitative approach was used to verify and prioritise the factors that affected the CEEDRW in the wider New Zealand context. Surveys, case studies, documents and experiments were considered as quantitative strategies. Experiments were not a suitable approach, as they focus on understanding correlations between variables with respect to environmental conditions and require the use of controls (Neuman, 2014). The verification process would be based on people's opinions on newly identified factors. Therefore, as previously noted, a document review was not suitable. Case studies were also removed as an option as they did not enable the verification of factors by a wide range of people. In the end, a survey method was used

as it helped ask a wide range of the target population about ‘how many’ and ‘what’ questions quickly and cost effectively (Gray, 2018). The survey aimed to collect answers to three main questions: how many people agree with the findings, what factors are important and what methods could be best used to incorporate these important factors into a CEEDRW.

Each of the research strategies required the use of different research methods. As part of the grounded theory strategy, semi-structured interviews with selected professionals were used to identify the factors that affect the variation between cost estimates and final costs associated with the CEQS. Even though there were other earthquakes that happened in New Zealand, knowledge related to the CEQS was much more mature and current, as the repair work to be considered spanned a period from 2010 and beyond 2019. The factors identified from these interviews were then verified and narrowed down according to their significance through a survey questionnaire. The questionnaire also asked participants to identify suitable methods to incorporate the significant factors into cost estimation processes. Based on the outcomes of each method, a cost estimation model was developed to improve CEEDRW. The developed model was then verified using a focus group interview.

3.6.1 Ethics approval

The ethical practice of data collection is imperative so that people involved in the data collection are not adversely affected by the methods used by the researcher. Therefore this research was reviewed and approved by the Massey University Human Ethics Committee: Northern, Application 4000017232 under the low-risk category.

3.6.2 Literature review

Sekaran and Bougie (2016) point out that functions of the literature review are to prevent the rediscovery of known knowledge, be familiar with the terminologies, have a better structure to the research, replicate methods of other researchers and include a contextual and theoretical background for the research for a broader debate. Saunders et al. (2019) added that a literature review would generate and refine your ideas and place the research within the context of the broader body of knowledge. Therefore, the literature review process is an essential part of the research.

The literature review for this research will comprise two parts. A background study was conducted to get a general idea of the research area and identify the research problem. The background study was expanded further in the literature chapter, where a critical review of the literature was conducted to justify the purpose of the research and understand the research problem.

Journal articles, conference papers, books, reports from acceptable entities and government reports were reviewed. The literature search was conducted on local and online databases, including the Massey University library database, Moratuwa University library database, Bonus database for books and articles in Australia and New Zealand libraries, Discover, Google Scholar, Google, Scopus and Web of Science. The literature review search started with keywords such as ‘earthquake damage’, ‘repair cost estimation’, ‘earthquake damage estimation systems’, ‘loss estimation systems’, ‘construction time estimation’ and ‘earthquakes’. The search was extended using the snowball method by referring to the references and key authors. The research was not confined to construction and earthquake engineering, as knowledge from general fields helped to triangulate the theories. The literature search

was also conducted on 'research methodologies' to identify the current knowledge on philosophical stances, research methods, research designs, data analysis methods and the most appropriate research design for this research study.

Based on the information acquired, the literature review is structured in a logical flow. A background review identifies the need for a cost estimation model for earthquake damage repair work; this was further explored in the literature review. The literature review focuses largely on three areas:

1. Earthquake characteristics, earthquake damage and damage identification methods.
2. Earthquake damage and damage evaluation process.
3. Cost and time estimation methods of damage repair and cost variation factors.

Furthermore, the literature reviews critically evaluated the practical damage estimation processes used in New Zealand. To make the research project practical within the time frame, it focuses on non-structural elements, specifically wall partition boards. Based on the information, the current cost models are critically reviewed. The critical review further identified limitations in these models and possible methods of solving the problem.

3.6.3 Semi-structured interviews

The current literature does not provide a clear understanding of the causes for the variation between the estimated costs and the final project costs for repair work related to the CEQS. Therefore, an exploratory study was required to understand the causes of these variations. An exploratory study focuses on reviewing cost estimation

processes from the onset of the earthquake to the final cost of repair work under review.

However, given the nature and topic of the research project, it was not possible to witness either the cost estimation process or total repair work process, as facts surrounding these areas were shared through interview meetings and the exchange of documented evidence. Therefore, an observation research method was deemed not suitable. Document analysis of cost estimations and evaluation reports did provide final outcomes of the process. However, they did not show or explain the subjective reasoning behind the decisions taken. Individuals with experience in cost estimation process and repair work had the most developed and current knowledge of cost estimation processes. Therefore, an interview method was selected as the most suitable method for the exploratory research.

Interviews can be defined as a communication activity through which an individual focuses their attention on another individual to gain an understanding of that person's knowledge, interests, values, beliefs, thought processes and perceptions (Schostak, 2006). When conducting research, an interviewer asks questions to direct the participant toward the research purpose, in order to gain an insider's perspective on a subject and co-create knowledge through their interactions (Hennink et al., 2020). Therefore, an in-depth understanding of personal accounts can be gained through interviews. If required, probing questions can be used in interviews based on the responses given by the participants to gain a better understanding. However, the co-creation of knowledge will depend on the researcher's ability to ask questions empathically and the creation and maintenance of a good rapport between the interviewer and participant(s), both of which will motivate sound responses (Hennink et al., 2020).

3.6.3.1 Interview type and design

As explained in previous sections, three main types of interview methods are structured, semi-structured or unstructured. According to the literature, there were a number of previous findings regarding the evaluation of earthquake damage to buildings and cost estimation processes. This existing knowledge could be used to develop topic points to explore current methods of CEEDRW. Therefore, interviews would not be unstructured. Because research into the topics to understand the mechanics of a CEEDRW necessitated a process that would generate in-depth answers, probing questions to further delve into the personal accounts provided by the participants would be useful. The interview would need to be able to go beyond structured questions and into detail, so a semi-structured interview method was selected.

3.6.3.2 Selection of interviewees

The participants selected for the interviews were all required to have professional experience in damage evaluation or cost estimation in repair work directly related to the CEQS. The research included participants involved in damage identification and cost estimation to get an overview of the cost estimation as well as the damage identification process. Since the data collection started in 2019 and the earthquake damage repair process started in 2011, some of the participants with the required experience had moved on to other companies, which made it difficult to recruit suitable participants. Additionally, the researcher did not have a significant rapport with members of professional communities related to earthquake damage repair work. Therefore, it was difficult to identify and recruit suitable participants for the study.

Hence, the research adopted a snowball sampling method to recruit suitable participants. The snowball method uses the knowledge and rapport of initial participants to identify and recruit additional individuals to participate in the study (Saunders et al., 2019). The snowball method is used due to difficulty in participant selection and recruitment (Hennink et al., 2020).

Initial contact with participants was made through consultancy companies, quantity surveyors and builders working within the Christchurch region. Participants selected for the research were engineers, engineering technicians, builders and quantity surveyors. Participants had experience in damage identification, cost estimation or repair work during the CEQS. These participants can be broadly categorised as coming from the following sectors: government, consulting and contracting. The study ultimately included nineteen professionals who expressed their inclination to participate in the research. The sample frame included seven engineers and twelve quantity surveyors. All participants had more than two years of experience in earthquake damage repair work (refer to Appendix 1 for details of the interview participants).

3.6.3.3 Interview template

The interview template for the research was based on the existing literature on cost estimation and damage evaluation processes. The sections of the interview template were divided to collect background information on participants, sources of damage identification, methods of damage identification, methods of cost estimation, methods of time estimation and further thoughts (refer to Appendix 3 for the interview template with probing questions). Interview questions included probing follow-up questions that were used depending on the responses of the professionals. The interview template

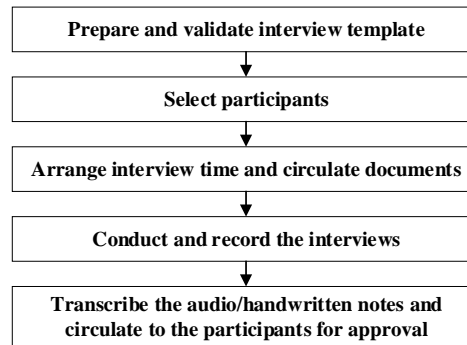
was validated by two quantity surveyors and three academics from the School of Built Environment (SBE), College of Sciences, at Massey University, Albany, Auckland, New Zealand.

3.6.3.4 Interview process

Once the participants had been recruited for the research, an information sheet, consent forms and interview questions were circulated. The details were forwarded prior to the interview to allow the participants adequate time to prepare for the session. The information sheet contained details of the research title, the purpose of the study, the time allocated for the research, the researchers' details, the ethics approval number for the study and data handling procedures.

The interviews were conducted at convenient locations suggested by the participants and included offices, homes and cafes. An informal conversational style was used for the interview session to build rapport and ease tension between the researcher and the participant. The duration of each interview varied from 30 minutes to 110 minutes. The interviews that were conducted beyond the estimated time frame were done with the approval of the participants. Audio recordings and handwritten notes were collected for each interview for transcription purposes. For interviews without audio recordings, handwritten notes were transcribed and emailed to the participant for approval because consent was not given for recording. Interview sessions were held between January 2018 and February 2019. The research required a year for data collection and interviews because participants were situated throughout the Christchurch area, and participant recruitment through the snowball method was difficult. The interview process is depicted in Figure 3.3.

Figure 3.3 - Interview process



3.6.4 Survey questionnaire

The outcomes from the qualitative research were based on grounded theory and focused only on the experience of the Canterbury earthquake sequence. Identified factors needed to be verified by cost estimators to determine their applicability to the New Zealand context, the significance of the factors and suitable processes to incorporate these factors into CEEDRW. Therefore, quantitative and deductive processes were needed both for verification and selection purposes. As noted in section **Error! Reference source not found.**, surveys can be used to collect both quantitative and qualitative data systematically from a wide range of participants quickly and cost-effectively (Saunders et al., 2019). Surveys can be conducted by questionnaires and structured interviews. The researcher chose to use electronically administered questionnaires that could: be administered easily, inexpensively and in a standardised way; reach a large number of respondents who were geographically dispersed; and collect answers automatically (Sekaran & Bougie, 2016).

3.6.4.1 Questionnaire development

The questionnaire for this study was designed to capture respondents' opinions and attitudes with regard to factors identified by the qualitative research and methods by which these factors could be incorporated into CEEDRW. The questionnaire was divided into six sections: project description and participant consent; overview of relevant experience of the participants; factors considered in cost estimation; the significance of the factors; suitable methods to incorporate the in CEEDRW; further thoughts and details. These sections contained open questions, yes / no questions, rating questions and list questions. The final version of the questionnaire was produced following three reviews and a pilot study (Appendix 4 - Survey questionnaire format). Because web-based questionnaires have a higher response rate compared to postal questionnaires (Neuman, 2014), the final questionnaire was built online using google forms; this format is easy to develop, complete and distribute (via a weblink).

3.6.4.2 Questionnaire sampling process

The questionnaire required professionals with experience in CEEDRW to participate as suitable respondents. The study did not require statistical inference about the factors, so random sampling was not required (Saunders et al., 2019). Additionally, the population and professionals with the required expertise were difficult to identify. Therefore, a purposive sampling method was used. A purposive sampling method is suitable when the required respondents are difficult to reach, come from a specific population and are targeted as relevant in relation to the questions being posed (Bryman & Bell, 2011; Neuman, 2014).

3.6.4.3 Questionnaire pilot study

Pilot studies are used to pre-test a research method using a small number of participants (Walliman, 2011). A pilot study can be used for preliminary data collection to, train researchers, test research instruments, verify research feasibility, clarify methodological questions, develop research protocols, evaluate recruitment strategies and determine suitable sample sizes (Connelly, 2008; Hertzog, 2008). The sample size of the pilot study itself is also crucial. According to Connelly (2008), the number of respondents for the pilot study should be at least ten percent of the main research sample, and the convenience sampling method can be used to select the participants. According to the convenience sampling method, suitable respondents are selected based on their availability and convenience to the researcher (Gray, 2018).

The study created a group for a pilot study using convenience sampling prior to the distribution of the questionnaire to the participants. The pilot study included ten participants, of whom a number came from the School of Built Environment at Massey University, and others were quantity surveyors with experience in cost estimation.

3.6.4.4 Questionnaire distribution

Suitable participants for the questionnaire were professionals with experience in CEEDRW. Since most of the cost estimators are professional quantity surveyors with industry association memberships, the New Zealand Institute of Quantity Surveyors (NZIQS) monthly newsletter was used in the first instance to send links to the questionnaire to all NZIQS members. However, the NZIQS newsletter only yielded four responses, making the response rate less than 0.2 percent. Therefore, online directories and databases, such as LinkedIn and Master Builders, were used to identify

and engage with the relevant participants. Questionnaire links were distributed to 310 participants via direct emails using this database harvesting approach.

3.6.4.5 Response rate

Response rates to questionnaires are an important factor in the collection of data, as the response rate will affect the validity of the questionnaire (Fellows & Liu, 2015). Non-responders may have systematically different responses compared to respondents, their lack of input creates non-response bias (Lund & Gram, 1998). To increase the response rate by using different methods, the researcher considered using monetary and non-monetary incentives, designing shorter and simplified questionnaires, writing persuasive covering letters and sending personalised reminders (Bryman & Bell, 2011; Gray, 2018).

Ultimately, several methods were used to improve the response rate to the questionnaire. These included the writing of well-scripted covering letters to the contact emails describing the short length of the questionnaire (the pilot survey group that used the questionnaire was able to complete it in around 10-15 minutes) and sending reminders by telephone and email. The covering letters contained a description of the findings of previous research, the aim of the research and the importance that the data from completed questionnaires by surveyed builders and professional cost estimators would have. Additionally, the ethics approval reference was provided along with a consent form.

According to the literature, 30 percent is an adequate response rate for a questionnaire (Fellows & Liu, 2015; Sekaran & Bougie, 2016). The active response rate for a questionnaire can be calculated using Equation 3.1 below (Saunders et al., 2019). This survey questionnaire achieved a response rate of 30.3 percent; this is further detailed in Chapter 4.

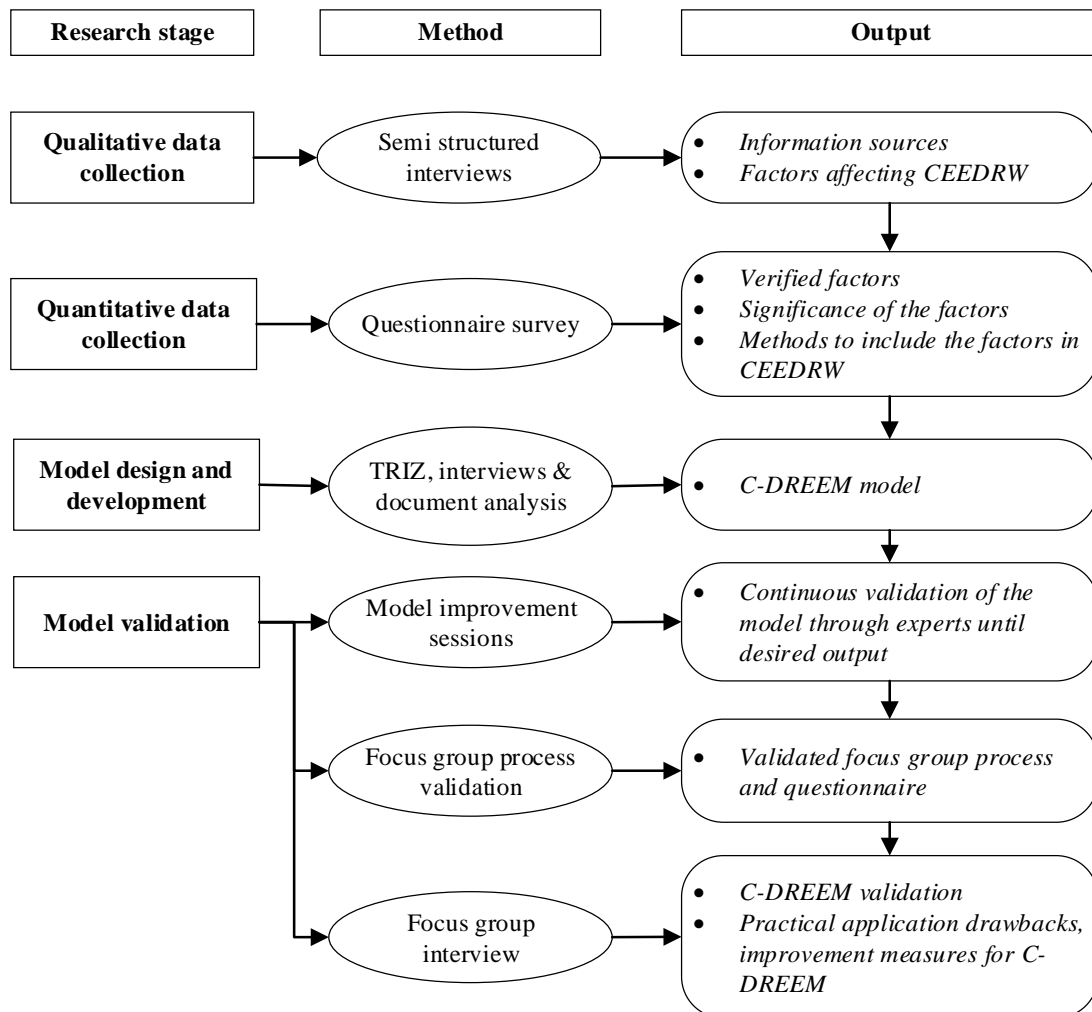
Active response rate

$$= \frac{\text{total number of responses (92)}}{\text{total number in sample (310) - (ineligible + unreachable)(6)}} \quad \text{Equation 3.1}$$

3.6.5 C-DREEM model development

The findings of the qualitative and quantitative studies were used to develop a final Cost of Damage Repair, Earthquake Estimation Model (C-DREEM) model that can be used for CEEDRW. The literature analysis was unable to identify models developed for post-earthquake CEEDRW. The probability-based cost estimation models used at pre-earthquake stages contained drawbacks and could not be used for post-earthquake damage loss estimation. Qualitative data analysis revealed information sources available and factors affecting CEEDRW. The subsequent quantitative data analysis verified that the factors mentioned in the semi-structured interviews were considered in CEEDRW, identified the significance of the factors and indicated methods for including the factors in CEEDRW. C-DREEM was developed to improve the CEEDRW and include the identified factors using new knowledge. The details of the C-DREEM development process is summarised in Figure 3.4 below.

Figure 3.4 - C-DREEM development process



3.6.5.1 Model design and development

Taking the first step in the process of designing a standardised and accurate post-earthquake cost estimation model for earthquake damage repair work that took into consideration the results of the qualitative and quantitative research required a problem-solving methodology. The review of the literature revealed that TRIZ methodology, developed by Genrich Saulovich Altshuller, is a proven and systematic problem-solving theory that supports innovation in product and process development (Altshuller, 1984; Livotov & Petrov, 2013). Therefore, the TRIZ methodology was

used to identify innovative methods that could be used in the C-DREEM development process. Based on the tools provided by TRIZ methodology and the simplified approach devised by Kalevi et al. (2018), the following process, expressed in Table 3.2, was developed to identify and apply suitable innovative principles to the research.

Table 3.2 - TRIZ based innovation process used for the research

Step	Step of TRIZ-based innovative methodology used in the research	Description of the step
1.1	Problem	Identify the problem required to be solved.
1.2	Causes of the problem	Identify the causes of the problem.
2.1	Selected Contradictions through TRIZ cycle	Note any contradictions by identifying what features that need to be improved and what features will be negatively affected by the improvements.
2.2	Intensify the contradictions	Increase the intensity of each example of contradiction to extreme ends to create breakthroughs.
3.1	Resources – Tools and objects	Identify the tools and objects of the system. Objects = parts that are most difficult to change Tools = the easiest parts of the problem to change
3.2	Resources in environment	Identify resources that can be used to improve the system.
4.1	Features related to the contradictions	Identify interrelated functionalities of the system that increase and decrease with the change.
4.2	Relevant principle(s) to be used for innovation	Select suitable innovation principle(s) from the 40 TRIZ principles with use of the contradiction matrix.
5.1	Removing contradictions	Use innovative methods to remove the contradictions.
5.2	Contradictions solved	Check if the contradictions were solved.
6.1	Product evaluations	Evaluate whether the suggested innovation achieves required outcomes

TRIZ was used to analyse the existing problem areas of CEEDRW and to identify suitable methods to improve CEEDRW by using TRIZ engineering parameters, the contradiction matrix and 40 inventive principles, as detailed in section 6.3 (Model development approach). Based on innovative principles, knowledge from the following sources were used in the initial model development process:

- Literature review
- Qualitative data analysis outputs
- Quantitative data analysis outputs
- Document analysis
- Interviews with builders and quantity surveyors

3.6.5.2 Model validation

The validation of the model was conducted in three stages: model improvement sessions through expert discussions, focus group process validation and a focus group interview. Each validation process was conducted with specific purposes, as detailed in the following section.

3.6.5.3 Model improvement sessions through expert discussions

The purpose of this step was to evaluate and upgrade the C-DREEM until the final desired output was achieved. The model improvement process was conducted throughout the development of the C-DREEM process until the finalisation of the model. The nine participants involved in the expert discussions included two quantity surveyors who were experienced in CEEDRW, three quantity surveyors who were involved in building repair work, three quantity surveyors who were involved in new construction, and a builder with experience in the repair of earthquake-damaged partitions. The participants were selected through the convenience sampling method.

3.6.5.4 Focus group process validation

The project relied on a focus group process validation session to evaluate the final focus group session in terms of; the required participants, the validation questionnaire and the model presentation process. The participants used in the model improvement process were also used for this process. Additionally, two quantity surveyors who lecture at the School of Built Environment at Massey University were also included in the team.

3.6.6 Model validation through a focus group interview

A focus group interview is a type of group interview in which small groups of participants, led by a moderator, interactively discuss specific issues (Hennink, 2014). A focus group usually contains six to eight participants sharing similar demographics based on, for example, occupation, social class or age (Wilkinson, 1998). Focus group interviews can be used as a triangulation strategy in sequential research design and also as a validation method (Caillaud & Flick, 2017). In the case of this study, the focus group method was selected to serve as a model validation method through which the C-DREEM was discussed in-depth and validated.

The focus group interview was conducted on 27 November 2020, from 10.30 am for 133 minutes at Canterbury University in Christchurch, because of its convenience to the participants. The interview session contained nine expert participants: eight quantity surveyors and an engineer with loss estimation model experience as detailed in Section 6.7.1. All the participants, except for the engineer (who had knowledge on probability-based loss estimation tools), were selected from the survey questionnaire using the selective sampling method. Participants involved in developing a model can

be biased towards its creation. Therefore, the chosen focus group participants had not been at all involved during the model development process, thus removing any bias towards validating the C-DREEM.

The focus group interview session contained four main sessions, each of which focused on validating the following specific aspects of the C-DREEM: (1) the clarity of the framework; (2) the basic concept and categorisation of rates; (3) the repair method classification and automation; and (4) the overall system. Each session included four parts: an explanation with a PowerPoint presentation, a discussion among the participants, a question and answer session and a survey questionnaire. Participants were asked to validate the above-mentioned aspects in terms of accuracy, buildability, usability, reliability, ability to increase the speed of estimation and coverage of factors affecting CEEDRW. At the end of the focus group session, participants' final comments were requested regarding the barriers to C-DREEM implementation, possible future improvements to the C-DREEM and the usability of the C-DREEM as a practical solution for CEEDRW.

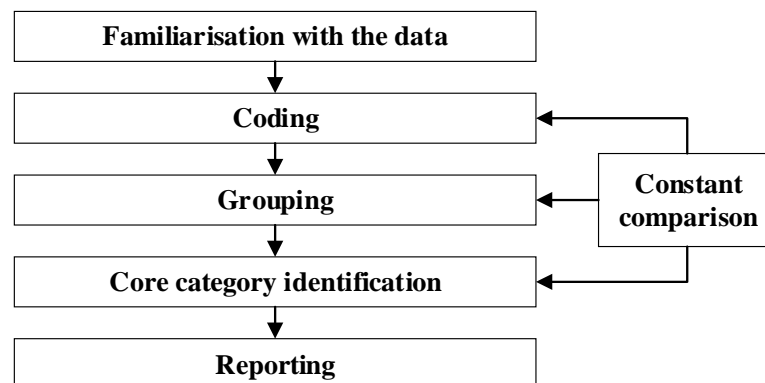
3.7 Data analysis

This section focuses on the data analysis methods and techniques employed by the research. The data analysis techniques are discussed in detail from the initial data collected from the semi-structured interviews through to the questionnaire and focus group sessions.

3.7.1 Qualitative data analysis

Perspectives raised in the relevant literature and thematic analysis can be used to analyse data generated using grounded theory methodology (Chapman et al., 2015; Tuckett, 2005). ‘Thematic analysis’ is a flexible, systematic and inductive approach used to create new theories from qualitative data. The thematic analysis also incorporates a deductive approach whereby existing knowledge is applied to draw out themes from the data (Saunders et al., 2019). For this study, the qualitative data from the semi-structured interviews were analysed using thematic analysis. The process involved immersing in the data by re-reading and reviewing it to create themes (Bowen, 2009). The thematic analysis procedure takes a researcher through six steps: familiarisation with the data, initial coding, searching for themes, reviewing themes, defining themes and reporting (Braun & Clarke, 2012). Saunders et al. (2019) specified the steps as: becoming familiar with the data, coding the data, searching for themes and recognising the relationship, refining the theme and testing propositions. Based on the processes identified by different authors, the research used the following steps shown in Figure 3.5.

Figure 3.5 - Qualitative data analysis process



The first step of the thematic analysis was to become familiar with the data. The activities related to the first step involved self-transcribing the data, re-reading the transcripts and creating summaries. According to Corbin and Strauss (J. Corbin & Strauss, 2008), this step enables the researcher to reduce the coding time in the subsequent steps and understand the meaning and context of the data.

The next steps of the process involved coding the data, data grouping and core category identification. The steps of his process can also be referred to as ‘open coding’, ‘axial coding’ and ‘selective coding’. The open coding process involves breaking the data into small segments to identify concepts and labelling the concepts for later analysis (Bhattacharjee, 2012). When labelling, the unit of code can vary from a single word to a couple of paragraphs. In the axial coding procedure, coded items are then grouped into categories using connections between concepts (Zhou et al., 2015). At the selective coding stage, subcategories are used to create core categories to establish a theory (Gray, 2018). According to Gray (2018), selective coding involves identifying core categories, connecting core categories and subcategories, validating the relationships using the data and further refining the categories.

In the case of this study, the coding process continued until theoretical saturation was achieved. ‘Theoretical saturation’ occurs when no new core categories can be created (Bhattacharjee, 2012). As stated by Corbin and Strauss (J. Corbin & Strauss, 2008), open coding, axial coding and selective coding can be conducted simultaneously through a process of constant evaluation that leads to the refining and updating of concepts and categories. This interlinking and constant comparison is the heart of the coding process (Belgrave & Seide, 2019). The qualitative data coding process for this study was conducted using NVIVO 10 and 11 computer software packages (QSR International, 2020).

Finally, the analysis was presented as a report. The report focused on presenting the core categorisations as findings and using the qualitative data as evidence. Even though the reporting process was specified as the last step of the analysis, the report development process, as exemplified in the literature, was initialised with the data summarisation at the first step of the analysis (Braun & Clarke, 2012).

3.7.2 Quantitative data analysis

The data collected from the survey questionnaire and the C-DREEM validation questionnaire were analysed using quantitative data analysis techniques. In general, the analysis techniques used for data depend on the type of quantitative data collected. The major types of data collected are nominal data, ordinal data, interval data and ratio data (Sekaran & Bougie, 2016)

Data collected for this research contained nominal and ordinal data. ‘Nominal data’ refers to data that has a categorisation or name-value that is unique and has no ranking sequence or inherent order. This data can be measured by frequency only (Gray, 2018). ‘Ordinal data’ refers to data that contains a specific order, but the interval between two adjacent values is not intended to be equal and cannot be measured (Neuman, 2014). Many different ranking scales can be used for ordinal data. In the context of this study, Likert and frequency scales were used. The Likert scale is an agree-disagree scale that focuses on collecting a participant’s opinion on a question. The Likert scale is a verified balanced scale with high internal consistency and internal reliability (Croasmun & Ostrom, 2011). Therefore, focus group questionnaire was conducted using a five-point Likert scale for ordinal data. Additionally, an unbalanced five-point frequency scale was used for the questions in the main survey questionnaire that involved responding according to a rating scale with one negative and four positive

points. According to the research conducted by Liao (2014), it is more reliable and useful to use an unbalanced scale than a balanced scale to develop a positive-oriented construct. Therefore, the research used an unbalanced scale in the survey questionnaire to rank the factors that were identified using the previous qualitative data collection. It is important to note that some ordinal data collection questions in the survey questionnaire contained the option for participants to give 'other' responses and select multiple responses.

3.7.3 Descriptive statistics

The survey questionnaire data were analysed using descriptive statistics. 'Descriptive statistics' are used to understand basic patterns in data (Gray, 2018). The appropriate descriptive statistic for a study depends on the number of variables in a data set. Frequency distribution, measures of central tendency (mode, median and mean), standard deviation, correlation, multiple regression and chi-square are some of the descriptive statistics that can be used (Neuman, 2014).

The objectives of the questionnaire should determine the appropriate type of statistical technique(s) to be used. The questionnaire in this study aimed to verify the factors identified through the qualitative study, rank them according to their significance and identify the most suitable methods to incorporate them into CEEDRW. The questionnaire contained a nominal dichotomous scale and nominal polytomous scales. The dichotomous scale focused on verifying which factors were considered in CEEDRW based on responses to yes and no answers. The nominal polytomous scale focused on identifying and categorising selected ways to include the aforementioned factors in CEEDRW. Nominal scales were analysed using percentage and mode. The questionnaire also contained options for participants to write in other choices and

select multiple responses. Options suggested by the participants were also cumulated based on meaning and frequency. The research calculated the percentage of choice for each multiple-choice question by dividing the frequency by the total number of survey participants, as detailed in Chapter 5. The ordinal data from the questionnaire were analysed using a weighted average, a relative importance index (RII), standard deviation and skewness.

3.7.3.1 Cronbach's alpha

Cronbach's alpha is a frequently used statistical technique for measuring the internal consistency of ordinal scale responses (Saunders et al., 2019). The alpha measures the inter-relatedness between the items included in a test (Tavakol & Dennick, 2011). The outputs of Cronbach's alpha will be between 0 and 1. Cronbach's alpha value for a reliable data set is 0.7 or above (Taber, 2018). However, internal consistency dichotomous items cannot be calculated using Cronbach alpha.

3.7.3.2 Kuder-Richardson 20

Kuder-Richardson 20 measurement is used to check the internal reliability of dichotomous data (Osborne et al., 2008). Kuder-Richardson 20 splits the results of a test into two halves, considering all possible scenarios, and calculates the correlation between both halves (Heale & Twycross, 2015). A higher correlation between each half will demonstrate greater reliability of the results. A data set is considered reliable if the value for Kuder-Richardson 20 is above 0.7. The formula used for Kuder-Richardson 20 is shown in Equation 3.2 (Wombacher, 2018).

$$\text{KR20} = \frac{K}{(K - 1)} \left[1 - \frac{\sum_{i=1}^k p_i q_i}{\sigma^2} \right] \quad \text{Equation 3.2}$$

In the equation, ‘K’ refers to the number of factors considered, ‘p’ refers to the number of people who selected one type of answer (e.g. ‘yes’), and ‘q’ refers to the number of people who selected the alternative answer (e.g. ‘no’). Next, Kuder-Richardson 20 removes the values of each, one by one, and checks the variation in Cronbach’s alpha levels. If the overall Cronbach’s alpha value decreases for all factor removals, then the data set is considered reliable.

3.8 Research bias

‘Bias’ in data collection, analysis, explanation and presentation can be defined as an intentional or unintentional variation from reality that can lead to an erroneous understanding (Šimundić, 2013). Research bias is the difference between the research results and the truth (Kumar, 2019). According to Smith and Noble (2014), it is important to understand research biases because research bias exists in all studies and is difficult to eliminate, research bias occurs at every stage of the study, validity and reliability of the findings can be affected by bias, and the misinterpretation of the conclusions of the study can have significant practical implications. The type of research bias that affects a given study depends on the research design and method. Table 3.3 depicts a collection of bias factors that can affect research. Research bias applicable to this research is addressed in the next section.

Table 3.3 - Types and descriptions of research bias according to stage of occurrence (Krishna et al., 2010; Pannucci & Wilkins, 2010; Saunders et al., 2019; Šimundić, 2013)

Stage of occurrence	Type of bias	Description
Research design stage	Design bias	Researcher beliefs and values affect selection of research question(s), aim(s), methodology and design.
Sampling	Selection bias	The sample selected for a study is not representative of the (target) population.
	Volunteer / referral bias	The research participants include only those who volunteer for the study.
	Non-respondent bias	Invited/selected individuals do not respond to or participate in the study.
	Inclusion bias	Similar participants are selected for a study.
	Survivor bias	The required participants are not available for the study. (Occurs during cross-sectional studies.)
Data collection	Measurement bias	The bias that occurs due to incorrect measurement of a variable.
	Instrument bias	The measuring instrument gives inaccurate outputs.
	Insensitive measure bias	The measuring tool does not have the required sensitivity to measure the required values.
	Expectation bias	The researcher measures the data according to their expectations.
	Recall or memory bias	Participants required to remember past events cannot remember the phenomena accurately.
	Response bias	Participants change/edit their responses because they know they are being studied.
	Verification or work-up bias	The participants selected have certain qualities. (Occurs during verification test.)
	Withdrawal bias	Participants leave the study.
	Proficiency bias	Controls in the study are not applied equally.
	Compliance bias	The rules of the study are not followed equally by the participants.
	Timing bias	Data collection does not occur concurrently, and the timing of the collection affects the subjects.
	Co-intervention bias	Subjects are affected by other studies that change the data.
	Contamination bias	The control group used in the study receives the same input as the other group.
	Interviewer bias	Verbal or nonverbal behaviour of the interviewer has an impact on participant response.
Payment bias	Payment to participants affects responses.	

Stage of occurrence	Type of bias	Description
Analysis bias	Analysis bias	Researcher ideology affects the choice of data analysis method, resulting in data omission, data fabrication, the use of inappropriate tests and changes in analysis methods to generate significant findings.
Reporting	Funding bias	The ideology of the funding organisation affects the research aims, objectives and design.
	Publication bias	Data is reported according to the needs of the publisher.
	Citation bias	Researchers are unwilling to publish unfavourable results.
All stages of the research	Researcher bias	Any factor creates systemic differences in the method of data acquisition, recording and interpretation. This is most likely to occur when the researcher is actively seeking specific outcomes of the research.

3.9 Quality of the research

Judging the quality of the research is essential when evaluating the dependability of the output. The quality of the research depends on its validity and reliability measures. These measures mainly focus on qualitative research, but there are some concerns related to quantitative and mixed methods research. Thus, it is essential to take validity and reliability measures.

3.9.1 The validity of the research

The ‘validity’ of research is a measure used to check the accuracy of the research outputs (Creswell, 2018). There are many definitions and subcategories of validity. Validity can be described as the process of verifying data collection, data analysis and the interpretation of the data in order to confirm its validity or credibility (Saunders et al., 2019). Sekaran and Bougie (2016) define validity as the extent to which the research tool measures what it is supposed to. Thus, the validity of research is essential.

Triangulation is one of the methods employed in this study to improve the validity of the research. Triangulation involves the use of multiple theories, methods, researchers

or data sources to study a single phenomenon (Denzin & Lincoln, 2018; Merriam & Tisdell, 2016). Triangulation was achieved when quantitative survey data outputs verified qualitative method outputs. Furthermore, the development of the model involved the use of qualitative and quantitative findings and was verified during the focus group interview.

Questionnaire validity can be evaluated using construct validity, content validity, criterion validity and face validity. A description of validity methods is summarised below, with reference to the literature (Heale & Twycross, 2015; Kumar, 2019; Saunders et al., 2019; Sekaran & Bougie, 2016):

1. Construct validity checks if the output of the tool correlates with similar knowledge.
2. Content validity checks if the total intended concept is measured through a tool.
3. Criterion validity checks if the instrument measures the intended concept.
4. Face validity checks if the measuring tool reflects the content required.

The employment of a given validity method depends on the aims of the research. Table 3.4 summarises the purpose of each validity method in relation to the questionnaire and the technique used.

Table 3.4 - Method of achieving required validity of the questionnaire

Type of validity	The question associated with validity type	The technique used to maintain validity
Content validity	Does the questionnaire cover the required scope and objectives of the research?	Content validity was quantitatively achieved. Survey questions were developed based on a review of the literature, qualitative data collection and reviews from costing professionals.

Type of validity	The question associated with validity type	The technique used to maintain validity
Construct validity	Does the questionnaire achieve the intended measurement of the phenomenon?	Construct validity was qualitatively achieved. The questions for the surveys resulted from the hypothesis. Furthermore, ten cost estimation professionals validated the questionnaire and its objectives based on their experience in CEEDRW in the pilot survey. Additionally, factors considered in previous CEEDRW and factors to be included in a new CEEDRW were compared (see section 5.5). Since these results were similar, validity was achieved.
Criterion validity	Was the accuracy of the predictions of the tools used checked through the use of other tools?	The research did not intend to achieve criterion validity due to the population's unknown size and non-random sampling. However, the findings did correlate with the literature and qualitative method outputs.
Face validity	Are the questions in the questionnaire correct?	Face validity was qualitatively achieved. The pilot study was used check meanings of the questionnaire

3.9.2 Reliability of the research

'Reliability' is concerned with the replicability and consistency of the research. Cavana, Delahaye and Sekaran (2001) and Sekaran and Bougie (2016) define reliability as determined by the internal consistency and stability of measuring systems over time. In simpler terms, a reliable research project should achieve similar results if the research process is repeated (Vogt & Johnson, 2011).

Due to the subjective nature of qualitative data, the reliability of this study can be affected. To minimise factors affecting reliability, the researcher used comprehensive descriptions of the methods used and described in detail the information collected. Saunders et al. (2019) have identified threats that could affect reliability. These threats to reliability and the appropriate mitigation methods taken for this study are expressed in the following Table 3.5.

Table 3.5 - Method to ensure the reliability of the qualitative data

Threat	Description	Mitigation method
Participant error	Factors affect the performance of the participants	The interviews were conducted for a predetermined period, following the direction of the interviewees, in order to ensure participant comfort.
Participant bias	Factors result in false responses	Rapport was developed between the participants before data collection. The participants were interviewed in enclosed rooms selected by the participants. Recording and transcripts of the interview and cost data were secured and not disclosed to others. Participant bias was also minimised using triangulation methods.
Researcher error	Factors alter the interpretation(s) of the researcher	Audio recordings were collected and transcribed from the interviews. For interviews without an audio recording, notes were transcribed, and transcripts were emailed to interviewees for verification. The data analysed was checked by other researchers.
Researcher bias	Factors induce the bias of the researcher	The final outputs of the research were verified by the focus group interview.

The reliability of quantitative data can be considered in terms of stability reliability, representative reliability and equivalence reliability (Neuman, 2014). ‘Stability reliability’ checks are required to determine whether the output of the tool is similar across different time frames. Stability reliability can be checked using the test-retest method, through which the participants fill in the questionnaire for a second time after a defined time period (Kumar, 2019). ‘Representative reliability’ checks are required to determine whether the results of the tool are similar across different samples (Payne & Payne, 2004). Analysis of data from different subcategories or including alternative forms of the same question in a questionnaire can be used to check representative reliability (Saunders et al., 2019). ‘Equivalence reliability’, also referred to as internal consistency, measures whether the output results are similar across different forms of measurement. Internal consistency can be checked using Kuder-Richardson 20 and Cronbach’s alpha calculations (Sekaran & Bougie, 2016).

The reliability of the quantitative data collected from the survey questionnaire was analysed using Cronbach's alpha and Kuder-Richardson 20 methods, as described in section 3.7.2. The test-retest method or alternative form questions were not performed in the survey. The test-retest method was not used in the research because of the difficulty associated with inviting the same respondents to participate a second time. Alternative forms of the same question were not used because adding them would elongate the survey and, in all likelihood, reduce the number of participants.

3.10 Summary

This chapter discussed the research methodology selected for the study in detail, based on the research aim and objectives. The chapter began with a literature summary with regard to research philosophy, research approaches, research designs, research methods and research bias. Decisions made based on the literature review, regarding research philosophy, research approach, research design, data collection and analysis techniques adopted for this study, were described and justified. Finally, measures used to maintain the validity and reliability of the research were discussed.

The research adopted pragmatism as the most suitable philosophical stance as it relies on using an exploratory sequential design which contains a qualitative data collection followed by a quantitative data collection. The method used was an abductive approach. The initial exploratory research collected qualitative data through semi-structured face-to-face interviews. Collected interview data was then analysed using thematic analyses and NVIVO software.

Findings identified from the qualitative research were validated through the quantitative data collected from a survey. Based on the results, the C-DREEM model

was developed, informed by the literature review findings, document analysis, TRIZ methodology and input from professionals. The C-DREEM was validated using a focus group discussion which involved expert participants. A questionnaire was used to collect data from the focus group sessions. Data collected from focus group questionnaires were analysed using descriptive statistics. Each research method included detailed explanations of design, participant selection, template and research process. Finally, the chapter discussed measures that were taken to maintain the reliability and validity of each research method.

4

INTERVIEW DATA COLLECTION AND ANALYSIS - REPORTING THE VIEWS OF INTERVIEWEES ON COST ESTIMATION PRACTICE IN NZ

4.1 Introduction

The literature review chapter indicated the availability of pre-earthquake loss estimation tools that have been developed to predict earthquake damage and estimate the probable loss. PACT, SLAT, SP3 and HAZUS were identified as available tools. However, drawbacks associated with the use of these tools prevented them from being used to fulfil the needs of post-earthquake loss estimation for earthquake damage repair work.

Therefore, the review of the literature identified a need for an accurate cost estimation model for earthquake damage repair work. For that purpose, the process of estimating costs after an earthquake needed to be analysed. To do this, semi-structured interviews

were conducted to obtain an understanding of the actual damage and collect primary data. These interviews provided information on current cost estimation processes and created a foundation of knowledge from which the problems associated with CEEDRW could be refined.

Exploratory semi-structured interviews were conducted with engineers, engineering technicians and quantity surveyors with experience related to the CEQS. This chapter presents the results of the semi-structured interviews conducted in this study.

Interviewee profiles are presented first, followed by a description of the current process used for damage identification and cost estimation. Finally, factors affecting the cost estimation of earthquake damage repair work are discussed. The findings identified in this chapter become the basis for chapter 5.

4.2 Participant profiles

The participant portfolio comprised 19 professionals who expressed their inclination to participate in the research. Participants represented the public and private sectors, as per Table 4.1.

Table 4.1 - Participants' profile

	Government	Consultant		Contractor	
Profession	Quantity surveyor	Engineer/engineering technician	Quantity surveyor	Engineer	Quantity surveyor
Sample size	2	6	5	1	5

Participants were asked to describe their experiences related to construction and earthquake damage repair work. All participants were involved in earthquake-related construction or consultancy work. The experience of the participants in the

construction industry ranged from two to 49 years, and their experience in earthquake-related construction varied from two to ten years, apart from one participant, who had 30 years of experience. The data collection was stopped at 19 participants due to data saturation which is acceptable for interview data collection (Saunders et al., 2019).

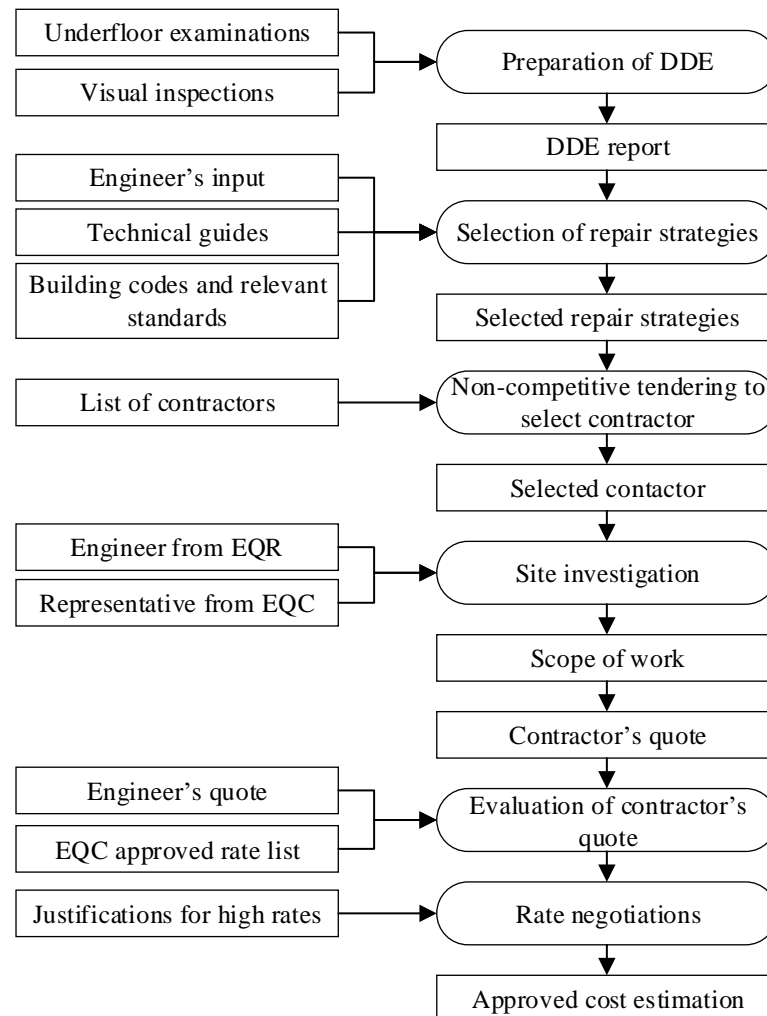
The thematic analysis results revealed three areas on which to focus: the damage estimation and repair process; the cost estimation process; and factors impacting repair work. These areas are detailed in the following sections. Each participant will be referred to by reference number, as detailed in Appendix 1.

4.2.1 Damage estimation and repair process

The initial damage estimation and repair process is most likely to be either government-supervised or insurance-company supervised. During the semi-structured interview, one participant (R.02) described the method of cost estimation used in government-supervised initial repair work associated with the CEQS (refer to Figure 4.1). They stated that an engineer's report was the preliminary document used to determine required repair work. Building inspections were conducted on houses which included visual inspections, robotic equipment and underfloor assessments in order to determine the extent of the damage. Another participant (R.17) added that the damage identification was mostly superficial, and no destructive tests were conducted. This participant (R.17) also gave an example by stating, "*... so, they wouldn't break out plasterboard on a wall to see if the framing was damaged*". Repair strategies were then selected and approved by a senior engineer using technical guides, standards and inspection reports. Next, a contractor was selected from a list of approved licenced building practitioners (LBP) using a non-competitive tendering method. According to

participants R.02 and R.17, non-competitive tendering was used due to the high demand for repair works and the small number of contractors available.

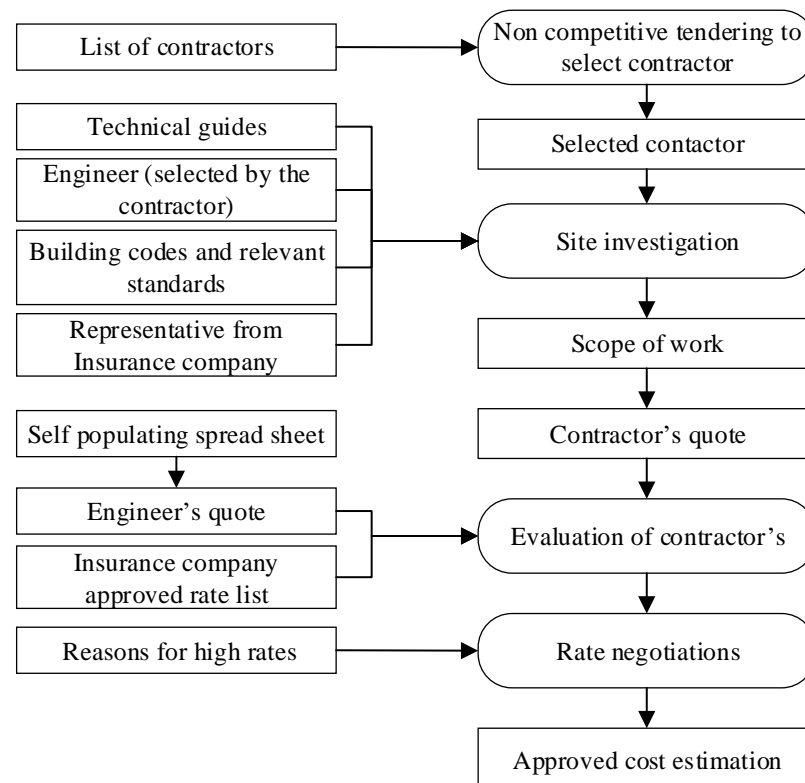
Figure 4.1 - EQC-EQR cost estimation process associated with the CEQS



According to a participant (R.02), once a builder was selected, the builder, a supervisor from Earthquake Recovery (EQR) and a representative from the Earthquake Commission (EQC) evaluated the damage to the property through site visits and document reviews (e.g., the engineer's report). One of the main aims of the process was to determine whether the damage had been caused by the earthquake (earthquake damage) or not (historical damage). That was because repair work only covered damage caused by the earthquake. After that, the scope of work was created.

Based on the scope of work, the contractor would give a quote according to their repair strategies. EQR would then evaluate the contractor's repair strategies and quote against the engineer's report and the EQR estimate. A set of EQC-approved schedules of rates were used by the EQR for this evaluation process. There were instances when a rate in the builder's quote was higher than the rate ceiling provided by the EQC. In such cases, EQR quantity surveyors investigated the site conditions and undertook a coordinated approach with engineers and contractors to identify why the rates in question exceeded their estimates. Subsequent negotiations were often held for the purposes of lowering the contractor's quote. Justifiable rates above the rate ceiling were accepted if approved by the client (EQC).

Figure 4.2 - Example of the cost estimation process conducted by insurance companies



A participant (R.17) described the insurance-company supervised repair processes (refer to Figure 4.2). A damaged building would be jointly viewed by a contractor, an

assessor from the insurance company and an engineer, if major work was required. The engineer would be selected by the contractor. According to the participant, the EQR-EQC system controlled the scope of repair work within its process. However, in the insurance company-monitored repair work, more contractor input was allowed when developing the scope. Insurance companies also used a non-competitive tender process and a predetermined rate set for quote evaluations. Additionally, they also had a spreadsheet with self-populating rates set that could be used to create quotes. Similar to cases working through the EQR-EQC system used for the government-supervised process, if the quote from the contractor was above the quote from the insurance company, justification was required from the contractor. A participant (R.17) added that the insurance company-monitored work “*had a very transparent process*”.

It is worth noting that, as part of the recovery from the CEQS, a need arose for a great amount of secondary repair work resulting from substandard repairs conducted on repaired buildings. Participants (six of 19) who were involved in secondary repair work explained the process. First, documents produced by the government bodies on preliminary repair work were analysed. Next, a secondary site investigation was conducted on the properties (Example activities performed in a site investigation for secondary repair work, according to R.04, is included in Appendix 2). In practice, the client’s representative and a representative from the insurance company responsible conducted the site investigation to identify the damage to the building and determine what damage was earthquake-related. Based on the extent and nature of the damage, the cost was manually estimated using cost databases and contractor quotations.

4.3 Information sources

The critical component of any cost estimation is project information available at that time. Therefore, to identify the current information sources used to identify earthquake damage to a building, participants were asked about typical damage identification methods conducted after an earthquake. Most participants described that, after an earthquake, two types of damage assessments are conducted on a building: Level-2 rapid building assessment and a detailed damage assessment.

4.3.1 Rapid building assessment (RBA)

According to one participant (R.10), Level 2 rapid building assessment (RBA) was the preliminary assessment conducted for buildings after the CEQS. The RBA was used to check whether a building was safe for occupancy. The RBA was simplified in nature, worked from checklists, and did not gather detailed information. Another participant added that:

“After an earthquake, we did the rapid assessments. But basically, you’re just running around saying this is not going to collapse on somebody. We were just doing a life safety assessment and had no time to do anything else because we were doing 10 or 20 a day that included writing a one-page report. It’s useless for developing a repair strategy.” (R.13)

According to a participant (R.13), the RBA was simple and vague by design, because of the limited timeframe and the high number of properties that required post-earthquake safety assessments. Therefore, the RBA was not used as a source to identify building damage in its current post-earthquake state.

4.3.2 Detailed damage evaluation (DDE)

According to two participants (R.08 and R.10), an engineer's report or detailed damage evaluation (DDE) describes in detail the damage caused to a building by an earthquake. Some participants (R.03, R.04, R.05 and R.13) mentioned that DDE was developed to use techniques such as visual inspections, floor level surveys, wall verticality checks, crack measurements, underfloor inspections, ceiling inspections and stress investigation of structural elements, all of which can be included in geotechnical reports, survey reports and structural reports. DDE was the primary source of information for assessing the cost of earthquake damage repair work.

Any input into an evaluation should be accurate, complete, duplicable, readable, accessible, consistent, useful and reliable (Batini and Scannapieco, 2016). According to the participants, there were some deficiencies when using DDE as an input source for cost estimation; these were primarily related to accuracy, completeness, consistency, usefulness and reliability. Two key issues were:

- There was no standard format for producing DDE. In some instances, variations were identified between the reports of multiple engineers produced for the same property which presented different damage assessment results. One participant noted that *“every engineer [who] comes to check the [site], they say different things. There is no standard in the report. What they feel, they write according to their experience”* (R.10).
- Engineer's reports focused on damage assessment. The information provided by engineering reports did not cover all the information

required to produce accurate cost estimates. A participant gave an example:

“For example, if there is a crack in the plaster to be repaired that is obstructed by a vent pipe, the engineer’s report will specify the crack, but obstructions of the vent pipe will not be mentioned. Likewise, the engineer will advise removing the building to repair the foundation, but there will be no space to remove the building.” (R.16)

Because DDE was the primary source of information for cost estimation, one quantity surveying participant noted the need to create a standardised DDE process by stating: *“If you don’t have that standard procedure, you are wasting a lot of money ... and if you are provided with a proper report, then you can save a lot of money at the construction phase”* (R.08).

4.4 Factors affecting estimated costs

Participants were asked about the cost estimation process and related difficulties. According to the quantity-surveying participants, a number of factors affected the variation between cost estimates and final costs. These are discussed in detail below.

4.4.1 Consequential damage repair (F 01)

A house is built out of a collection of elements that are interrelated. Therefore, damage to one element can result in consequential damage to another element. A participant expressed an example to show how damage in one element can indicate damage to another, *“...if cracks are visible and part of the ceiling is broken down, a licenced builder needs to come and check that. If he sees they are larger cracks, the builder*

may link this to structural damage...” (R.10). These hidden damages can be categorised as initially unforeseen damage (F08).

Participants identified other types of consequential damage that needed to be taken into consideration in cost estimation when calculating the value of damage repair work. There could be undamaged building elements that would be damaged or require alteration work because of other damaged building elements. According to an example expressed by one participant (R.10), repair work to substructure damage could cause damage to partition work, for example, if the house needed to be lifted or moved as part of the repair work. This could require the removal of heavy exterior cladding, the removal of heavy roof structures and damage to the building frame. The lift itself could damage building elements, as expressed below;

“If the house was getting lifted to repair the foundations, whether it’s concrete or a ring foundation, effectively, they would take out the bottom meter of the wall plaster boards, so they could run beams through the building then tie these to the frame and jack it up. And I used to argue that as soon as you lift that house, no matter how evenly you lift it, you’re going to get consequential damage for just about every sheet of plasterboard.” (R.17)

Another participant added that even though contractors were responsible for making the maximum effort not to damage the building, consequential damage was always inevitable. These additional costs to repair were covered by insurance policies or EQC funding. This idea is exemplified in the following statement: “*Yes, there are cases of extensive consequential damage. When the contractor signs the contract with the owners, the contractor must take maximum care. Failing this, additional consequential damage is covered by the EQC or insurance.*” (R.08)

Additionally, participants also mentioned that a change in one element could lead to a lot of changes to related items. One participant gave a specific example in which a change to a building's cladding system increased the width of the walls.

“If you focus on that, let's say if you are replacing the cladding system with the new alternative, because this cannot be reinstated to as new condition. So, with the new cladding type, you are changing a number of things, starting from the width of the walls and so on. Your windows will not be the same, and so we need new windows and associated flashings.” (R.03)

4.4.2 Cost of professional services (F 02)

Earthquake damage repair work requires the input of different professionals in areas such as damage identification, repair strategy identification, repair cost estimation and dispute resolution. The participants in the interview sessions were mainly structural engineers and quantity surveyors. Participant (R.14) gave a breakdown of the cost of each professional service. The cost of services from architects, structural engineers, hydraulic engineers, mechanical engineers and project managers would be 5 to 8 percent, 1.5 to 2.5 percent, 0.5 percent, 0.5 percent, and 2 percent of the total cost of construction, respectively. However, the cost of the geotechnical report would be based on the size of the project, and was, on average, around NZ \$10,000 to \$15,000 for houses during the CEQS. Even though total percentages associated with the costs of professional services were around 12 percent, two participants (R.14 and R.15) stated that only 10 percent of total construction cost attributed to the cost of professional services would be generally acceptable. However, participants added that this percentage could acceptably increase in small projects (R.18) up to about 15 percent (R.14) of the total cost and should be costed using contractor's quotes (R.17).

Additionally, one participant stated that cost of lawyers could add significantly to the total cost of the repair work:

“The reason for that is because the client by themselves cannot defend their case against the insurance company. That’s an important factor that must be included in your costs. You need to include all legal fees ... And it can sometimes cost 60 plus grand. Hence, fighting for what you are entitled to can cost you a lot. Their fee for service might vary from zero up to 30 percent of your final settlement amount. Without legal support, insurance companies will not take you seriously.” (R.03)

Therefore, due to its substantial impact and necessity, cost estimates should include the cost of legal services in the project cost estimation process.

4.4.3 Type of contract (F 03)

According to the participants, the percentages incorporated into quotes to allow for profit and overhead margin changes were often based on the type of contract used. Participants indicated that such margins would generally be 10 percent of the quote (R.14, R.15 and R.17). However, for projects with fewer repair work items, this margin could be as low as 5 to 8 percent (R.14).

One participant from the government explained that the type of contract used in the repair work related to the Canterbury earthquake sequence was “*a fixed-price contract*” (R.02). However, this participant also mentioned that even in terms of fixed-price or lump sum contracts, scope changes could lead to increases in costs on the approval of the client, saying: “*In some incidents, the client has approved an increase in costs, even if the builder had entered into a fixed-price contract*” (R.02).

In reference to other repair projects, some participants (five out of 19) mentioned that cost-plus contracts were frequently used in repair work. One participant stated that “*our standard contract to repair is cost and margin on top of it*” (R.10). Other participants also supported the cost-plus approach, saying: “*For urgent work, you don’t have any other way*” (R.07) and, “*Anywhere, it’s the only method*” (R.06). Another participant stated that cost-plus contracts should be used in emergency situations, as they take less time to start work and pay the contractor but acknowledged that they could lead to higher costs if not managed properly.

“That is the main advantage of cost-plus. Work can be completed quickly. But if you go and measure, do the estimate, tendering, and all these things it takes time... but you need to have qualified and honest people in managing the cost-plus contracts. If you don’t have that, the contractor will put all his resources on-site and charge you accordingly.” (R.08)

One participant from a consultation company supported the above statement by giving an example from the Kaikōura earthquake: “*For Kaikōura, the first stage of emergency work was done like that, cost-plus. For the second stage, they used the measure and pay method*” (R.05).

Another participant also added that daywork rates were often used for emergency work: “*Emergency repairs were just done on a daywork basis. Because there was no detailed assessment, it was a case of just, ‘Let’s get it done’*” (R.17).

4.4.4 Restrictions during repair work (F 04)

In some instances, during repair work, the partial occupation of buildings by tenants restricted repair work. A participant from the government (R.02) expressed that some

houses were occupied during repair work because the tenants did not have money or insurance to secure alternative accommodation. According to the semi-structured interview participants, this increased both repair time and repair costs for many reasons. For example, when occupants are on site: work cannot be conducted in tenant-occupied spaces (R.02); repair work has to be conducted at specified times, such as outside working hours (R.11, R.14 and R.19); building elements need to be protected every night before starting work and temporary protection work removed before leaving work (R.02 and R.14); alternative equipment, such as a lift to transfer material at night rather than a crane, has to be used (R.14); and repair work needs to be conducted in stages, shifting from one space to another (R.02). According to one participant (R.02), these obstacles could extend the duration of a project by 30–50 percent.

According to one participant (R11), restrictions during repair work could also add additional preliminary and general items to the total project cost. Examples of such cost-increasing additional items include: daily erection and removal of temporary walls, floor coverings and hoardings; daily cleaning; overtime costs for after-hours work; and temporary disconnections and reconnections of services. An example of a typical repair process of an occupied building can be understood from the following statement.

“Let’s say you have to take out the insulation. So, you must make certain allowances. In the case of a supermarket rebuild, you must put up hoardings for most of the isles to maintain public safety. All the shelves must be covered or cleaned up every morning after a 10:00 pm to 6:00 am [construction] work shift. The supermarket cannot close, as they will lose customers.” (R.11)

4.4.5 Aftershocks, earthquake-induced hazards and weather conditions (F 05)

Participants (seven out of 19) noted that, other than the main earthquake itself, supplementary factors also caused damage to buildings. These included aftershocks, earthquake-induced hazards and weather conditions that created complexities and made it difficult to estimate the repair cost.

4.4.5.1 Aftershocks

One participant described the occurrence and impact of aftershocks by stating: *“There were more than 10,000 aftershocks which caused continuous damage”* (R.10). According to a few participants (R.02, R.17 and R.18), these aftershocks created further damage that required re-inspections for each instance. Their comments, exemplified by the following, clearly indicated the impact of aftershocks: *“Probably about 80 percent of the jobs were not finished within time because there were other earthquake events that occurred. And that put us back to square one every time.”* (R.02).

Aftershocks also had an impact on the maximum amount set for insurance claims. According to one participant (R.17), each aftershock occurrence was considered as a separate claim event. This was a major problem for the government and insurance companies because the damage caused by each aftershock needed to be calculated separately. When repair costs of each event were cumulated, in some instances, the total would exceed the maximum claimable amount.

4.4.5.2 Earthquake-induced hazards

As described in the literature, the main tremor of an earthquake can cause secondary damage-causing effects which include tsunami, landslide, fire, soil liquefaction, surface faulting and seiches (Bachmann, 2003; Jia, 2017b). Participants specifically mentioned the impacts of liquefaction, fire and flood during the CEQS. One participant stated that liquefaction was a major cause of damage after the Canterbury earthquake sequence by noting: *“Worse than the main earthquake – the damage was mainly from liquefaction”* (R.10). Additionally, several participants (R.02, R.15 and R.17) added that damage from fire and floods created by the earthquake were also considered for repair, but as separate claims, as they required further investigation. Earthquake-induced changes in land elevations causing flooding were also considered, but under land remediation claims (R.15).

4.4.5.3 Weather conditions

When the earthquake damages buildings, their integrity is compromised. In such cases, the natural weather conditions can incrementally increase the damage already caused by the earthquakes. Participants R.02, R.17 and R.18 stated that weather conditions, like heavy snow combined with rain and flooding, that occurred after the main earthquake of the CEQS amplified the earthquake damage. An example of impact from the weather is found in the following example.

“The first winter, we had heavy snow. It shut everything down. We had flooding in the city that had never historically occurred in certain areas. It’s because the land had dropped so much. So that affected a lot of houses and a lot of repairs. We had to move these into a different insurance category.” (R.02)

A couple of participants (R.17 and R.18) also mentioned that there could be additional cost items related to weather damage and damage prevention and protection measures, such as temporary emergency repair done by covering up windows with plywood, putting tarpaulins over roofs and repairing deterioration caused by weather.

4.4.6 Earthquake-induced high rates and price fluctuations (F 06)

The sudden demand to repair damaged buildings was created as a result of the CEQS. This demand was on a large scale and created cost fluctuations for earthquake-related repair costs. All quantity surveying participants agreed that a demand surge affected repair costs after the CEQS. Three participants specifically attributed a 20 to 30 percent increase in construction costs as a result of this surge in demand (R.10, R.11 and R.16).

Participants R.02 and R.14 expressed that price fluctuation was driven by a lack of availability of skilled professionals, skilled labour and material. They also noted that additional incentives, such as set up fees and accommodation, were required to fulfil labour needs drove fluctuations in price. These observations are revealed in the following two examples:

“...They just could not get the skilled staff. So, recruitment drives were put into the UK and Ireland and Australia. Incentives were given to the people from the north to come down and work in Christchurch. Set-up fees and accommodation costs were given to staff to try and get the resources required for repairs.

...there was a lack of a skilled labour force down here to carry out the work. We would only have four or five teams of external plasterers doing the whole city...” (R.02)

Participants further outlined reasons why post-earthquake repair work can cost more than new builds, including: the required high speed of construction (R.02); difficulties associated with repair (R.19); small jobs increasing costs due to economies of scale (R.14); high wastage associated with repair work (R.14); increased time required to understand proper procedures (R.02); and lack of repetition of tasks and demand for higher-level professional inputs (R.14).

The participants also discussed costing methods employed to incorporate such high rates and price fluctuations, including: adding a fixed amount to a rate used for new construction, for example, adding NZ \$5 to an hourly rate of NZ \$55 (R.14); adjusting rates using quarterly price indexes (R.17); adjusting rates using reports produced by reputable consultancy companies and government bodies (R.18); and adjusting according to changes in market rates (R.17).

Price fluctuations were also impacted by project start dates. The start date determines the applicable rates associated with a project. Interview participants from the government indicated that damage caused by aftershocks had a high impact on the start date. One participant stated:

“We couldn’t finish within time because there were other earthquake events that occurred, and that put us back to square one again, where you needed to assess the new damage, and so the aftershocks caused a ripple effect into time.”

(R02)

According to the participants, there were other factors that had an impact on actual start dates, including: occupancy of the building (discussed in F04); recurring damage caused by aftershocks (discussed in detail in F05); and building inspection completion

date, approval of repair funds by EQC or insurance companies and allocation of builders (R05, R06, R16, and R.07).

Specific factors such as building occupancy and insurance coverage can affect start dates. A participant (R.02) expressed that it was difficult to give a contractor a start date during the tender process because occupants might be using the building. Adding to this challenge, the vacating date for the building to allow for repair work to begin could depend on factors such as insurance coverage for alternative accommodation. One participant noted:

“It’s hard for us as well, because you have to have a start date. Because you have to factor in the homeowner’s availability to allow someone into their house or to be able to get them to move into alternative accommodation.”

(R.02)

4.4.7 Repair time (F 07)

According to participants, anticipated repair time was also used in calculating the price to cost, in order to quantify project duration-related cost items and to adjust rates according to inflation. Such calculations were based on two perspectives: repair duration and start date of construction. The impact of the start date has been described above (F 06). The views of participants regarding repair duration are explained in detail below.

‘Duration’ of a project refers to the total time, from the start date, required to complete building repairs. A participant from the government expressed that “*around 80 percent of the initial repair works supervised by EQR did not finish within the estimated time duration*” (R.03). Some of the specific reasons given for the project exceeding the

estimated time included: scope changes created by initially unforeseen conditions (R.05, R.10, R.11); each contractor requiring different amounts of time to finish projects, depending on their experience and abilities (R.02 and R.16); and delays in professional inputs and approvals (R05, R06, R16, and R.07).

Participants described using different methods to calculate duration. The duration was calculated using: a percentage of the total cost of building repair work (R.14); the required total labour hours and the capability of labourers to be employed (R.14); or expectations set according to professional experience (R.18).

4.4.8 Initially unforeseen damages (F 08)

Most participants (18 out of 19) indicated that they often encountered damage that had not been identified during the detailed damage inspection stage and was later identified during damage repair work. A quantity surveying participant offered the following example: “...*only when you open up the floor and look at the piles and foundations will you know you what you have to repair or rebuild. There were cases that caused 100– 150 variations in total project cost*” (R.10). Other participants (R.02 and R.03) also gave examples of damage hidden by covered services in the ceiling and or under the external cladding.

These forms of damage were included in cost estimates only when identified (R.14). Participant (R.17) noted that it could be prudent to add the potential damage from initially unforeseen damage to cost estimates in order to get a clear picture of the total cost and remove it as a negative variation if the damage has not, in fact, occurred.

4.4.9 Changes to the required final state of the building (F 09)

The cost of construction work also depends on the required final quality expected and the specifications set to achieve the final product (Ashworth & Perera, 2015). The final quality of the repaired work must be completed to the same standard to which it was built. However, according to the participants, the required final quality of the building deviated from the as-built state, in response to the needs of the stakeholders and the current prescribed building code. Each of these instances is explained in detail, below.

4.4.9.1 Changes to the building code

When an earthquake causes damage to buildings, the repair work should be conducted according to the current building code. However, the building code might have changed over a period, and this has an influence on the type of repair required, depending on the pre-earthquake state of the building. One participant supported this notion by stating:

“Basically, it was set up, if you got a house, and you have to replace that wall, that wall will need to be up to code. Yeah. But you don’t have to bring the whole house up to building code.” (R.11)

According to another participant (R.17) there were also instances in which building elements were brought up to code even if they had not been damaged by the earthquake, such as in a case when old wiring that had been done in the 1930s was replaced as a safety measure.

According to the participants, within the expected life span of a building of 50 years, it was very likely that there would have been changes to the building. With regards to

frequency of change, participants (R.02 and R.17) mentioned that there were also instances in which they had to respond to building code changes that were introduced by the EQC even after the CEQS. Chimney replacement and boiler position changes are such examples.

Participant R.13 also pointed out that changes to requirements associated with building code were, in some instances, unclear. Participants (R.06 and R.10) mentioned that the insurance companies and EQC were against the improvement to the current building code. They argued that buildings should be returned to their pre-earthquake state and not be repaired according to the current building code. According to another participant (R.17), one reason insurers and the EQC gave for this argument was that earthquake damage claims did not cover betterment. However, the definition of 'betterment' was initially contentious. Bringing a building back to a condition that was compliant required the use of current building practices based on existing science, engineering and materials. This, according to one participant (R.02), did not constitute betterment, but compliance and resulted in the ability for the repaired building to be reinsured going forward.

4.4.9.2 Complying with main stakeholder requirements

As the participants perceived it, other than the building code, two main stakeholders directly influenced changes to programmes of repair work. These were the insurance companies and the building owners. As the two often opposing parties in insurance claims, the different needs of these parties also factored into setting the specifications required for final repair quality.

The goal of the building owner or client was to gain the best quality from any repair work done, and the expected aesthetics of the finished work was a major factor in decision-making regarding work to be done. In an example case given by one participant (R.03) was a cracked concrete slab that needed to be repaired. There were two possible methods: repair the slab with an epoxy filling or replace the slab. The low-cost option was to use epoxy filing. However, the client argued that the slab could not be repaired with epoxy due to the impact this would have on the final finish and requested a replacement of the slab. The client's justification for the replacement was that the epoxy finish would fail to fulfil the main function of the concrete, which was to create a monolithic concrete finish. However, the participant identified that it is difficult to justify meeting the aesthetic requirements of building elements. In response, the client argued that, although the slab repaired with epoxy might be returned to its original finished floor level, and would be able to be walked on with confidence, their pre-earthquake slab did not have cracks. The argument followed that they did not insure, from day one, a cracked slab that had failed. In the words of participant R.03:

“As an example, there was a cracked polished concrete floor. I have a couple of clients with the same repeating problem with their concrete structure. The floor for construction was cracked all over. Option A - repair with epoxy. It will be the same. It will perform like as-new from the structural point of view. However, if it comes to the aesthetics, the client might say that, okay, this house was specifically designed for this [uncracked] floor. So, the aesthetics of the repair work also might need to be considered. It depends on what you want to consider, and what standard to go to. Do you want to reinstate as-new condition

or just repair with visual defects? Based on your advice to a client, the settlement sum offered may be for 50 grand or might cost \$200,000.” (R.03)

Generally speaking, the participants acknowledged that the aim of the insurers was to resolve claims with minimum pay-outs and to reduce the likelihood of future claims. Therefore, the scoping of any claim was required to reflect the insurance policy standard.

Participants (four out of 19) expressed that arguments of the above type have prompted insurers to change coverage associated with particular building elements, as identified in the scoping reports, to reduce the cost of claims. In one instance, the insurer offered to increase the approved claim amount if the heavy roof coverings were to be changed to a lighter-weight material during repair work. Such a change would reduce the probability of future earthquake damage.

“For example, replace the heavyweight cladding saying: ‘Okay, we might not give you the full amount for the foundations. However, we will give you something for the roof.’” (R.03)

4.4.10 Pre-earthquake state of the building (F 10)

Almost all the participants (18 out of 19) stated that the pre-earthquake state of a building played a major factor in defining the scope of the earthquake damage repair work to be done for that building. Participants stated that most of the repair work was funded by insurance companies and government organisations, which only covered damage that was deemed to be earthquake-related. However, during the life span of a building, it might have incurred damage before the earthquake. Participants noted that such repair work was considered as betterment and “*the insurance companies will say:*

'We don't insure betterment. We don't have to make it better'' (R.11). Therefore, these 18 out of 19 participants explained that damage inspection and detailed damage evaluations had to differentiate earthquake damage from pre-earthquake damage.

One participant stated that differentiation between the two in some instances is difficult, saying: *"sometimes it's a bit hard to tell what's historic and what's not"* (R.10). Another participant (R.03) commented that, typically, old cracks might have moss in them which could indicate pre-earthquake damage, but that this was not true on all occasions. This statement is clarified in the following example in which moss was observed growing in a cracked foundation.

".....if there is moss on the ring foundation...it is old. But if you check the moss there, you will figure out that the gutter ring has collapsed, and the water was dripping there, and that's why you have that amount of moss. It has nothing to do noting age as old, [That moss] ... could be accelerated ageing." (R.03).

These comments reveal the difficulty of determining whether damage has been caused by an earthquake or not. It is useful to note that floor level differences were often used as an example indicator of earthquake damage. In one instance, the observed floor level difference was deemed to be the result of poor maintenance that had been hidden by mediocre repair work (R.03). In a second instance, the floor level difference was found to be due to substandard workmanship during initial construction (R.12). In a third instance, the floor level difference was considered to have been caused by the earthquake (R.03).

A participant (R.03) summarised the impact of pre-earthquake damage on the programme of post-earthquake building repair work by stating: *"It is completely affecting the reinstatement strategy of how to repair the earthquake damage."*

4.4.11 Substandard repair work (F 11)

Any construction repair work should be completed according to the requirements set by the client and the relevant shareholders. Participants from the government mentioned that some repair work conducted after the CEQS was re-inspected and found to be substandard.

“Ministry of Business and Innovation and Employment (MBIE) had inspected some of our properties. So, they said that subfloor repairs were not up to our standard. We did a full audit of every subfloor repair that was ever carried out and every engineer’s report. We got in, re-inspected everything again and realised that the works carried out were not up to standard.” (R.02)

According to many of the participants (10 of 19), substandard repair work was one of the main reasons that secondary repair work had to be conducted. One participant (R.12) stated that secondary repair work was much costlier and more difficult because the initial repair work had not been conducted properly. According to one example from this participant, repair work had hidden original damage indicators such as diagonal cracks on walls. Therefore, more investigations were required to identify the actual earthquake damage to a building. As participant R.12 explained: *“To try and repair now is a bigger job than it would have been if they hadn’t touched the thing in the first place. Yes, it made it worse... and made it an additional major cost”* (R.12).

There were many causes for the substandard repair work, some of which are explained in detail below.

4.4.11.1 Differential and incorrect input from professionals involved.

One participant (R.02) stated that the unavailability of standard damage estimation methods had led engineers to provide dissimilar DDE reports. Another participant supported this statement by stating: “.... *even if every engineer comes to check the plot, they say different things. There is no consistent reporting*” (R.10). Another participant indicated that some of the professional inputs were opinions provided without factual basis, stating: “...*so basic assessments, here in New Zealand, are mostly enough to give an opinion. Everybody’s free to give an opinion. Many times, it’s not supported by facts or calculations*” (R.03).

Another participant alluded to the notion that the judgment of professionals could be compromised by the company for which the professional was working, saying:

“We cannot work [in good faith]. Before, we were working for a consultant company. So, we were working to minimise the damage [assessed] as much as possible and bring down the cost estimate. Now, we are working for a homeowner. We are working against the EQC and insurance. Now, we have to maximise [our estimation of] the damage as much as possible. Also, the lawyers [for our client] are also trying to cover their fees [through the estimate], and they are checking the estimates and telling us to add more.” (R.10).

Clearly, a number of factors had an impact on the ability of professionals to provide accurate estimations for post-earthquake repair work.

4.4.11.2 Lack of skills among contractors

Due to the challenges associated with earthquake repair work, it is important for those involved to select a suitably qualified contractor. A number of participants (R.03, R.10, R.14 and R.17) specifically mentioned that substandard contractors had been involved in repair work. A participant (R.17) stated that in response to opportunities created by the sudden demand, people without experience became involved in repair work such as painting, which was considered easy. For example, one participant noted:

“Prior to the earthquakes, there were 200 painters, of which 50 percent were tradespeople. And 50 percent had developed good quality brush hands but hadn’t done an apprenticeship. Within six to nine months [after the earthquake], we probably had 2,000. Now, [these painters] did not come out of trade school. So, overwhelmingly, it was people who didn’t have any work for the carpenters. So, the plumber might be painting. [One tradesperson] might be asking the brother-in-law, or the wife or the husband to do the painting, because everybody thinks painting is easy.” (R.17)

A participant from a government agency further added that inexperienced contractors were later identified and restricted from doing repair work, stating: “*There were initially about 500 to 600 contractors. We eliminated about 300 to 400 of these. And some were blacklisted*” (R.10). Therefore, it is evident that there were contractors who were unsuitable to conduct work as tradespersons.

4.4.11.3 Lack of skills among supervisors

Supervisors played a key role in coordinating and auditing the post-earthquake repair work. According to the participants (three of 19), unethical practices, a limit to the number of supervisors available and conducting lack of proper supervision were the primary causes of substandard repair work.

For example, one participant claimed that the limited number of supervisors led to a lack of proper supervision and, in turn, poor or incomplete inspections led to substandard repairs.

“How many houses can a work supervisor supervise? You have 40, 50, and 60 houses to supervise. So, sometimes when the bill came in, they just signed it off and gave it back. We found that contractors did not do a complete job, especially [regarding] underfloor work, which was not checked.” (R.10).

Another participant stated that supervisors colluded with contractors such that proper audits were not conducted after repair work. In some cases, the supervisor would ask the contractors to quote a lower price initially and would also exclude items from his initial scope. Once the contractor secured the job, these items were included as variations and approved at a higher price in order to cover the supervisor’s share. This also generated higher costs. This process is demonstrated by the quote below.

“There was a lot of bribery, as well, because the contractors are under supervisors, and they had their own favourites. So, they [the supervisors] tell the contractor to price low, and they will get the job. The supervisor goes to the house, does the scope, and he gives it to us [the government consultants] and the contractor. So, in the scoping, the supervisor can miss two or three

rooms. So, when the variation comes in, an additional amount would be added.

This happened because of a lack of auditing.” (R.05)

One participant also added that most of the supervisors involved in initial damage assessments did not have the required experience, stating that “*EQC actually had people who were appointed as appraisers. A lot of them did not have direct construction experience. Some of them were retired police officers*” (R.17). This lack of experience certainly had an effect on the estimation and delivery of post-earthquake damage repair in the CEQS.

4.5 Summary

The semi-structured data collection focused on the deliberations of 19 participants, all of whom had experience in earthquake damage repair work after the CEQS. These participants were engineers, engineering technicians, quantity surveyors, government employees, private consultants and construction crew. The information captured by the semi-structured interviews was categorised into the three main areas:

1. The damage estimation and repair process,
2. Information used for cost estimation, and
3. Factors impacting repair work

The research focused on two processes that were used by the government-centred EQC-EQR system and the insurance companies involved. The study also identified additional processes related to secondary repair work that was required as a product of substandard primary repair work. The study further identified that initial rapid building assessments did not provide enough details to contribute to complete cost estimation and that DDE reports were the main source of information for repair work. However,

DDE reports were not prepared according to a standard format and did not contain all the information required for CEEDRW. The main findings identified from the semi-structured interviews were the 11 factors that had an impact on the CEEDRW.

The next chapter presents the results of the follow-up survey questionnaire, which focused on investigating the usage of these factors in CEEDRW, significance factors on CEEDRW and potential methods that can be used to incorporate the impact of the factors in cost estimation.

5

**QUESTIONNAIRE DATA
COLLECTION AND ANALYSIS -
REPORTING THE CRITICAL
FACTORS IDENTIFIED THAT HAVE
BEEN PERCEIVED AS IMPORTANT
TO AFFECT COST ESTIMATION**

5.1 Introduction

This chapter presents the results from the online questionnaire completed by 92 cost estimators who had experience in earthquake repair work. The survey aimed to investigate further the consideration of key factors in past CEEDRW, the significance these factors had in terms of CEEDRW and the potential methods that could be used to incorporate the impact of these factors into future cost estimation.

The first section of the chapter describes the results of the questionnaire deployment process and its response rate. The results related to the stated aims of the survey are

presented in successive sections. Results for the rating questions are represented as descriptive statistics (quantitative) and results of the open-ended questions are presented in narrative form and through quotations.

5.2 Survey questionnaire Administration

5.2.1 Survey questionnaire distribution

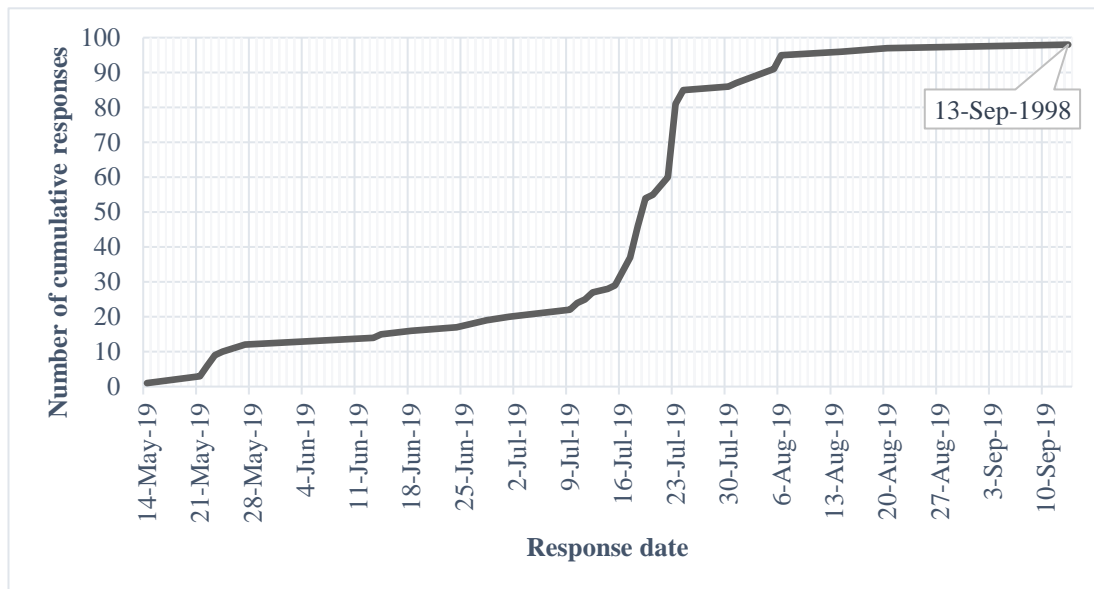
A total of 310 questionnaires were deployed to cost estimators and builders with experience related to earthquake damage repair work. Initially, questionnaires were distributed through the monthly newsletter of The New Zealand Institute of Quantity Surveyors' (NZIQS) to all members of this organisation. The NZIQS had 4,072 members at the time of distribution. However, the NZIQS newsletter only yielded four responses, making the response rate less than 0.2 percent. In response to the low response rate, a secondary method of online directories and databases (LinkedIn and Master builders) of cost estimators and builders was used to send 310 direct emails to engage the participants. The professional details investigated were their experience in earthquake damage building repair work or their employment in companies engaged in CEEDRW and related work. These initial contacts were followed up by reminder emails and telephone calls.

5.2.2 Response rate and participant screening

As presented in Figure 5.1, the collection time for responses to the questionnaire was 122 days between 14 May 2019, and 13 September 2019. The questionnaire yielded 98 replies, which represented a 30.3 percent response rate. From the total responses, six participants were removed, as they did not have experience in CEEDRW.

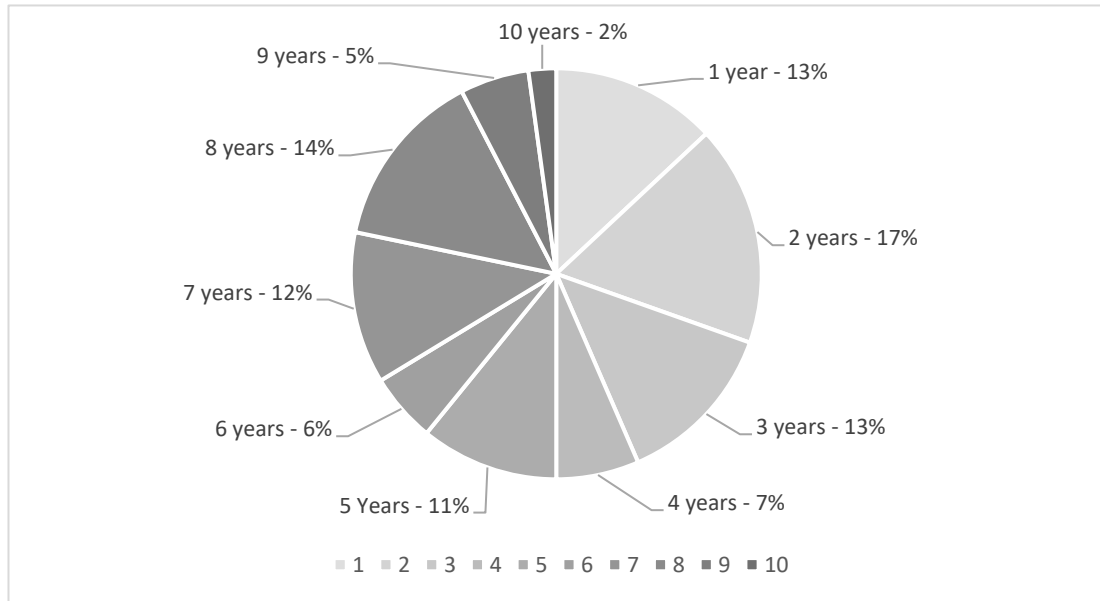
Therefore, the final total of participants was 92. All these participants had experience in CEEDRW. The structure of the questionnaire did not allow for missing values; therefore, no adjustment was required for the results.

Figure 5.1 - Cumulative response rate to the questionnaire



5.3 Background information

Participants were asked to provide their years of experience related to earthquake damage repair work (refer to Appendix 5). The questionnaire was distributed in 2019, which was ten years after the initial earthquake. Participants' years of experience in CEEDRW ranged from one to ten years. Two participants had ten years of experience. Half of the participants (46) had more than five years of experience. However, the highest percentage of the participants had two years of experience. A breakdown of participant experience is given in Figure 5.2, below.

Figure 5.2 -Years of experience in CEEDRW

5.4 Validity and reliability

As discussed in the methodology section, several actions were taken to evaluate the validity and reliability of the survey data. The validity of the survey questionnaire was considered in four main aspects: content validity, construct validity, face validity and predictive validity. Content validity of the questionnaire was achieved by means of the literature research and analysis of the semi-structured interview data. In order to achieve the construct validity, survey questions developed were based on the results of the semi-structured interview data. Additionally, the questionnaire was validated in terms of its construct by five cost estimation professionals with experience in CEEDRW, who completed the pilot survey. Face validity of the questionnaire was achieved by evaluating the questionnaire through five non-experts who completed the pilot survey. The research did not seek to achieve criterion validity, as it was not possible to calculate the population of professionals who were involved in CEEDRW. Additionally, as previously expressed in the methodology section, other methods of

questionnaire validation, such as retest and alternative forms of the same question, were not conducted due to the difficulty in acquiring participants for the second time and elongation of the questionnaire, respectively.

Several procedures were used to maintain the reliability of data sources. Participants invited to complete the survey were verified and selected by using databases (LinkedIn and master builder) that contained professional details. The professionals were chosen if they had experience in earthquake damage building repair work or if they were employed in such companies. Participants were also asked to provide honest answers. Additionally, each participant's responses to each set of questions were separately analysed to check internal reliability. As per Table 5.1, Cronbach's Alpha (α) was greater than 0.7 for each set of questions evaluated. In addition, Kuder-Richardson 20 calculations were conducted on nominal dichotomous values of the research considered in section 5.6. The Kuder-Richardson 20 values of the data set were 0.735. These results indicate an acceptable level of internal reliability, as discussed in the methodology section.

Table 5.1 - Internal reliability

Section related to the question	Intended to measure	Cronbach's Alpha / Kuder-Richardson 20	Number of items	Reliability
5.5	Factors considered in CEEDRW	0.735	21	Reliable
5.6	Significance of the factors on CEEDRW	0.877	21	Reliable

Thereafter, the data set was further checked to determine what would result if the internal reliability of the measurement tool was decreased by a singular factor, by removing one factor at a time from the cumulated value. As per Table 5.2, none of the factors reduced the reliability of the scale. Therefore, all factors were deemed valid to consider for the research.

Table 5.2 - The impact of each factor on overall reliability

	Kuder-Richardson 20 if Item Deleted	Overall Kuder-Richardson 20	Variance	Factor reduces reliability (Yes/No)
Q1F 01 - Consequential damage repair	0.727	0.735	-0.008	No
Q1F 02.1a - Cost of structural engineering services	0.733	0.735	-0.002	No
Q1F 02.1b - Cost of geotechnical engineering services	0.732	0.735	-0.003	No
Q1F 02.1c - Cost of land-surveying services	0.728	0.735	-0.007	No
Q1F 02.2 - Cost of architectural services	0.720	0.735	-0.015	No
Q1F 02.3 - Cost of quantity surveying services	0.721	0.735	-0.014	No
Q1F 02.4a - Cost of lawyers' / advocates' legal services	0.719	0.735	-0.016	No
Q1F 02.4b - Cost of dispute resolution facilitators' / dispute resolvers' services	0.720	0.735	-0.015	No
Q1F 03 - Varying profit margins depending on the type of building contract	0.724	0.735	-0.011	No
Q1F 04 - Restrictions during repair	0.731	0.735	-0.004	No
Q1F 05.1 - Damage from aftershocks	0.722	0.735	-0.013	No
Q1F 05.2a - Damage from earthquake-induced hazards - flood	0.732	0.735	-0.003	No
Q1F 05.2b - Damage from earthquake-induced hazards - fire	0.730	0.735	-0.005	No
Q1F 05.3 - Damage from weather conditions	0.712	0.735	-0.023	No
Q1F 06 - Price fluctuations due to change in demand for resources as a result of an earthquake	0.729	0.735	-0.006	No
Q1F 07 - Duration of repairs	0.730	0.735	-0.005	No
Q1F 08 - Initially unforeseen damage	0.732	0.735	-0.003	No
Q1F 09.1 - Changes required to final repair state - to meet statutory compliance	0.727	0.735	-0.008	No
Q1F 09.2 - Changes required to final repair state - to meet stakeholder requirements	0.719	0.735	-0.016	No
Q1F 10 - Pre-earthquake state of the building	0.734	0.735	-0.001	No
Q1F 11 - Substandard initial repair work	0.719	0.735	-0.016	No

Other indicators of validity and reliability were as follows: nearly half of the participants (42) provided optional comments; comments provided by the participants did not include any additional factors that were not covered by the research; and approximately half of the participants (44) were interested in the results of the survey and provided their contact details. This evidence of participant engagement through optional comments further illustrated that participants were interested and actively participated in the survey, which added to the validity and reliability.

5.5 Comparison between factors that were considered in previous CEEDRW and factors that should be included in CEEDRW

A number of factors considered in the cost estimation could have an impact on the accuracy of the cost estimate. In addition, consideration of different factors in CEEDRW could result in cost variations. Therefore, the participants were first asked to indicate whether they had considered factors identified in the questionnaire in their CEEDRW (refer to Table 5.3). These results were then compared with the factors that should be included in CEEDRW, as indicated by the participants, according to the results described in section 5.7, which identified suitable methods to incorporate the factors in CEEDRW; these results were used to determine the factors that should be included in CEEDRW. For the comparison, answers for which participants chose the responses *'do not include'*, *'hard to calculate'* and *'depending on other responses to factors'* were deducted from the total answers to select the answers of participants who directly confirmed the factors to include in future CEEDRW.

Overall, factor consideration varied from 95 to 16 percent. Over 90 percent of the participants indicated that the factors *'changes required to final repair state to meet*

statutory compliance’ (F 09.1) and ‘consequential damage’ (F 01) were considered in their cost estimations. These two factors had the highest consideration rate. Ultimately, almost all of the factors (ten out of 11) were considered in the CEEDRW by the majority of participants (more than 50 percent).

However, some of the sub-factors were only considered by a minority of the participants. These were: ‘damage from aftershocks’ (F.07), ‘cost of lawyers’ / advocates’ legal services’ (F 02.4a) and ‘cost of dispute resolution facilitators’ / dispute resolvers’ services’ (F 02.4b), which were considered by 40, 20 and 16 percent of the participants, respectively.

Additionally, Table 5.3 reveals the results of the comparison between potential future usage of the factors in CEEDRW and consideration of the factors in past CEEDRW. The highest increase was observed for the factors ‘cost of dispute resolution services’, ‘cost of legal services’ and ‘cost of land surveying services’ with 43, 40 and 37 percent increases, respectively. Decreased approval ratings were identified for three factors: ‘initially unforeseen damage’ (F 08), ‘pre-earthquake state of the building’ (F 10) and ‘damage from earthquake-induced floods’ (F 05.2a). Additionally, there was no variation associated with ‘the approval for changes required to final repair state to meet statutory compliance’ (F 09.1).

Table 5.3 - Comparison between factors that were considered in previous CEEDRW and factors that should be included in CEEDRW

Rank	Factor	Considered in previous CEEDRW (A)	To be considered in future CEEDRW (B)
1	F 09.1 - Changes required to final repair state - to meet statutory compliance	95%	95%
2	F 01 - Consequential damage repair	92%	93%

Rank	Factor	Considered in previous CEEDRW (A)	To be considered in future CEEDRW (B)
3	F 07 - Duration of repairs	88%	92%
4	F 08 - Initially unforeseen damage	86%	84%
5	F 02.1a - Cost of structural engineering services	85%	93%
6	F 02.1b - Cost of geotechnical engineering services	83%	95%
7	F 02.2 - Cost of architectural services	83%	92%
8	F 02.3 - Cost of quantity surveying services	79%	93%
9	F 06 - Price fluctuations due to change in demand for resources caused by an earthquake	78%	87%
10	F 10 - Pre-earthquake state of the building	75%	59%
11	F 04 - Restrictions during repair	68%	78%
12	F 05.2a - Damage from earthquake-induced hazards - flood	68%	64%
13	F 11 - Substandard initial repair work	65%	75%
14	F 03 - Varying profit margins depending on the type of building contract	64%	67%
15	F 05.3 - Damage from weather conditions	64%	66%
16	F 05.2b - Damage from earthquake-induced hazards - fire	60%	65%
17	F 02.1c - Cost of land surveying services	57%	93%
18	F 09.2 - Changes required to final repair state - to meet stakeholder requirements	55%	66%
19	F 05.1 - Damage from aftershocks	45%	60%
20	F 02.4a - Cost of lawyers' / advocates' legal services	20%	60%
21	F 02.4b - Cost of dispute resolution facilitators' / dispute resolvers' services	16%	60%

5.6 Significance of the factors on CEEDRW

Participants were asked to rate from 1 (Not important at all) to 5 (Extremely important) the significance of the aforementioned factors on CEEDRW. Based on the input of the participants (refer to Table 5.4), 'cost of structural engineering services' (F 02.1a) had the highest significance for CEEDRW, with a weighted average above 4.5 and 61

percent of participants stating it is very important. Additionally, ‘changes required to final repair state - to meet statutory compliance’ (F 09.1), ‘cost of geo technical engineering services’ (F 02.1b), ‘initially unforeseen damage’ (F 08), and ‘consequential damage repair’ (F 01) were deemed significant, with weighted averages above 4.0 and standard deviations below 1.04; these factors were considered by more than 83 percent of the participants in past CEEDRW.

According to the participants, ‘cost of lawyers’ / advocates’ legal services’ (F 02.4a) and ‘cost of dispute resolution facilitators’ / dispute resolvers’ services’ (F 02.4b) were the least significant factors, with a 2.46 weighted average for each. These factors were also considered by less than one-fifth of participants in past CEEDRW. Additionally, nine factors, ranked from 14 to 21, had weighted averages lower than three.

Table 5.4 - Significance of the factors affecting CEEDRW

Rank	Factors affecting CEEDRW	Percentage considered in past CEEDRW	Weighted Average	RII	Standard deviation	Skewness (Std. Error 0.251)
1	F 02.1a - Cost of structural engineering services	85%	4.52	0.90	0.98	-2.47
2	F 09.1 - Changes required to final repair state - to meet statutory compliance	95%	4.45	0.89	0.87	-1.69
3	F 02.1b - Cost of geotechnical engineering services	83%	4.27	0.85	1.04	-1.71
4	F 08 - Initially unforeseen damage	86%	4.22	0.84	1.15	-1.56
5	F 01 - Consequential damage repair	92%	4.02	0.80	1.07	-0.90
6	F 07 - Duration of repairs	88%	3.84	0.77	1.13	-0.59
7	F 06 - Price fluctuations due to change in demand for resources caused by an earthquake	78%	3.82	0.76	1.19	-0.59
8	F 02.2 - Cost of architectural services	83%	3.74	0.75	1.22	-1.01

Rank	Factors affecting CEEDRW	Percentage considered in past CEEDRW	Weighted Average	RII	Standard deviation	Skewness (Std. Error 0.251)
9	F 02.1c - Cost of land surveying services	57%	3.73	0.75	1.17	-0.73
10	F 11 - Substandard initial repair work	65%	3.71	0.74	1.28	-0.77
11	F 04 - Restrictions during repair	68%	3.70	0.74	1.39	-0.66
12	F 10 - Pre-earthquake state of the building	75%	3.67	0.73	1.39	-0.68
13	F 02.3 - Cost of quantity surveying services	79%	3.23	0.65	1.33	-0.37
14	F 03 - Varying profit margins depending on the type of building contract	64%	2.98	0.60	1.33	-0.08
15	F 09.2 - Changes required to final repair state - to meet stakeholder requirements	55%	2.96	0.59	1.04	-0.08
16	F 05.1 - Damage from aftershocks	45%	2.78	0.56	1.16	-0.04
17	F 05.3 - Damage from weather conditions	64%	2.77	0.55	0.97	0.10
18	F 05.2a - Damage from earthquake induced hazards - flood	68%	2.67	0.53	0.78	0.03
19	F 05.2b - Damage from earthquake induced hazards - fire	60%	2.59	0.52	1.27	0.21
20	F 02.4a - Cost of lawyers' / advocates' legal services	20%	2.46	0.49	1.23	0.23
21	F 02.4b - Cost of dispute resolution facilitators' / dispute resolvers' services	16%	2.46	0.49	1.58	0.36

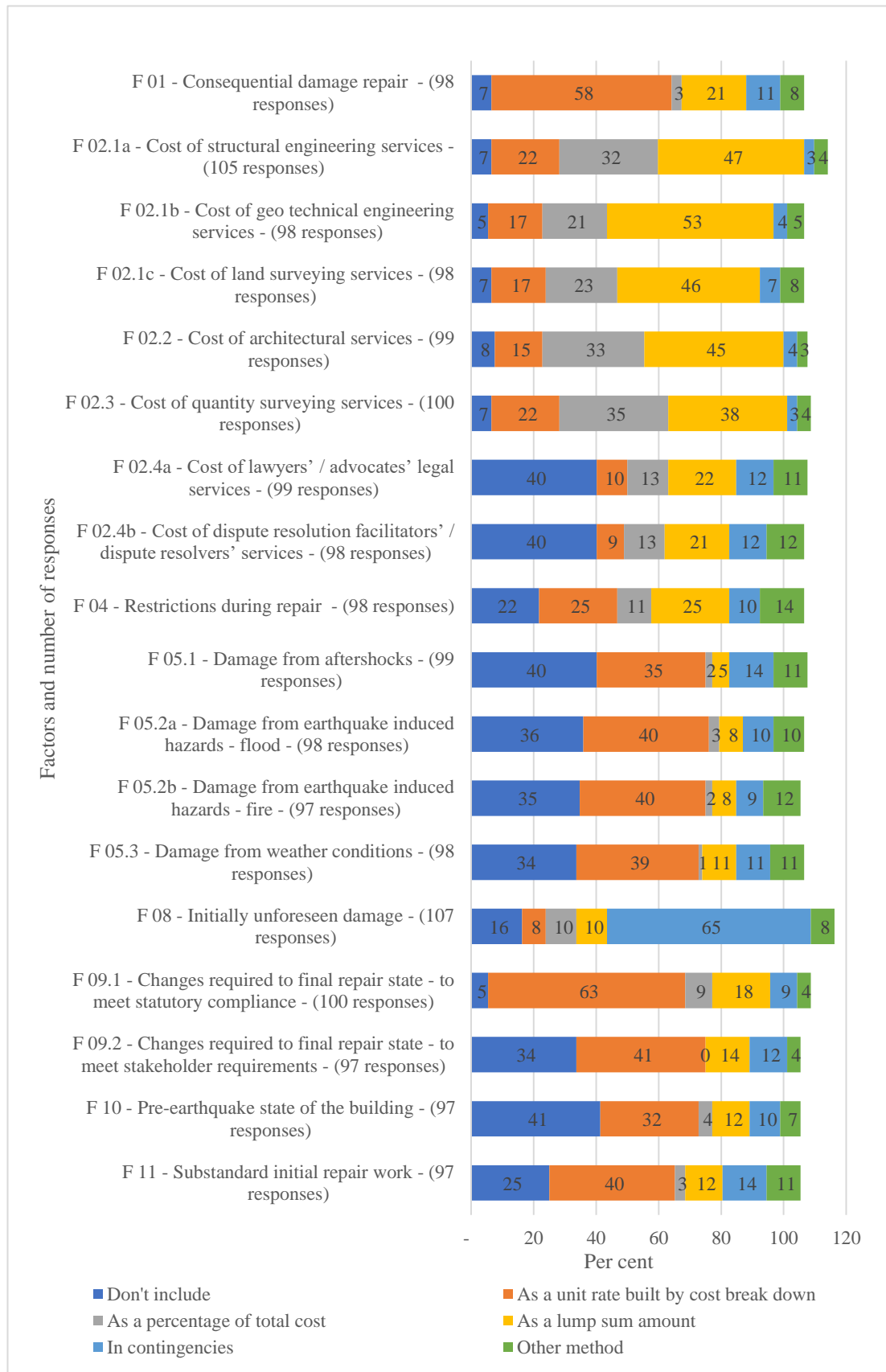
It is important to note that, while three factors had a weighted average just below three, these factors had a slight negative skewness. These factors were: 'varying profit margins depending on the type of building contract' (F 03), 'changes required to final repair state to meet stakeholder requirements' (F 09.2) and 'damage from aftershocks' (F 05.1).

5.7 Suitable methods to include the factors in CEEDRW

Participants were asked to indicate suitable methods that could be used to include the impact of the factors in CEEDRW. The selection criteria provided were: ‘don’t include’; ‘as a unit rate’; ‘as a percentage of the total cost’; ‘as a lump sum amount’; ‘in contingencies’; and ‘other methods’. The resulting selection percentage is represented in Figure 5.3 (responses/number of participants). This section did not include varying profit margins and duration as they were considered separately.

Overall, ‘development of unit rate method’ obtained the highest approval rating for more than one-third of the factors (7 out of 17 factors). The use of a ‘lump sum amount’ obtained the second-highest number of responses, mostly as a strategy for estimating costs associated with professional services (6 of 17 factors). The ‘in contingencies’ option obtained the highest response percentage for a single method, 65 percent. The response ‘do not include’ obtained the highest percentage response for a single method across four factors. However, ‘do not include’ was selected by a minority of participants in all four instances when compared cumulated number of participants that selected to include the impact of these factors in CEEDRW.

Figure 5.3 - Suitable methods to include the factors into CEEDRW



According to Figure 5.3, ‘development of unit rate method’ was the most suitable method for including the impact on estimations of costs of the following: ‘consequential damage repair’ (F 01); ‘restrictions during repair’ (F 04); ‘damage from flood’ (F 05.2a); ‘damage from fire’ (F 05.2b); ‘weather damage’ (F 05.3); ‘changes to the required final repair state to meet statutory compliance’ (F 09.1); ‘changes to the required final repair state to meet stakeholder requirements’ (F 09.2); and ‘substandard initial repair work’ (F 11) with approval ratings of 58, 25, 40, 40, 39, 63, 41 and 40 percent, respectively. When the ‘do not include’ response was disregarded, ‘development of unit rate method’ was considered to be most suitable for ‘aftershocks’ (F 05.1) and ‘pre-earthquake state of the building’ (F 10), factors with approval ratings of 35 and 42 percent, respectively.

The use of ‘as a lump sum amount’ was also considered to be the most suitable method for a number of factors. These were: ‘cost of structural engineering services’ (F 02.1a), ‘cost of geotechnical engineering services’ (F 02.1b), ‘cost of land surveying services’ (F 02.1c), ‘cost of architectural services’ (F 02.2), ‘cost of quantity surveying services’ (F 02.3) and ‘restrictions during repair’ (F 04) with response rates of 47, 53, 46, 45, 38 and 25 percent, respectively. When the ‘do not include’ response was disregarded, the ‘as a lump sum amount’ response had the highest rating for ‘cost of lawyers’ / advocates’ legal services’ (F 05.4a) and ‘cost of dispute resolution facilitators’ / dispute resolvers’ services’ (F 05.4b), with 22 and 21 percent approval ratings, respectively.

Use of ‘lump sum amount’ was rated second-highest as a strategy to calculate estimations for other factors, including ‘consequential damage repair’ (F 01) and ‘changes to the required final repair state to meet statutory compliance’ (F 09.1) with ratings of 21 and 18 percent, respectively.

The method 'In contingencies' obtained the highest response for only one factor, which was 'initially unforeseen damage' (F 08), with a rating of 65 percent.

'Percentage of the total' and 'other methods' did not gain the highest rating for any of the factors. However, 'percentage of the total' did gain the second-highest rating for all costs associated with professional services, except for dispute resolution and legal services (F 02.1a, F 02.1b, F 02.1c, F 02.2, and F 02.3) with ratings of 32, 21, 23, 33 and 35, respectively.

Direct similarities can be observed regarding the responses given by participants to a number of factors. As can be seen in Figure 5.3, similar percentages of participants (between 38 and 53 percent) would estimate the cost of professional services (excluding legal and dispute resolution services) as 'lump sum amounts' and between 21 and 35 percent (the second-highest option across all factors) would estimate these 'as percentage of the total cost'. Costs associated with dispute resolution and legal services shared the same rating: 40 percent of the participants indicated that both sets of costs should not be included in CEEDRW.

Another set of factors with similar ratings are: 'damage from aftershocks' (F 05.1); 'damage from fire' (F 05.2a); 'damage from floods' (F 05.2b); 'damage from weather conditions' (F 05.3); 'changes to the required final repair state to stakeholder requirements' (F 09.2); and 'pre-earthquake state of the building' (F 10). For these factors, 'development of unit rate' and 'do not include' methods obtained a combined rating of 73 percent or more. Percentages associated with these two methods had a variation of 9 percent in all instances.

Finally, similarities can also be observed in responses associated with 'consequential damage repair' (F 01) and 'changes to the required final repair state to meet statutory

compliance' (F 09.1). For these two factors, 'development of unit rate method' received a response rate of near 60 percent (plus or minus 3 percent), and the 'use of a lump sum' method received the second-highest response rate, at around 20 percent (plus or minus 2 percent).

When the participants were asked whether the contractor's margin should change based on the type of contract or whether it depends on other factors, according to Figure 5.4, the majority indicated that it should change based on the type of contract (67%). A negligible number of participants noted that it would depend on other factors (2%).

Participants were also asked to choose the most suitable method to estimate the project price fluctuations for CEEDRW. According to Figure 5.5, the majority of participants (36%) indicated that published price indices should be used. Additionally, almost one-third of the participants (32%) suggested that actual price changes should be allowed in the contract. Finally, 17 and 13 percent of the participants, respectively, stated that price fluctuation should be considered according to their own calculations or should not be included.

Regarding the most suitable method to estimate the project duration for CEEDRW, almost half of the participants indicated that relying on the experience of professionals would be the most suitable method for estimating the duration of the project (48%) (refer to Figure 5.6). Additionally, almost one-third of the participants (30%) suggested 'use of total repair hours' as a suitable method. According to 8, 7 and 7 percent of the participants, respectively, duration should: not be calculated in CEEDRW, be calculated using a critical path method based on a construction program or should be calculated using a percentage of the total repair costs.

Figure 5.4 - The Contractor's margin should change based on the contract type (F 03)

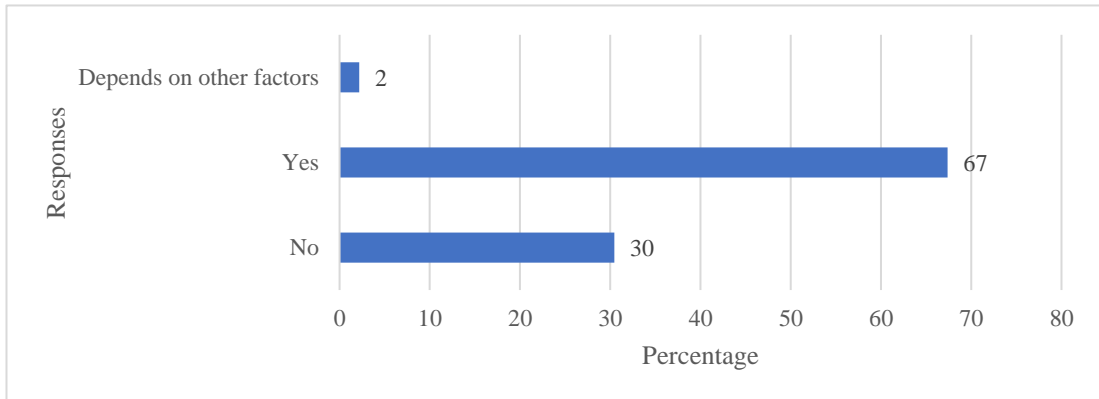


Figure 5.5 - Most suitable method to estimate price fluctuation for CEEDRW (F06)

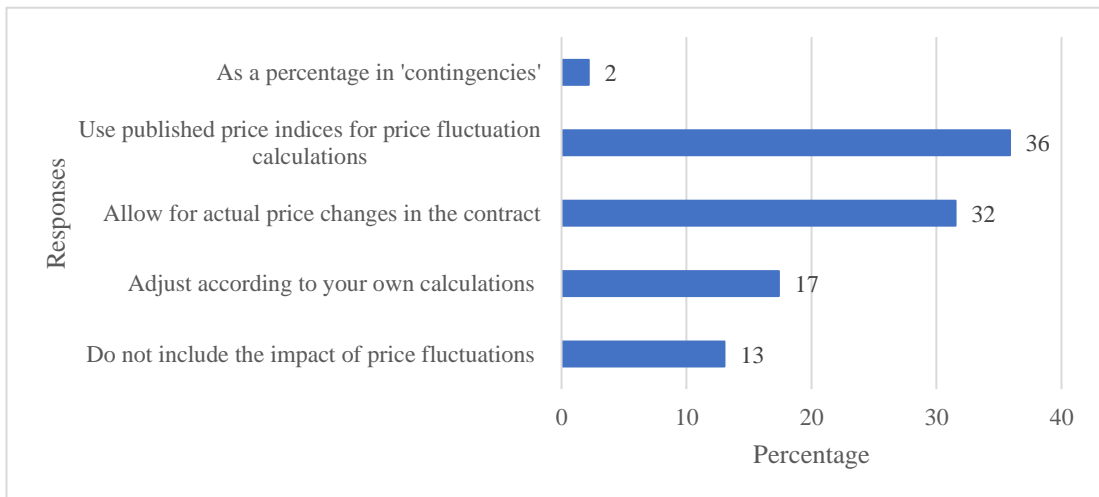
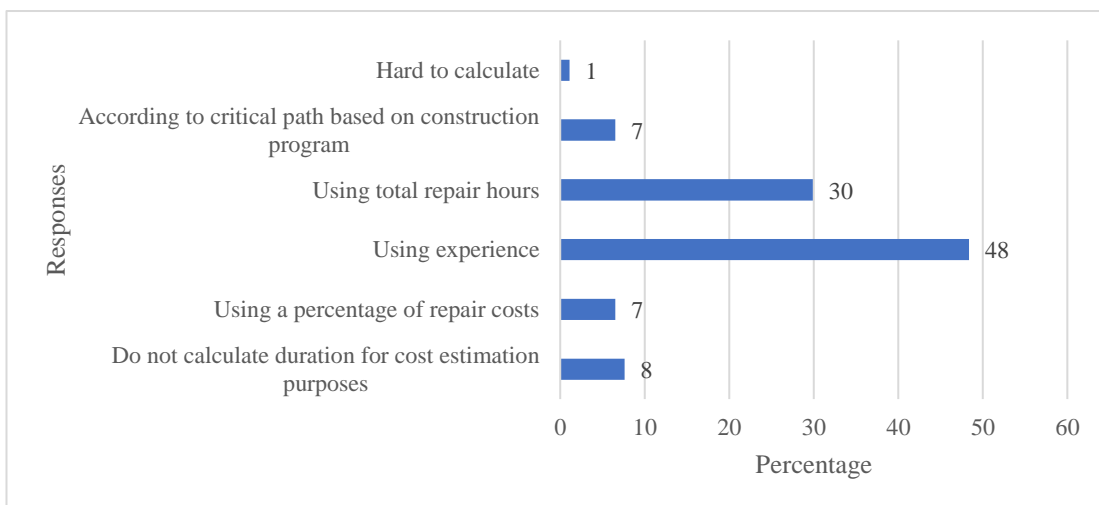


Figure 5.6 -Most suitable method to estimate project duration for CEEDRW (F07)



The questionnaire results indicated the most suitable methods to be used to include the impact of key factors in the CEEDRW process. The study selected the methods that were rated highest and second-highest rated as the most suitable; these are summarised in Table 5.5. When the difference between the second-and third-highest rated methods was less than or equal to one percent, three suitable methods were suggested.

Table 5.5 - Suggested methods of including the impact of each factor into CEEDRW

Factor ID	Factor	Most suitable methods of inclusion
F 01	Consequential damage repair	In contingencies / a lump-sum amount
F 02.1a	Cost of structural engineering services	A lump-sum amount / as a percentage of the total cost
F 02.1b	Cost of geotechnical engineering services	A lump-sum amount / as a percentage of the total cost
F 02.1c	Cost of land surveying services	A lump-sum amount / as a percentage of the total cost
F 02.2	Cost of architectural services	A lump-sum amount / as a percentage of the total cost
F 02.3	Cost of quantity surveying services	A lump-sum amount / as a percentage of the total cost
F 02.4a	Cost of lawyers' / advocates' legal services	A lump-sum amount / as a percentage of the total cost / in contingencies
F 02.4b	Cost of dispute resolution facilitators' / dispute resolvers' services	A lump-sum amount / as a percentage of the total cost / in contingencies
F 03	Varying profit margins depending on the type of building contract	Should be changed according to contract type
F 04	Restrictions during repair	A unit rate built by cost breakdowns / a lump sum amount
F 05.1	Damage from aftershocks	A unit rate built by cost breakdowns / in contingencies
F 05.2a	Damage from earthquake-induced hazards - flood	A unit rate built by cost breakdowns / in contingencies
F 05.2b	Damage from earthquake-induced hazards - fire	A unit rate built by cost breakdowns / in contingencies
F 05.3	Damage from weather conditions	A unit rate built by cost breakdowns / in contingencies
F 06	Price fluctuations due to changes in demand for resources caused by an earthquake	Allow price variations according to published price indices / allow price changes in the contract
F 07	Repair time (Duration of repairs)	Professional experience/total repair hours

Factor ID	Factor	Most suitable methods of inclusion
F 08	Initially unforeseen damage	In contingencies / as a percentage of the total cost / a lump-sum amount
F 09.1	Changes required to final repair state - to meet statutory compliance	A unit rate built by cost breakdowns / a lump sum amount
F 09.2	Changes required to final repair state - to meet stakeholder requirements	A unit rate built by cost breakdowns / a lump sum amount
F 10	Pre-earthquake state of the building	A unit rate built by cost breakdowns / in contingencies
F 11	Substandard initial repair work	A unit rate built by cost breakdowns / in contingencies

5.8 Additional comments on the factors affecting CEEDRW

There were 36 final comments on the questionnaire and its contents regarding CEEDRW processes. Most of the comments focused on the factors that were identified in the questionnaire and offered the participant's professional experience on the factors. However, there were no comments regarding 'consequential damage repair' (F 01) and 'restrictions during repair' (F04). Participants also suggested methods that could be used to improve CEEDRW processes. These comments are summarised in the following sections.

5.8.1 Cost of professional services (F 02)

There were 14 additional qualitative comments offering opinions about the most suitable way to include the factors into CEEDRW. Most of the comments were on the subject of professional costs. For example, one participant (RS47) stated that "*most associated fees would be calculated as part of the project P&Gs (preliminaries and general)*" and another participant (RS64) suggested the inclusion of costs associated with other professional costs, such as those for a "*building surveyor, valuer, planner, environment consultant*". Some of the comments made specific mention of legal

services costs. One participant (RS35) mentioned that, *“lawyers and dispute resolution come into play when required. These are not a given a budgeted cost. Even in the case of dispute, they are only occasionally required.”* and another (RS86) stated that *“legal services are mostly time-based charges”*.

With regard to the impact and usage of cost of professional services (F02), one participant stated that *“professional fees were not included in building contractors’ pricing of repairs”* (RS71). Participants made specific reference to the high impact of legal battles between owners and insurance on costs, noting, for example: *“...30 to 40 percent of the overall cost was wasted on lawyers or re-repairing previously poorly repaired homes again and again”* (RS08). These fees were described by another participant as *“...extortionate”* (RS36). One participant specifically stated that legal fees were *“...not construction costs”* (RS35). Another explained that *“[Claiming the legal fees] would depend on the insurance policy, whether the insured [claimant] would be able to claim for those costs if they were incurred during the process of the build”* (RS28). Another participant added that the cost of legal services would also include the cost of other professional services, mentioning that *“the lawyers will engage the quantity surveyors for the stakeholders to carry out this service”* (RS10).

5.8.2 Type of contract (F 03)

With regards to profit margins (F03), one participant stated that these should be directly associated with the work conducted, and *“...assessed per unit and not percentile over the contract price”* (RS17). Additionally, participants pointed out that the margins incorporated into lump-sum contracts were higher to account for the high risk of such contracts (RS24) and that contractors were more willing to go for cost-plus contracts due to their risk-averse natures (RS36).

5.8.3 Aftershocks, earthquake-induced hazards and weather conditions (F 05)

On the topic of damage caused by earthquake-induced hazards and weather conditions (F05), one participant (RS28) supported the notion of considering this type of damage as a separate claim. However, according to another participant (RS61), the impact of including these damages in CEEDRW would depend on the instructions given by other experts to the cost estimator.

5.8.4 Earthquake-induced high rates and price fluctuations (F 06)

Participants also gave their opinions on earthquake-induced high rates and price fluctuations (F06). In this regard, participants stated the following reasons for price inflations: high demand and low supply (RS10); increased time to completion (RS30); and insurance companies only focusing on satisfying the customer by paying more (RS54). Another participant claimed that price fluctuations were arbitrary and without justification (RS36).

5.8.5 Repair time (F 07)

Regarding repair time (F07), one participant indicated that timeframes had been greatly extended, stating: *“Even today – 10 years since the earthquake – I know of homes which are still not finished or [have been] repaired badly”* (RS08). Another (RS34) mentioned homeowner delays, availability of contractors and delays in required policy changes as causes of extended repair duration.

5.8.6 Initially unforeseen damages (F 08)

On the topic of initially unforeseen damage (F08), one participant (RS28) mentioned that unforeseen damage was not considered in their estimates because it should be considered as a variation, instead. They further added the high impact of such variations, stating: “*Variations ran to an average close to 50 percent of the initial pricing of the job, due to unforeseen damage*” (RS39). According to another participant (RS54), one of the causes of unforeseen damage was the lack of availability of original building plans.

5.8.7 Changes to the required final state of the building (F 09)

Participants’ views on changes to the final repair state focused on both changes created by stakeholders and changes to the building code (F09). With regards to changes inflicted by the stakeholders, participants stated that the value of the cost estimate changed depending on the party creating the cost estimate, which could be the “*insurer, owner or builder*” (RS36) and on the repair methodology used, such as “*MBIE guidelines or insurer’s policy*” (R86). Regarding the changes to the building code, participants noted that changes in the building code should be considered from the date the building element was constructed to the date the CEEDRW was prepared (RS81) and that repair work conducted immediately is less impacted by these changes (RS33).

5.8.8 Pre-earthquake state of the building (F 10)

On the topic of the pre-earthquake state of the building (F10), participants stated there were pre-earthquake damage caused by “*...lack of maintenance, poor workmanship,*

etc.” (RS50). Another participant (RS74) mentioned that since most of the repair was funded by insurers, issues like weather-tightness or poor-quality construction were identified and excluded.

5.8.9 Substandard repair work (F 11)

The occurrence of substandard repair work (F11) was confirmed by the participants. Some mentioned that substandard repair resulted from builders trying to reduce project duration (RS49), not completing the repairs within a suitably short project duration (RS80), experiencing complications and difficulties related to the process of cost estimation of earthquake damage repair works, which requires “*experienced QS*” (RS08), and professional ethical issues like “*human greed*” (RS36). These causes support the unavoidability of substandard repair work.

5.8.10 Methods to improve the CEEDRW process

Participants also offered written opinions on how to improve the CEEDRW process. One participant indicated a need for a set of standard guidelines for CEEDRW, noting that there is a “*lack of guidelines for repair work*” (RS31). Another participant added that the most qualified professionals required for CEEDRW are the “*experienced builders & QS teams*”, and that other professionals should be considered to provide support when required (RS08). Another participant stated that the inputs used for the CEEDRW process should be accurate and reliable, as the cost estimate “*depends heavily on the actual individual assessments and reports of the house and property*” (RS25). These improvements can be used to build a better CEEDRW process.

5.9 Summary

This chapter aims to investigate the factors impacting CEEDRW through an analysis of the findings of the survey questionnaire and presents the key results.

There is a positive indication that all factors were considered in CEEDRW during the repair work associated with the CEQS. The factors most consistently considered in CEEDRW were ‘changes required to final repair state - to meet statutory compliance’ and ‘consequential damage repair’. The least-consistently considered factors in the CEEDRW process were ‘damage from aftershocks, cost of lawyers’ / advocates’ legal services’ and ‘cost of dispute resolution facilitators’ / dispute resolvers’ services’.

With regards to the significance of the factors, ‘cost of structural engineering services’, ‘changes required to final repair state to meet statutory compliance’, ‘cost of geotechnical engineering services’, ‘initially unforeseen damage’, and ‘consequential damage repair’ were considered the most significant. On the other hand, ‘cost of lawyers’ / advocates’ legal services’ and ‘cost of dispute resolution facilitators’ / dispute resolvers’ services’ was the least significant. Ultimately, the inputs from a majority of participants indicated that all factors should be included in CEEDRW.

The results also revealed the popularity of different methods that could be used to include the impact of these factors into the CEEDRW process. The results show that the ‘development of unit rate method’ and ‘lump sum amount’ were the most commonly suggested methods for including these factors in the cost estimation process.

The next chapter presents the development validation of a model that can be used to increase both the speed and accuracy of the CEEDRW process. The model aims to

incorporate the impact of the identified factors, using the methods suggested by the research.

6

MODEL DEVELOPMENT AND VALIDATION

6.1 Introduction

This chapter describes the development, design and validation of the proposed Cost of Damage Repair for Earthquakes Estimation Model (C-DREEM). The C-DREEM aims to improve the process of CEEDRW in terms of standardisation, accuracy and speed of estimation, and incorporation of the factors impacting cost estimation of earthquake damage repair work.

The first section of the chapter summaries the findings from the literature review (chapter 3), the preliminary interviews (chapter 4) and the survey questionnaire (chapter 5) with regards to CEEDRW. The chapter then outlines the model development process of the C-DREEM and presents a description of the model. The subsequent section focuses on the C-DREEM model validation process and analysis of the results of this process. In the final section, the drawbacks and future improvement measures identified through the validation process are discussed.

6.2 The current state of CEEDRW

At the time that this study commenced, there were no known post-earthquake cost estimation models. Therefore, the main purpose of the C-DREEM is to provide a standardised process that can produce rapid and accurate cost estimates for a large number of buildings. Previous data collections were used to formulate post-earthquake cost estimation examples, identify methods that could improve the speed of estimation using Bills of Quantities (BOQ) and select a process that could incorporate these factors into the CEEDRW process.

6.3 Model development approach

A model is a simplified description of a particular system or a process (Oxford University Press, 2021). It can be used to provide an empirical understanding of a concept through an illustration. To build the model for this research project, research findings from the data collection required analysis. After the analysis, the main themes impacting the CEEDRW process were identified. Thereafter, a comprehensive literature review was conducted to identify different methods that could be used for the model development process. From these methods, the most suitable was selected: the TRIZ methodology. This method also reflects the pragmatic approach adopted by this research. TRIZ methodology was applied in order to systematically develop a rapid, accurate and standardised model for CEEDRW that considers the factors that impact the CEEDRW, as detailed in section 3.6.5.1. The C-DREEM development process is laid out in Table 6.1.

Table 6.1 - TRIZ methodology-based approach for identifying innovative methods for CEEDRW

No	Steps of the TRIZ process	Description of the step	Project details
1.1	Problem	Identify the problem required to be solved.	Current CEEDRW do not have standardised processes that can produce accurate and rapid cost estimations for a large number of damaged buildings.
1.2	Causes of the problem	Identify the causes of the problem.	The current cost estimation process does not have a standard method to include all 11 factors that impact CEEDRW. The high number of CEEDRWs required after an earthquake reduces the time that can be spent on a single project.
2.1	Selected Contradictions through TRIZ cycle	Note any contradictions by identifying what features that need to be improved and what features will be negatively affected by the improvements.	The number of CEEDRW factors included in the estimations (increase to increase the accuracy of the costs / decrease to reduce the time required to create detailed evaluations and detailed cost estimates). Quantity surveyor's repetitive work input (decrease to improve the speed of rapid cost estimations / increase to reduce the complexity and adoptability of the CEEDRW process).
2.2	Intensify the contradictions	Increase the intensity of each contradiction to extreme ends to create breakthroughs.	Increase VS decrease the number of CEEDRW factors included in estimations. Quantity surveyor's and professional repetitive work should be included VS quantity surveyor's repetitive work input should be excluded.
3.1	Resources – Tools and objects	Identify the tools and objects of the system. Objects = parts that are most difficult to change Tools = the easiest parts of the problem to change	Tool - quantity surveyor, cost estimation software (including excel) and cost database. Object - information about the earthquake-damaged buildings.
3.2	Resources in environment	Identify resources that can be used to improve the system.	3D modelling knowledge and equipment, probability-based loss estimation tools, past earthquake data.
4.1	Features related to the contradictions	Identify interrelated functionalities of the system that increase and decrease with the change.	Reliability increase VS Loss of time decrease Automation and productivity increase VS adaptability and complexity decrease

No	Steps of the TRIZ process	Description of the step	Project details
4.2	Relevant principle(s) to be used for innovation	Select suitable innovation principle(s) from the 40 TRIZ principles with the use of the contradiction matrix.	<p>Segmentation (Principle 1) (fragmentation of elements) - Divide the system into smaller standard fragments.</p> <p>Symmetry change (Principle 4) (Change the shape of an object) - Change the functions of the system so that each section works on a specific standard function.</p> <p>Preliminary action (Principle 10) (Perform a function before it is needed) - Use the data from PACT to estimate probable damage and include it in contingencies.</p> <p>Dimensionality change (Principle 17) (change the dimension) - Use a 3D BIM model rather than building plans for damage estimation.</p> <p>Feedback (Principle 23) (introduce feedback to improve the process) - Use results from the system to create new consequence functions and compare these with previous consequence functions.</p> <p>Mechanical interaction substitution (Principle 28) (change the method used) - Develop and use standardised rates and quantity calculation methods to automate repetitive work.</p>
5.1	Removing contradictions	Use innovative methods to remove the contradictions.	<p>Use data from probability-based loss estimation tools and include probable damage in the CEEDRW process.</p> <p>Restructure the costing process to reduce repetitive work done by the quantity surveyors through a series of innovative steps, as follows: divide larger rates into smaller segments; standardise the set of rates that do not change; connect the standardised rates with BIM model elements; automate the costing process.</p> <p>Automating functions include: damage identification, BOQ item selection, rate development, quantity calculation and final cost summary.</p>
5.2	Contradictions solved	Check if the contradictions were solved.	<p>Increase or decrease the usage of the number of factors considered in CEEDRW - solved.</p> <p>Increase or decrease quantity surveyor's repetitive work - solved.</p>

No	Steps of the TRIZ process	Description of the step	Project details
6.1	Product evaluations	Evaluate whether the suggested innovation achieves the required outcomes	<p>Are all harmful features minimised or eliminated? Yes</p> <p>Are new features maintained and improved? Yes</p> <p>Is there any addition of new harmful features? Yes, there is a reduction in usability and an increase in system complexity.</p> <p>Is there a decrease in complexity? No. However, greater complexity is required to solve the core problems</p> <p>Were primary trade-offs and contradictions removed? Yes</p> <p>Were idle and ignored resources used? Yes</p> <p>Were the other development requirements fulfilled? Yes</p>

The innovative developments created by following the TRIZ methodology were vital to the creation of C-DREEM. TRIZ methodology identified two main problems that needed to be resolved. These were the high number of buildings that require CEEDRW after an earthquake event and the non-consideration of the 11 factors identified in this study that have an impact on the CEEDRW process (refer to step 1.2 in Table 6.1).

Based on the problem, the next steps of the TRIZ process were to identify contradictions, resources available and features related to the contradictions. These steps are detailed in rows 2.1 to 4.0 of Table 6.1. The features related to the contradictions were 1) increase reliability vs decrease loss of time and 2) increase automation and productivity vs decrease adaptability and complexity.

As explained in the methodology (chapter 3), the TRIZ matrix table and the 40 principles of TRIZ were used to identify six principles that can be used to improve the CEEDRW process. These six principles are expressed in row 5.0: segmentation (Principle 1); symmetry change (Principle 4); preliminary action (Principle 10); dimensionality change (Principle 17); feedback (Principle 23); and mechanical

interaction substitution (Principle 28). Using these principles, a number of innovative methods were developed.

The developed innovations can be boiled down into two main actions. The first innovative action aimed to use data from probability-based loss estimation tools and include probable damage to the CEEDRW process. The focus of the second innovative action was to restructure the costing process to reduce the repetitive work done by the quantity surveyors through a series of innovative steps, as follows: divide larger rates into smaller segments; develop a standardised set of rates (thus removing the need to redevelop rates for each project); connect the standardised rates with BIM model elements; and automate the costing process. Automating functions include damage identification, BOQ item selection, rate development, a quantity calculation process and a final cost summary.

In the final phase of the TRIZ process, innovative principles were internally evaluated as per row 7 of Table 6.1. The internal evaluation revealed that the improvements would: fulfil development requirements; minimise harmful features (non-consideration of the factors affecting CEEDRW and repetitive work conducted by quantity surveyors); add new features; remove primary contradictions; and utilise idle resources. However, the evaluation also revealed that the incorporation of these improvements would increase complexity and difficulty in usage. Kalevi et al. (2018) argued that innovations are unlikely to achieve all the evaluation requirements against which they are measured. Therefore, the innovations associated with the C-DREEM were considered acceptable even with their identified drawbacks.

Further developments of the C-DREEM were based on the literature review, results from interviews, results from the questionnaire, document analysis and reviews from

professionals with experience in CEEDRW. The information collected from each section of data collection is depicted in Table 6.2.

Table 6.2 - Information collected for the C-DREEM development process

Information sources and development process	Information collected
Literature review	Methods of cost estimation for repair work Earthquake damage estimation process Information sources for CEEDRW Standard methods of measurement Fragility curves and consequence functions used in probability-based tools (PACT tool) Model design methodology
Interview	Practical methods used for damage evaluation and cost estimation Information used in CEEDRW processes Factors impacting CEEDRW
Questionnaire	Verification of the factors impacting CEEDRW Importance of the factors impacting CEEDRW Possible methods to incorporate the factors impacting CEEDRW into a cost estimation model
Document analysis	Cost databases (QV builder) SMM (ANSMM 2018) Probability-based loss estimation tools (PACT, SLAT)
Reviews from builders and quantity surveyors	A detailed description of the damaged items repair process Damage repair work costing Evaluation of iterations of the model iterations and suggestions for improvement

6.4 Aim of the C-DREEM

The proposed Cost of Damage Repair, Earthquake Estimation Model (C-DREEM) aims to include the factors impacting CEEDRW and improve the current cost estimation process. The cost estimation process will be improved in terms of speed, accuracy and the introduction of a standardised process. The proposed model aims to be a blueprint for a software system that can be used for CEEDRW. The C-DREEM was designed to produce standard CEEDRW at any post-earthquake stage. As an example, it could produce preliminary estimates shortly after the occurrence of the

earthquake, as well as detailed estimates required at the final stages of construction. Additionally, the proposed model will be easy to use and can be used by government regulatory bodies, clients, consultants, builders, insurance companies and other cost estimating parties.

6.5 Structure of the C-DREEM

To reveal the structure of the proposed model, three aspects are described in detail in this section: system mechanics, high-level design, and lower-level design.

1. ‘System mechanics’ refers to the automation process that was developed to improve the output of the CEEDRW. The automation process is described using partition board damage repair work as an example, due to its importance as demonstrated in the literature review section (refer to sections 2.4.2.2 and 2.4.2.3).
2. The ‘high-level design’ of C-DREEM contains three divisions. Each division contains three sections, so there are nine sections in total. Each section addresses the key functions related to cost estimation identified by the research.
3. The ‘lower level design’ of C-DREEM is the secondary section. This level details the process of each section of the model. This includes the description, the inputs, process, outputs and the factors covered by each section.

6.5.1 System mechanics

The system mechanics operate the core functions of the proposed C-DREEM model. and contains four interlinked pillars, as expressed below:

- Basic principle

- Rate categorisation
- Repair method classification
- Automation

6.5.1.1 Basic principle

The ‘basic principle’ used in the C-DREEM is derived from one of the fundamental functions in cost estimation: quantities multiplied by rates equals cost. Improvements to these two elements, quantities and rates, can result in a better cost estimation process.

The basic principle used in C-DREEM is to break down large rates into a set of standard micro rates. The standardised micro rates should have the following characteristics:

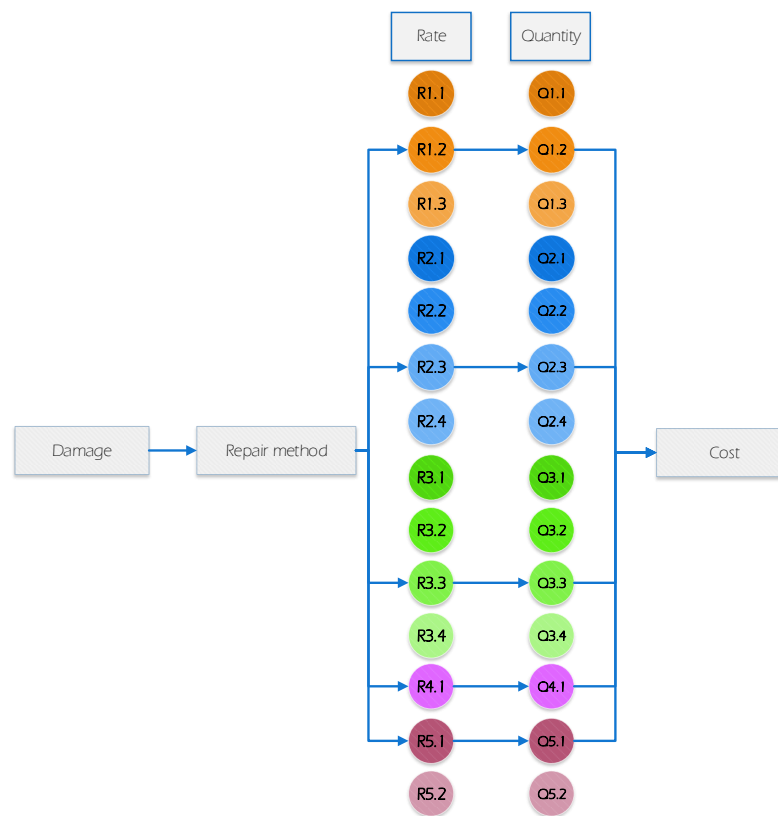
- Cover smaller work activities
- Cover all possible scenarios
- Combination of micro rates and relevant quantities to cover the main work
- Not require changes based on the work
- Be automatically updatable according to changes in price and external factors

The aim of using a set of standardised micro rates is to eliminate the time required to develop rates during the cost estimation process. The use of standardised rates has helped to calculate cost estimations related to new construction, as evidenced by the popularity of SMMs. SMMs are used in the construction industry for the purpose of standardising rates as well as to standardise methods for measuring given quantities (NZIQS et al., 2018). In the same way, standardised rates can help facilitate the costing

process. However, the standardised rates used in new construction are not directly applicable to repair work rates. Nevertheless, rates required for repair work are usually a collection of standardised rates used in new construction. Therefore, it is expected that standardised micro rates can be used to develop a standardised cost estimation process for repair work.

Once a set of standardised micro rates are developed, suitable rates can be selected based on the method of repair. The selected rates would also have an accompanying pre-defined and standard quantity calculation method. The cumulated output of the rates and quantities will be able to produce the cost of repairing damage, as depicted in Figure 6.1. Of course, the accuracy of the method would depend on the accurate selection of the correct repair method.

Figure 6.1 - Visual presentation of the basic concept



6.5.1.2 Repair activity-based rate categorisation

The process of ‘repair activity-based rate categorisation’ involved categorising the standardised micro rates. The purpose of repair activity-based rate categorisation is to help the rate selection process.

A standard rate categorisation for the C-DREEM was developed based on the repair activities to be conducted. The results from the document analysis and inputs from professionals with experience in CEEDRW were used to determine which activities to include. The document analysis identified rates included in probability-based loss estimation models, and cost databases such as QV builder and BOQs developed for past earthquake-damaged building repair work. The ANSMM 2018 standard, the current standard in New Zealand used to produce a cost construction estimate, was also analysed as part of the document analysis process. The data analysis process extracted details of processes of damage repair, sequence of work and costing processes.

In light of the findings from this analysis, six rate categorisations were proposed:

1. Remove, store, and reinstate
 - These rates cover costs associated with removing and storing items until repair work is completed and then restored to its former state.
2. Consequential damage
 - These rates cover the cost of repairing damage caused to other elements during the repair work.
3. Remove and dispose
 - These rates cover the cost of removing and disposing items.

4. Replace

- These rates cover the cost of replacing items.

5. Pre-finish

- These rates cover preparing surfaces for final finishing.

6. Final Finish

- These rates cover final finishing work.

According to the literature, light partition boards were one of the elements frequently damaged by earthquakes. Therefore, the research focused on light partition board repair work as an example to illuminate the rate categorisation process. All rates related to repairing general partition boards were divided into the six aforementioned categories; these are depicted in Table 6.3, below.

Table 6.3 - Categorisation of rates required for light partition board repair work

No	Section	Item	Unit of measurement
1	Remove, store and reinstate	Furnishing and equipment	m ²
		Architraves	m
		Cornices	m
		Skirting	m
2	Consequential damage	Doors and windows	Item / no
		Air tightness treatment for D/W	Item / m ²
		Electrical connections	Item / m ²
		Water connections	Item / m ²
		Gas connections	Item / m ²
		Network connections	Item / m ²
		Other fixtures	Item / m ²
		Flooring	Item / m ²
		Ceiling	Item / m ²
		Attached partitions	m ²
3	Remove and dispose	Damaged plaster boards	m ²
		Damaged internal corner trim	m
		Damaged external corner trim	m

No	Section	Item	Unit of measurement
		Wallpaper (if applicable)	m2
4	Replace	Plaster boards and wastage	m2
		Internal corner trim	m
		External corner trim	m
5	Pre-finish	Fibre fuse tape	m
		Plastering - base coat	m2
		Plastering - 1st coat	m2
		Plastering - 2nd coat	m2
		Sanding	m2
		Wall preparation for wallpaper	m2
6.1	Finish - type 1	Painting - base coat	m2
		Painting - 1st coat	m2
		Painting - 2nd coat	m2
6.2	Finish - type 2	Wallpaper installation	m2

6.5.1.3 Repair method classification

Once the rates were categorised, the next step was to identify the instances in which the rates were used. A repair method classification function was used to define different variants of repair methods and assign required micro rates.

Different types of damage to partition boards are used as examples to show how rates could be categorised as described in Table 6.3. Based on damage states used in probability-based loss estimation tools, three damage states are related to the repair of earthquake-damaged partition boards (Dhakal et al., 2016). These damage states, damage descriptions and repair methods are summarised in Table 6.4, below.

Table 6.4 - Damage states and repair methods for light partition damage (Adapted from Dhakal et al., 2016)

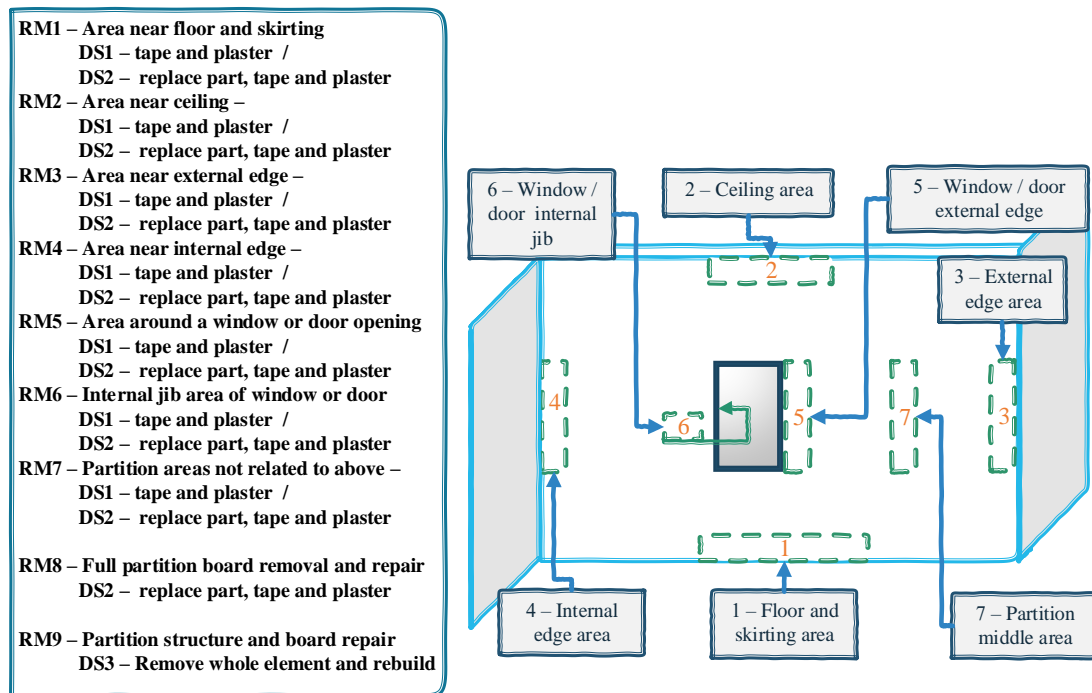
Damage state	Description of damage	Repair method
DS1	Cracked surface layer	Tape, sand, and paint.
DS2	Major cracks, buckling of wallboards at corners of walls	Replace wallboard panels, and then tape, sand and paint
DS3	Stud failure, sill plate splitting and failure, wall panel failure	Replace entire partition walls

However, these instances can be further categorised based on the location of repair work and the repair activities required. Nine locations were identified at which rates required for partition board repair work varied. Location-based repair methods were defined using the identification code: ‘repair method (RM) 1 to 9’. Each RM can cater to more than one damage state. The nine location-based repair methods are:

1. First seven locations (RM1 to RM7) covered smaller damage related to DS1 and DS2 levels
 1. Area near floor and skirting - RM1
 2. Area near ceiling - RM2
 3. Area near external edge - RM3
 4. Area near internal edge area - RM4
 5. Area around a window or door opening - RM5
 6. Internal jib area of window or door - RM6
 7. Partition areas not related to above - RM7
2. Full partition board removal and repair which is considered under DS2 type of damage - RM8
3. Partition structure and board repair which is considered under DS3 type of damage - RM9

Details and locations of the identified location-based repair methods are depicted in Figure 6.2.

Figure 6.2 - Identification of location-based repair methods (RM)



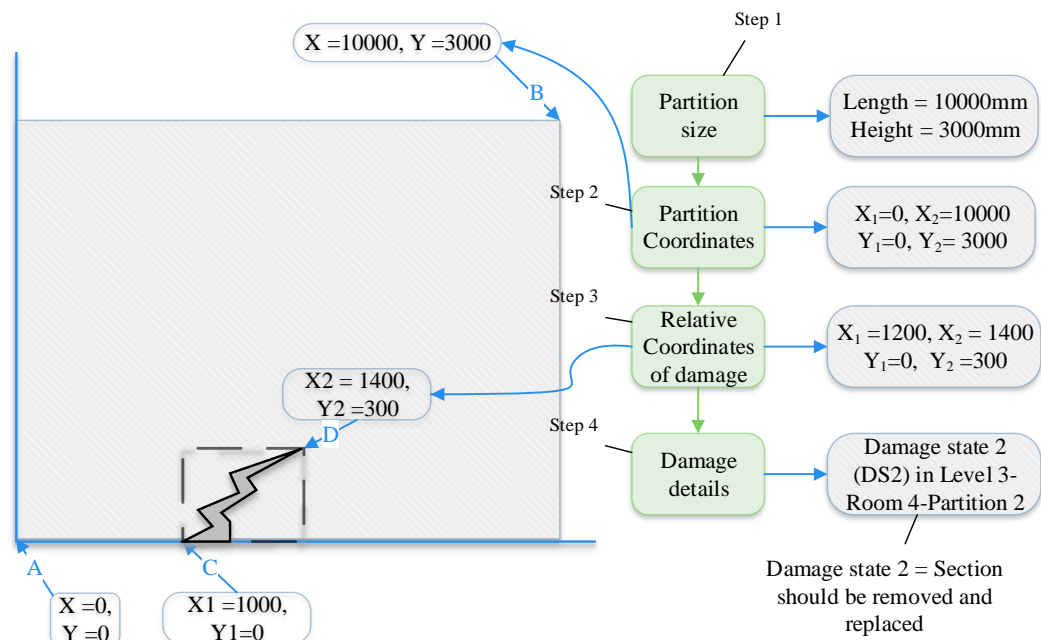
Next, the standardised micro rates were linked to the relevant repair methods. The standardised micro rates required for each RM are included in the Appendices (refer to Appendix 6). A similar process was used to link the RM to the required preliminary items (refer to Appendix 7).

6.5.1.4 Automation process

Once the damage is linked to the standardised micro rates, the quantity calculation process can be automated (refer to Figure 6.1). For the automation process, C-DREEM uses details from the BIM model to calculate relevant quantities. When we are using standardised micro rates, the quantity calculation process can also be standardised. For that purpose, a quantity calculation process was integrated into the model to generate

automated outputs. The automation process is described below, using light partition board damage, a small crack near the skirting area on a light partition board, as an example. The damage is considered DS2 (refer to Figure 6.3).

Figure 6.3 - Automation process (part 1)



According to Figure 6.3, the first step (Step 1) of the process was to extract details of the building element as included in the BIM model. For this example, the partition is 10,000mm in length and 3,000mm in height. Next (Step 2), these sizes are converted to coordinates relative to the partition board, using A and B locations ($X_1=0, Y_1=0, X_2=10000, Y_2=3000$).

Once partition coordinates are established, locational details of the damage can be extracted (Step 3). A separate function should be developed to incorporate the damage to the relevant element represented in a BIM model. This damage function should incorporate damage type, damage size, damage location and damage state. Once the damage is represented in the BIM model, C and D positions can be used to extract the

coordinates of the damage ($X_1 = 1200$, $Y_1 = 0$; $X_2 = 1400$, $Y_2 = 300$). These coordinates should be relative to the partition board (step 4).

Once these steps have been completed, a suitable damage repair method is selected (refer to Figure 6.4). According to the example, the lowest coordinate of the damage is less than the skirting width (step 5). This means that the damage is within the skirting area. Therefore, the suitable repair method is RM1-DS2. The repair method associated with RM1-DS2 requires the replacement of the partition board near the floor area. Using the details related to the RM1-DS2 repair method, relevant repair activities can be selected as per step 6. The repair activities required in this case are highlighted in blue in Figure 6.4.

Figure 6.4 - Automation process (part 2)

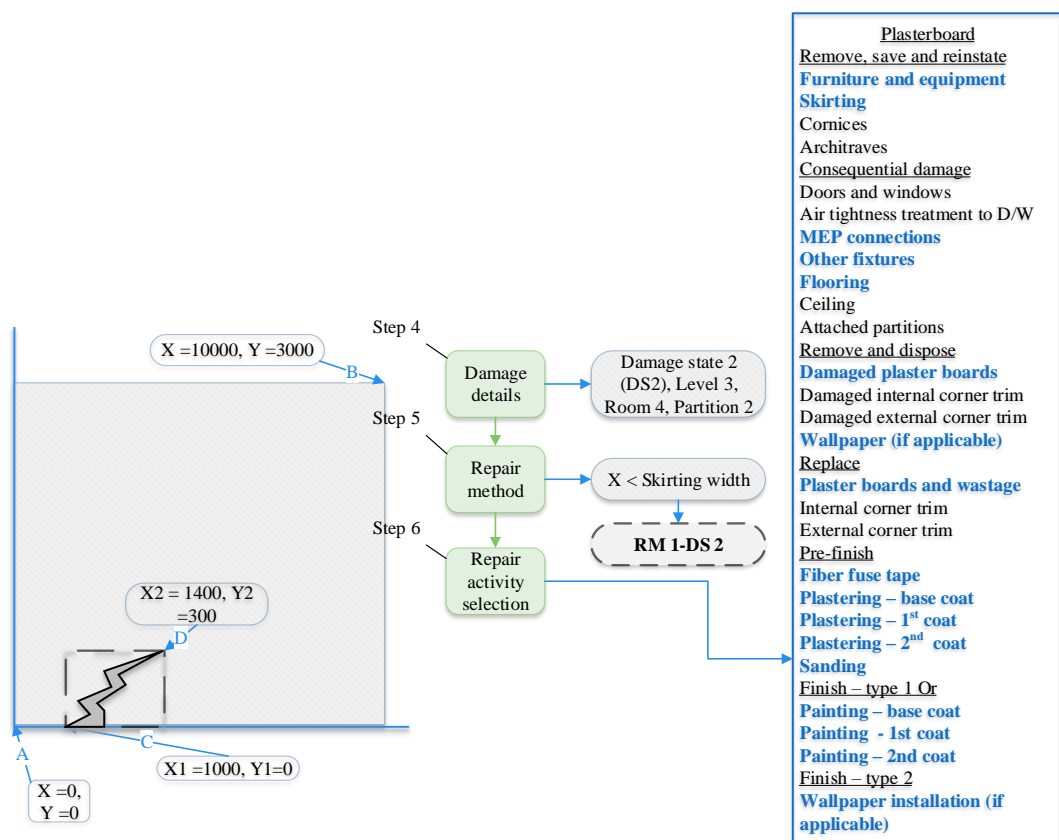
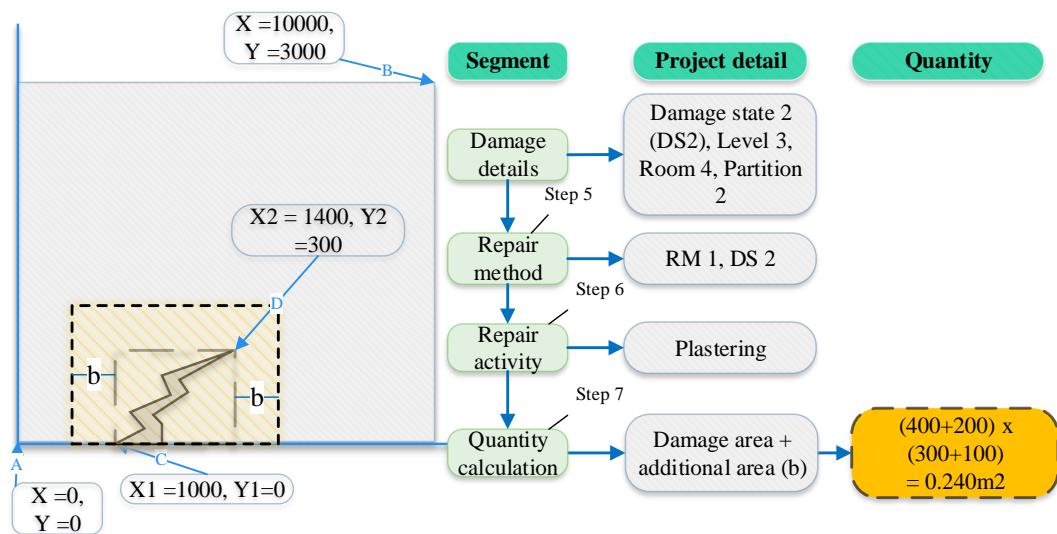


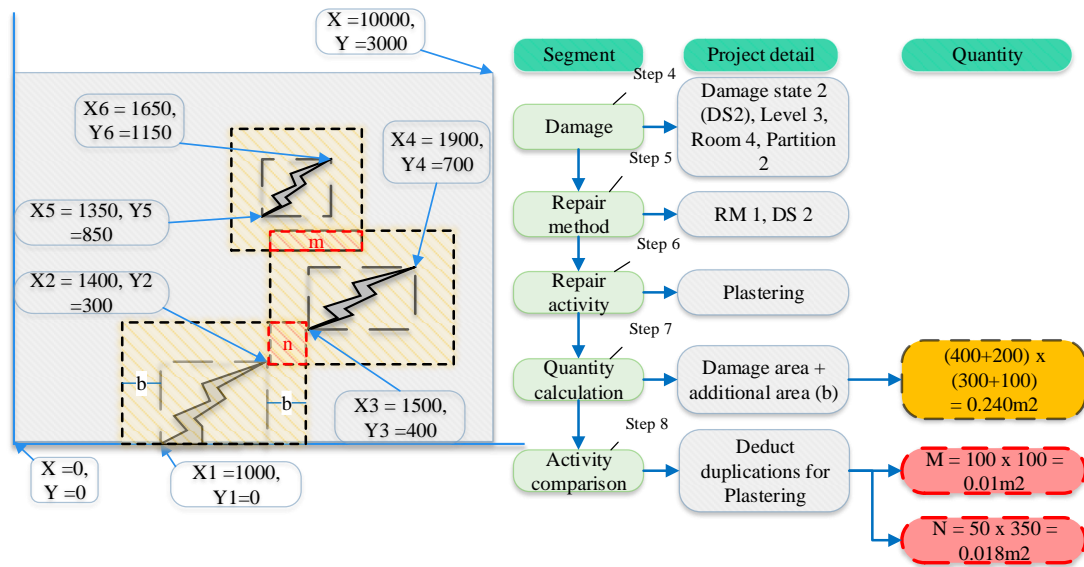
Figure 6.5 - Automation process (part 3)



Once the repair activities have been selected, quantities can be calculated as per step 7 in Figure 6.5. This calculation may include additional area(s) beyond the specific location of the damage. For example, consider plastering work conducted during repair work. Additional areas beyond the repair location also need to be plastered. This additional width is considered in the automation process as 'b'. If 'b' equals 100mm, the total plastering area in the partition repair example detailed in Figure 6.3, Figure 6.4 and Figure 6.5 would be 0.240 square meters.

It is critical to note that, when quantity calculations are based on individual damage locations, there can be overlaps in and duplication of estimated quantities. These duplicated quantities can be deducted, as shown in Figure 6.6, by repeating the process used for quantity calculations to identify and measure areas of overlap. In the eighth step, an example for duplication deduction is detailed. In the example, plastering quantities are duplicated, as illustrated by areas, 'm' and 'n', marked in red. Since all quantity calculations made in the system include location details, these duplications can be quickly identified and deducted from the estimation.

Figure 6.6 - Automation process (part 4)



The above process can be extrapolated to calculate activity durations, quantities of preliminary items, costs of professional services and other costs. The total automation This process follows Principle 28 (mechanical interaction substitution) of the TRIZ methodology.

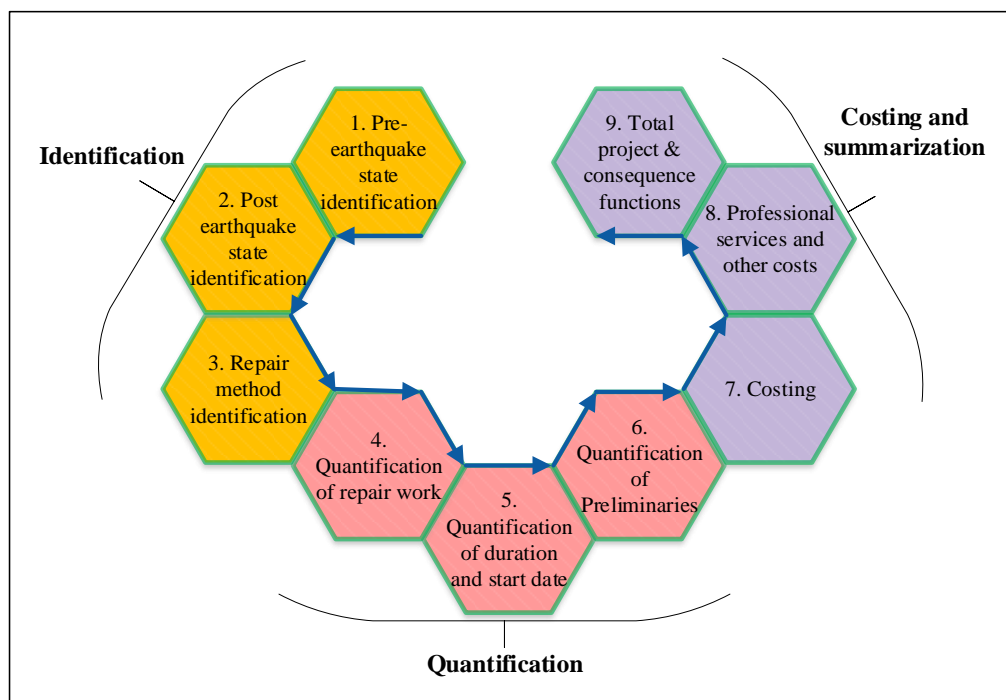
6.5.2 The high-level design of C-DREEM

The C-DREEM model was developed based on the system mechanics process described above. Turning to the high-level design of C-DREEM, as it is visually presented in Figure 6.7, we can see that it has three main divisions: 'identification', 'quantification' and 'costing & summarisation'. The 'identification' division involves identifying the project and damage details. This division includes three tasks: pre-earthquake state identification, post-earthquake state identification and repair method identification. The subsequent 'quantification' division aims to calculate quantities associated with time and cost related items. This division quantifies the direct repair work, repair time (duration and start date) and preliminaries. The final 'costing and

summarisation' division refers to applying the rates, (including other external costs), summarising the project costs, developing consequence functions and evaluating the output.

Each of the nine sections of C-DREEM was designed as independent components utilising the TRIZ methodology principles of Segmentation (Principle 1) and Symmetry change (Principle 4). The method of 'segmented system architecture' is defined as component-based software engineering (CBSE) (Sommerville, 2016). The segmented nature of the system allows each section to function separately, communicated through specified standards, such that each section can be upgraded without interference to the other sections.

Figure 6.7 - High-level design of the C-DREEM

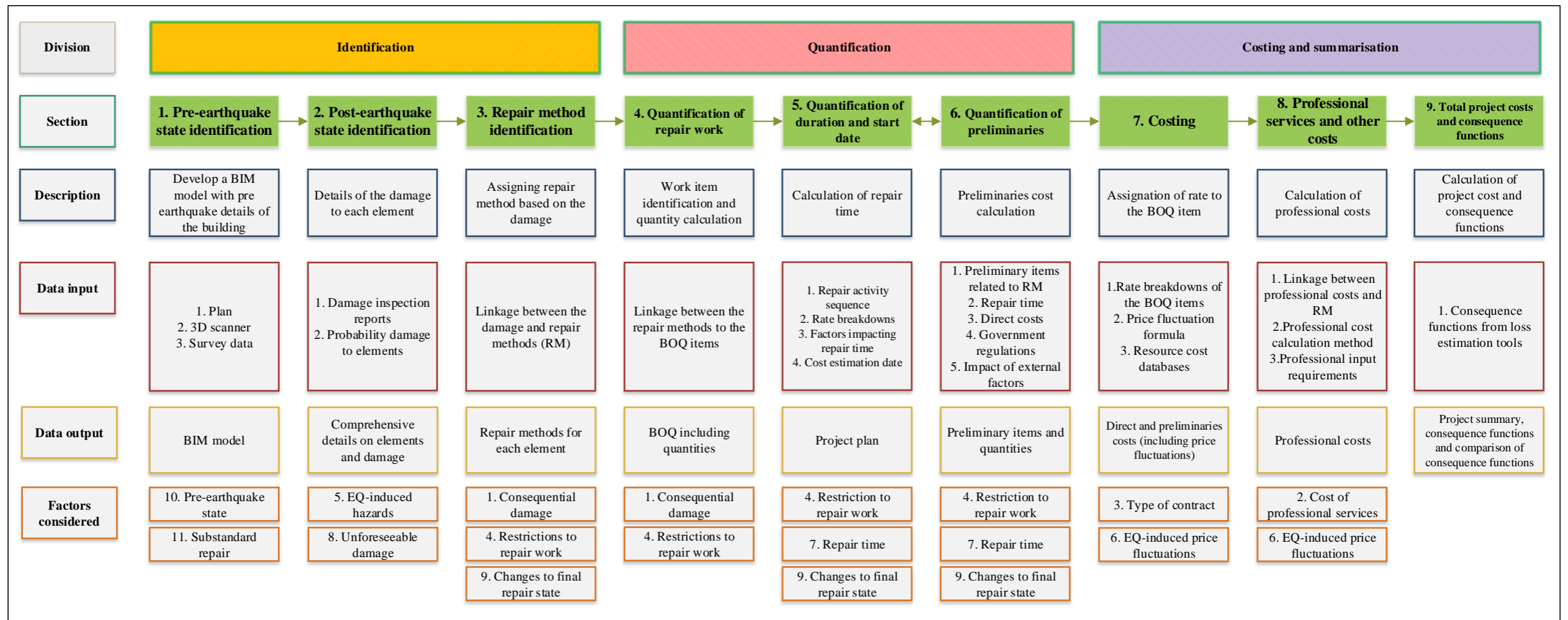


6.5.3 Lower-level design of C-DREEM

Taking a view of the lower-level or secondary-level design of the C-DREEM, as expressed in Figure 6.8, reveals further details for each section. Each column of Figure 6.8 represents a section of the model. Rows of the model refer to the section name, description of the section, input requirements for the section, output requirements of the section and factors covered by the sections.

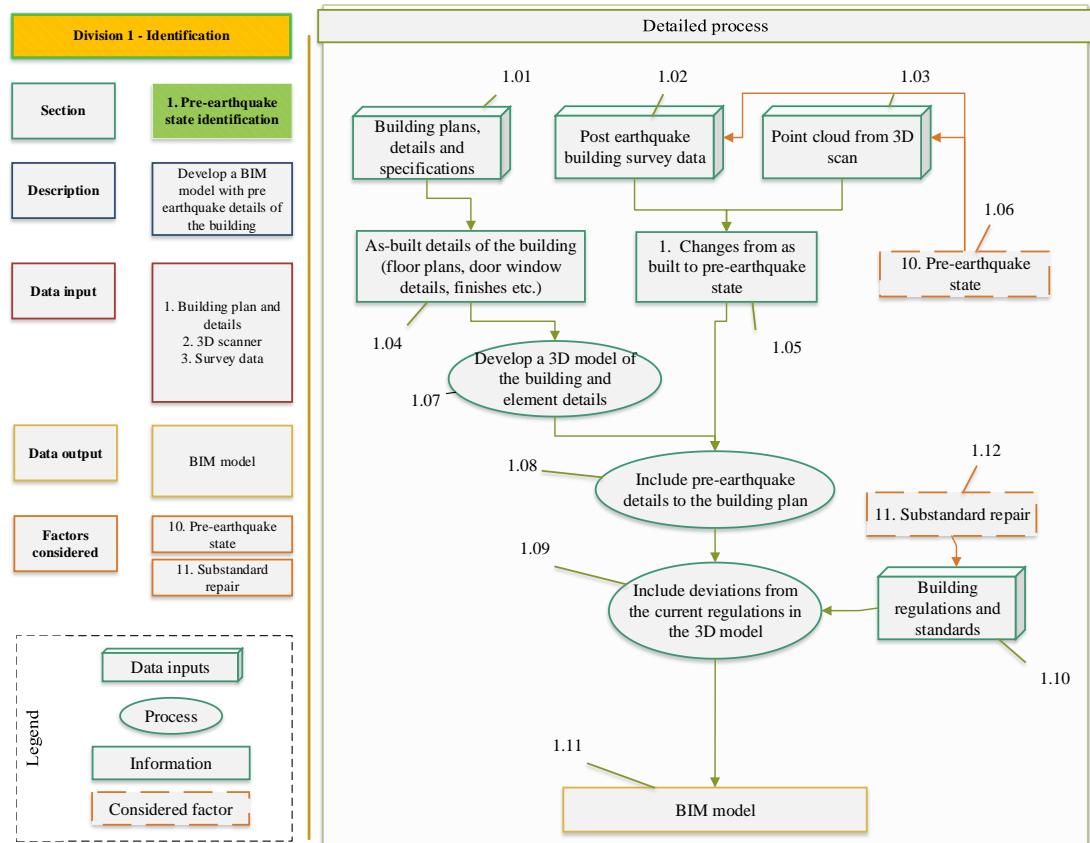
The arrows in the model represent the information flow of the C-DREEM. The default information flow is from left to right. However, there is information that goes backwards between sections six (quantification of duration and start date) and seven (quantification of preliminaries). Backward information flow is depicted by the double-headed arrows. The process of each section is detailed below.

Figure 6.8 - Lower-level design of the C-DREEM



6.5.3.1 Pre-earthquake state identification (Section 1)

Figure 6.9 - Pre-earthquake state identification (Section 1)



Process of the pre-earthquake state identification section (1)

The detailed process associated with the first step of the identification stage of the C-DREEM model involves cumulating and organising the details of an affected building (refer to Figure 6.9). The final output of this process is a 3D model updated with the pre-earthquake state and final output specifications for the repair work.

As shown in the figure, the process starts with the identification and use of building plans and specifications available on the building (1.01) to develop a 3D model (1.07) of the building. The use of a 3D model follows principle 17 (dimensionality change) of the TRIZ methodology. Floor plans, door window details, finishing details and

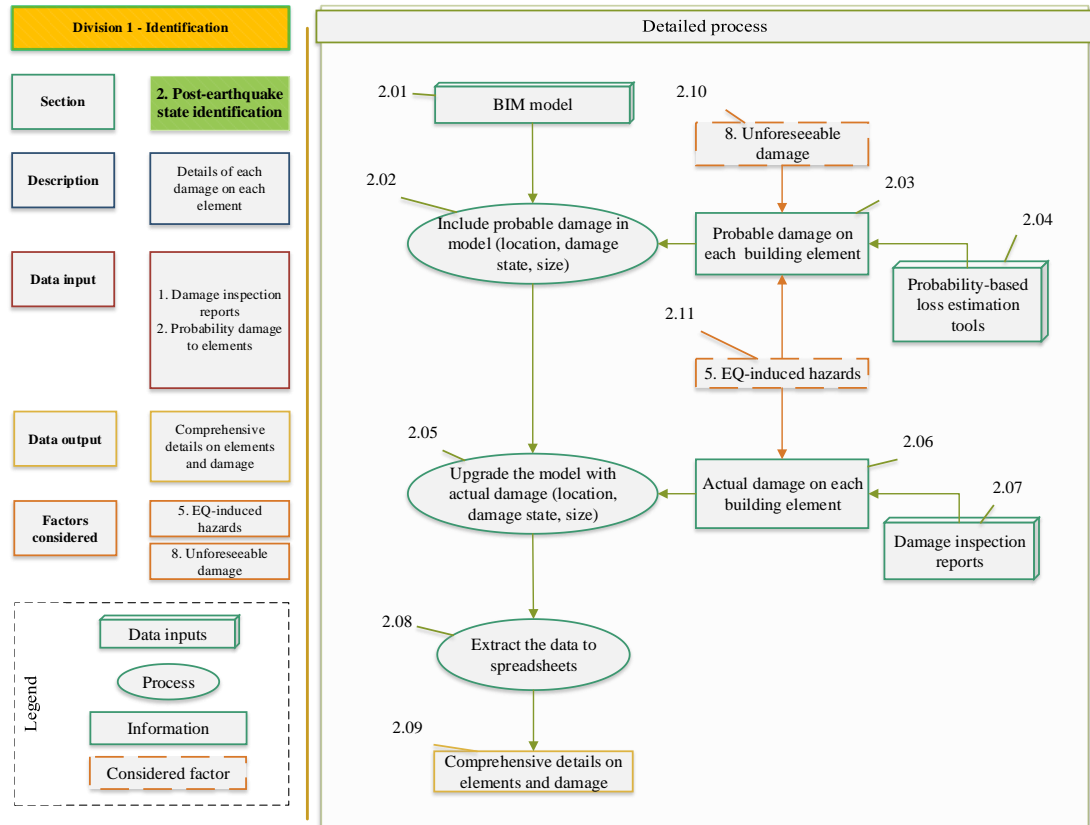
specifications are examples of some of the information required (1.04) for 3D model development. The resulting 3D model is further developed through the inclusion of the pre-earthquake state of the building (1.08), using the building survey data (1.02) to extract the information related to the variations between the ‘as-built state’ and the pre-earthquake state (1.05). The post-earthquake building survey data considers the ‘pre-earthquake state of the building’ factor identified by the study into consideration (1.06). If available, 3D scans can also be used for the 3D model development process (1.03).

Once the 3D model has been initially developed, current building regulations and standards (1.10) are used to identify changes required to the model in order to formulate the final repair state (1.09). The factor ‘impacts of substandard repair work’ are covered, to an extent, by this process (1.12), when the relevant building regulations (1.10) are compared with the current conditions of the building and included in the BIM model. However, this evaluation of the substandard repair work might be limited to visual identifications.

The final output produces a BIM model and required specifications of the final repair work. The BIM model would be developed to LOD (Level Of Development) 350 or above detail, which is the general level of detail required for construction documentation (BIM Acceleration Committee, 2019b) (1.11). The BIM model developed to LOD 350 level contains the location, size, shape, alignment, quantity and interfaces of the building elements, objects or systems (BIM Acceleration Committee, 2019a). If either the survey data or the 3D scan is not available, only the building plans can be used, and such an approach might affect the accuracy of the output.

6.5.3.2 Post-earthquake state identification (Section 2)

Figure 6.10 - Post-earthquake state identification (Section 2)



Process of the post-earthquake state identification section (2)

The second section of the identification stage of the C-DREEM model focuses on identifying probable and actual post-earthquake damage to incorporate into the model (refer to Figure 6.10). The final outputs of the section are: the extraction of details of the damaged building elements, which can be used in the later stages of the cost estimation development process; and a model that includes earthquake damage.

Through this section, the C-DREEM continues to update the BIM model that was produced in the first identification section (2.01). The process starts with the identification of the probable damage to elements of the building (2.03). These details

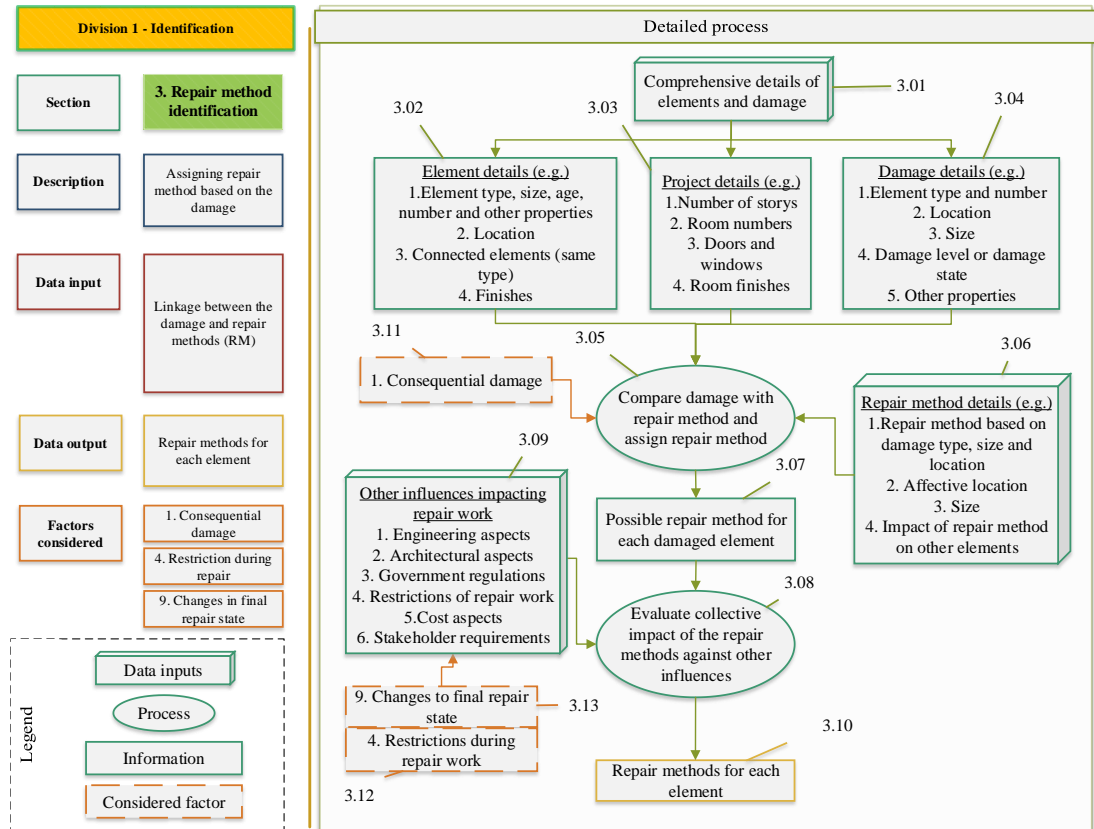
are extracted from probability-based models (2.04). This integration is based on principle 10 (preliminary action) of the TRIZ methodology. The identified probable damages are linked and represented in each element of the BIM model (2.02). Usage of data from the probability-based loss estimation tools (2.04) enables the inclusion of the impact of initially unforeseen damage (2.10) and earthquake-induced hazards (2.11), key factors identified in the research, into the model. It is important to note that the accuracy of the probable damage depends on the accuracy and availability of the data input.

When details of the actual damage become available, this information is then included in the BIM model (2.06). These details would be extracted from the initial and detailed damage survey reports (2.07). These actual damage details would supersede the probable damage inputs. The impact of earthquake-induced hazards (2.12) are thus more accurately included into the model through information acquired from damage inspection reports (2.07).

The resulting updated BIM model contains details of each building element and the relevant damage to that element. Damage details include the location, size and level of damage. Finally, the comprehensive details of the building, its elements and damage to those elements (2.09) are extracted into spreadsheets (2.08). This extraction is required because the cost estimation process is conducted through the use of spreadsheets.

6.5.3.3 Repair method identification (Section 3)

Figure 6.11 - Repair method identification (Section 3)



Process of the repair method identification section (3)

The third and final section of the identification division (refer to Figure 6.11) involves the selection of suitable repair methods, based on the damaged building elements pinpointed in the previous stage. The comprehensive details of damage to building elements (3.01) are used to select a suitable repair method for each. These details of damage and elements are extracted from the BIM model. Details required are project details, element details and damage details.

The data sought for 'project details' refers to the scope of the building. For example, the number of stories and rooms, door and window details and different room finishes

(3.02). ‘Element details’ gather specific information regarding the element. These details supersede the project details when required (3.03). Examples of element details include type, size, properties, location, unique identification number, connected elements (same type and other types) and finishes (if applicable). ‘Damage details’ specify the extent of the damage to the element (3.04). Damage details include a damage identification number, element type, location of the damage on the element, size of the damage, severity of the damage and other relevant details (3.04).

The repair method selection process (3.05) is conducted using information included in preloaded functions. Preloaded functions (3.06) define the most suitable repair method based on project, element and damage details.

The selected repair method takes into consideration repair location, method of repair and size of repair (3.07). Additionally, it also considers the impact of consequential damage to attached elements (3.11), another key factor identified in the research. Details of any consequential damage are recorded into relevant building elements in the BIM model.

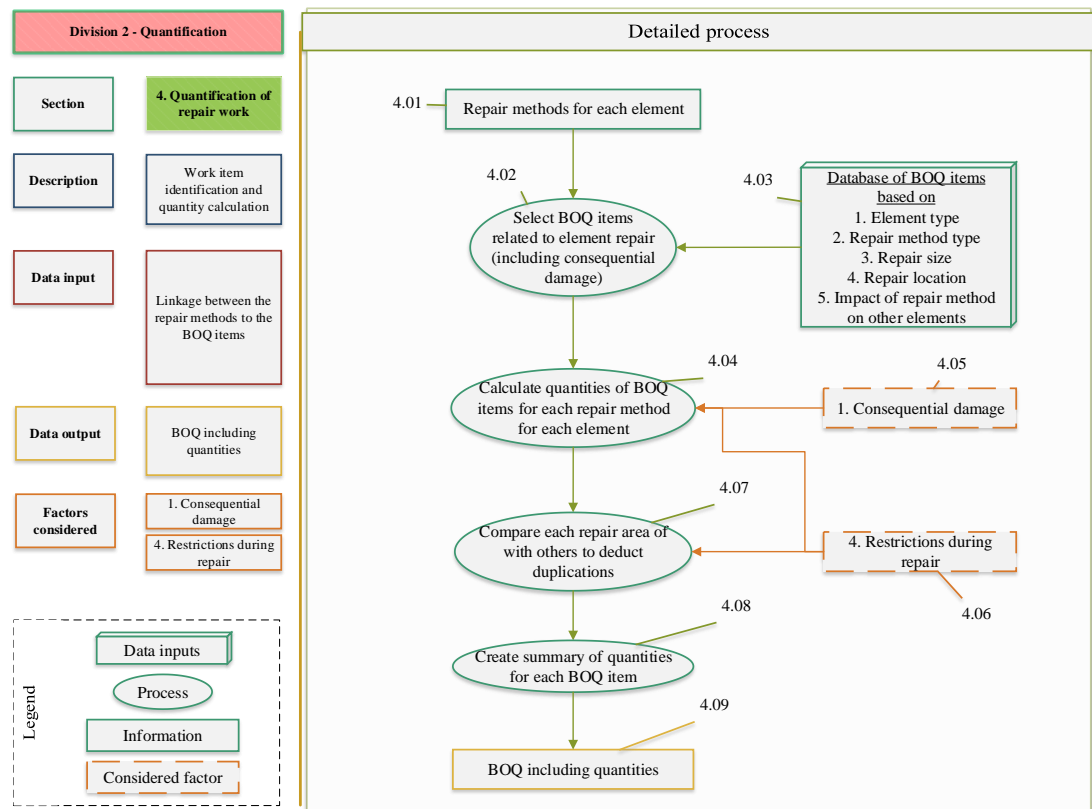
Next, the collective impact of all damage repair work on the project is compared against other influences that have an impact on repair work (3.08). These include engineering aspects, architectural aspects, building regulations, restrictions during repair work, cost aspects and stakeholder requirements (3.09). Results from this comparison and evaluation modify the selected repair method, if required. Changes to the final repair state (3.13) and restrictions during repair work (3.12), key factors established by the research, are evaluated through the other influences evaluation (3.08) process. As an example, if there is a change in regulations that will have an

impact on the final state of repair work, then the repair methods are be modified accordingly.

The output sought for this section is the repair method(s) selected for each building element (3.10).

6.5.3.4 Quantification of repair work (Section 4)

Figure 6.12 - Quantification of repair work (Section 4)



Process of the quantification of repair work section (4)

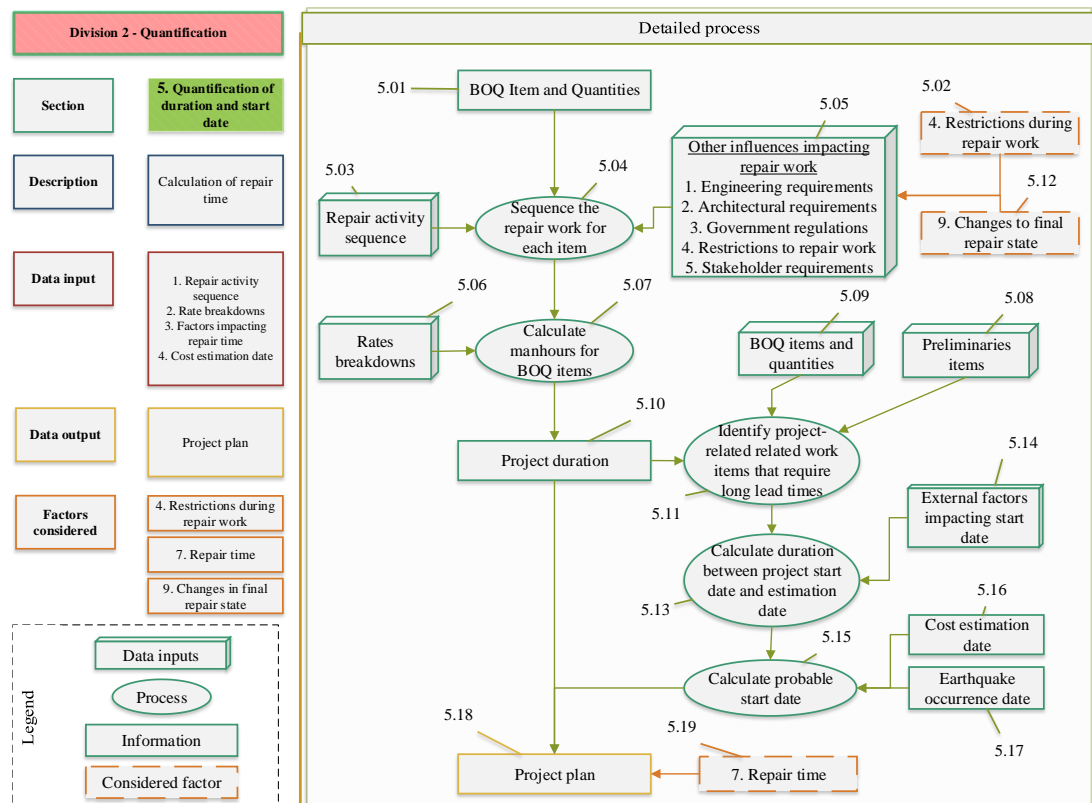
The fourth section of the model (refer to Figure 6.12), the first of the three ‘quantification’ sections, calculates the quantities of repair work items. Based on the repair methods identified (4.01) in section 3, appropriate BOQ items are selected (4.02). A preloaded function included in the model links damage repair methods to

required BOQ work items (4.03). Based on the repair method details and BOQ items, the quantities and repair locations associated with each item are calculated (4.04). Selected BOQ items and related quantities also include items related to consequential damage (4.05), another key factor identified in the research.

As the quantities are calculated separately for each damaged element, the next step of the process is to deduct any duplicated quantities, as explained in the system mechanics section (4.07). Any restrictions affecting the repair work not addressed in the repair method selection process are considered during the quantity calculation (4.04) and duplication deduction (4.07) processes. Finally, all the quantities are summarised (4.08), and a BOQ with quantities is produced (4.09).

6.5.3.5 Quantification of duration and start date (Section 5)

Figure 6.13 - Quantification of duration and start date (Section 5)



Process of the quantification of duration and start date section (5)

The fifth section of the model establishes the project plan by calculating the repair duration and the start date (refer to Figure 6.13). The process starts with sequencing the repair work for each item (5.04) based on the BOQ items and related quantities (5.01). Preloaded functions that contain the general order of work activities (5.03) are used to create the repair work sequence (5.04). The general sequence of work items is superseded by the other influences that have an impact on repair work, which include; engineering requirements, architectural requirements, government regulations, restrictions during repair work and stakeholder requirements (5.05). Other influences that impact repair work (5.05) include factors identified in the research: restrictions impacting repair work (5.02) and changes to the required final repair state (5.12).

Next, labour requirements for the work items are extracted from the rate breakdowns of each BOQ item (5.06). The quantified labour requirements are then used to calculate the labour needed for each work activity (5.07) and determine the project duration (5.10).

Once the project duration is calculated, the start date calculation process begins. The calculation of the start date (5.15) is made with reference to the cost estimation date (5.16), earthquake occurrence date (5.17) and the duration between the start date and the cost estimation date (5.13). The cost estimation date (5.16) and the date of the earthquake (5.17) are generally known and can be extracted from the project details.

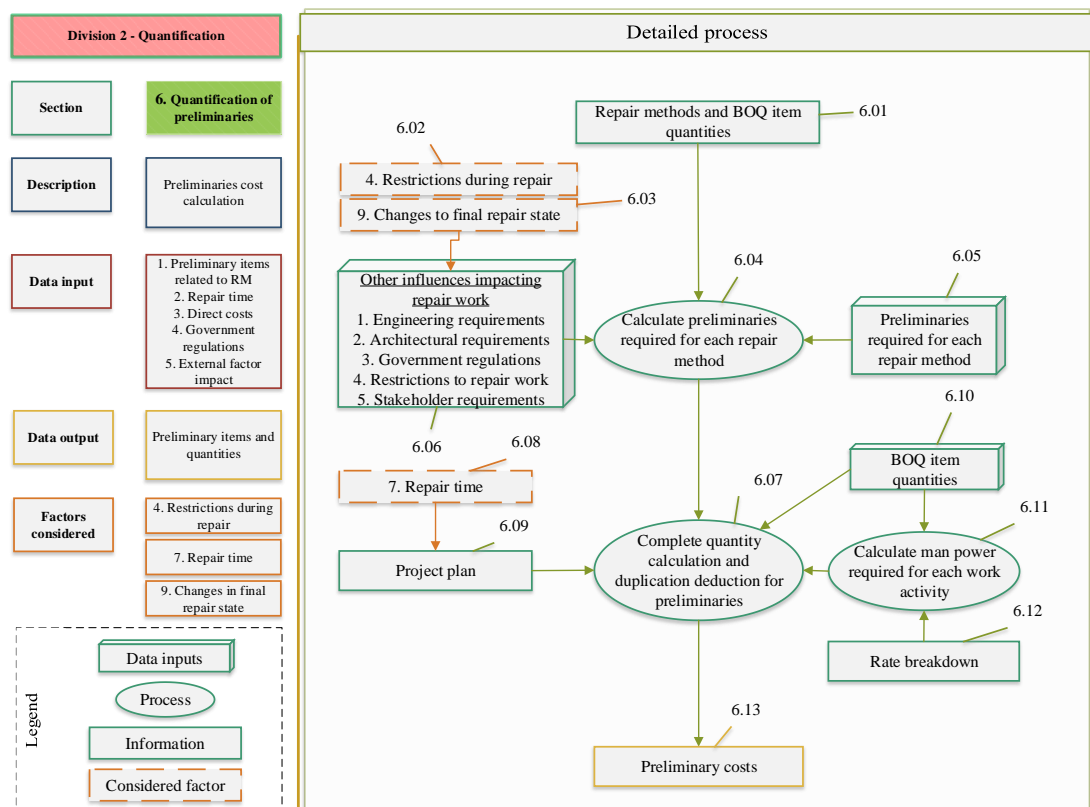
The duration between the start date and cost estimation date (5.13) is based on external factors that affect the start date (5.14) and project-related work items that require long lead times (5.11). Until a separate process is developed, the processes employed by SP3 modelling (Almufti & Willford, 2013) can be used to calculate the impact of

impeding factors that prevent the start of a project (5.14). Material and equipment that require a long lead time are calculated (5.11) using preliminary requirements extracted from section six (Quantification of preliminaries) (5.08), project duration (5.10) and BOQ items and quantities (5.09).

The combination of the project duration (5.10) and start date (5.15) outputs produces the project plan (5.18), which is directly related to repair time (5.19), another key factor identified in the research.

6.5.3.6 Quantification of preliminaries (Section 6)

Figure 6.14 - Quantification of preliminaries (Section 6)



Process of the quantification of preliminaries section (6)

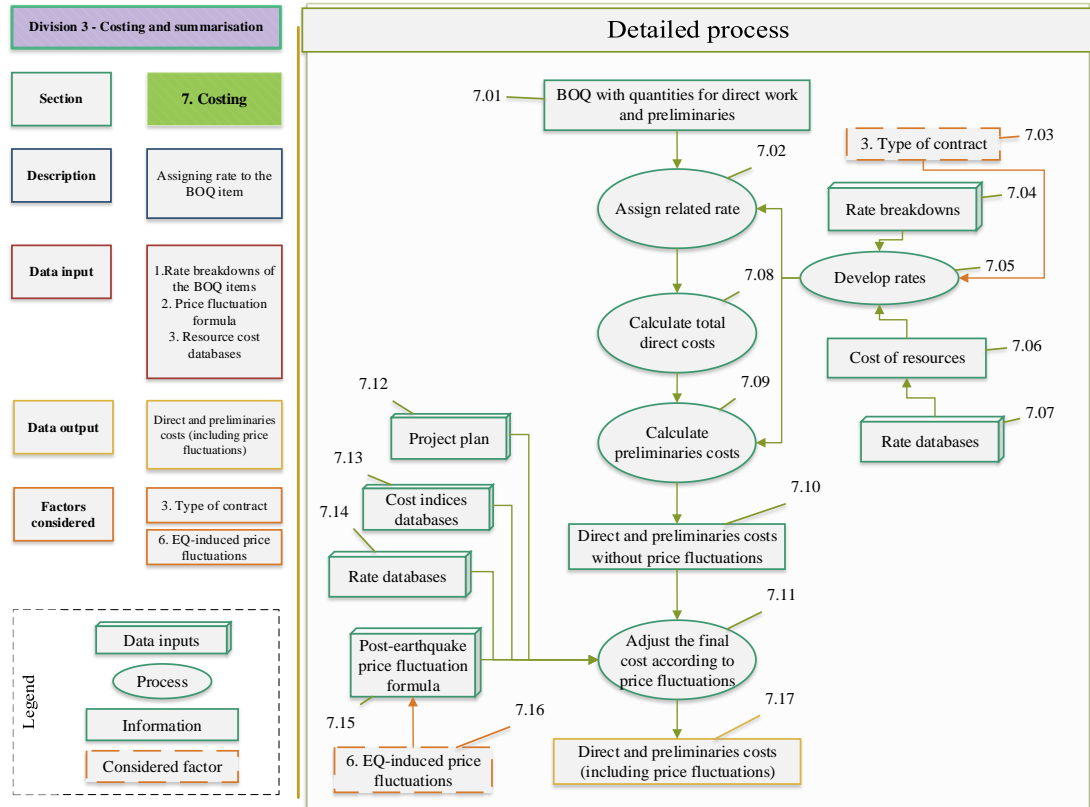
The sixth section of the model establishes the process of selecting and quantifying preliminary items based on the identified repair method (refer to Figure 6.14). A preloaded function included in the model links repair methods to preliminary item requirements (6.05). The selection of required preliminary items is based on the repair methods (6.01), BOQ item quantities (6.01), and other influences impacting the repair work (6.06), including: engineering requirements, architectural requirements, government regulations, restrictions to repair work, and stakeholder requirements (6.06). As per previous sections, other influences impacting repair work (6.06) would also take into consideration the impact of restrictions to repair work (6.02) and changes to the required final repair state (6.03).

The quantification of preliminaries is based on the project plan identified in the previous section (6.10), BOQ item quantities (6.10) and the labour required for the repair work (6.11). The use of a project plan (6.09) would include the impact of the repair time (6.08), a key factor identified in the research.

Quantification of the labour required for the project is based on the BOQ item quantities (6.10) and rate breakdowns (6.12). Any preliminary items that require total project costs in order for their quantities to be calculated are considered in the 'costing' section. Calculating quantities for preliminaries also includes the deduction of quantity duplications (6.11). A summary of preliminary items and relevant quantities is the final output of the section (6.13).

6.5.3.7 Costing (Section 7)

Figure 6.15 - Costing (Section 7)



Process of the costing section (7)

The seventh section of the model, the first of the 'costing and summarisation' division, breaks down the process associated with costing the quantified items and adjusting for price fluctuations.

The process starts by extracting quantities related to direct work items and preliminaries (7.01). Thereafter, suitable rates are assigned to the extracted cost items (7.02) (refer to Figure 6.15). The required rates are developed (7.05) using rate breakdowns (7.04) and the current market prices of resources (7.06). Any changes in the cost of resources (7.06) are updated using cost databases (7.07). Any impact from

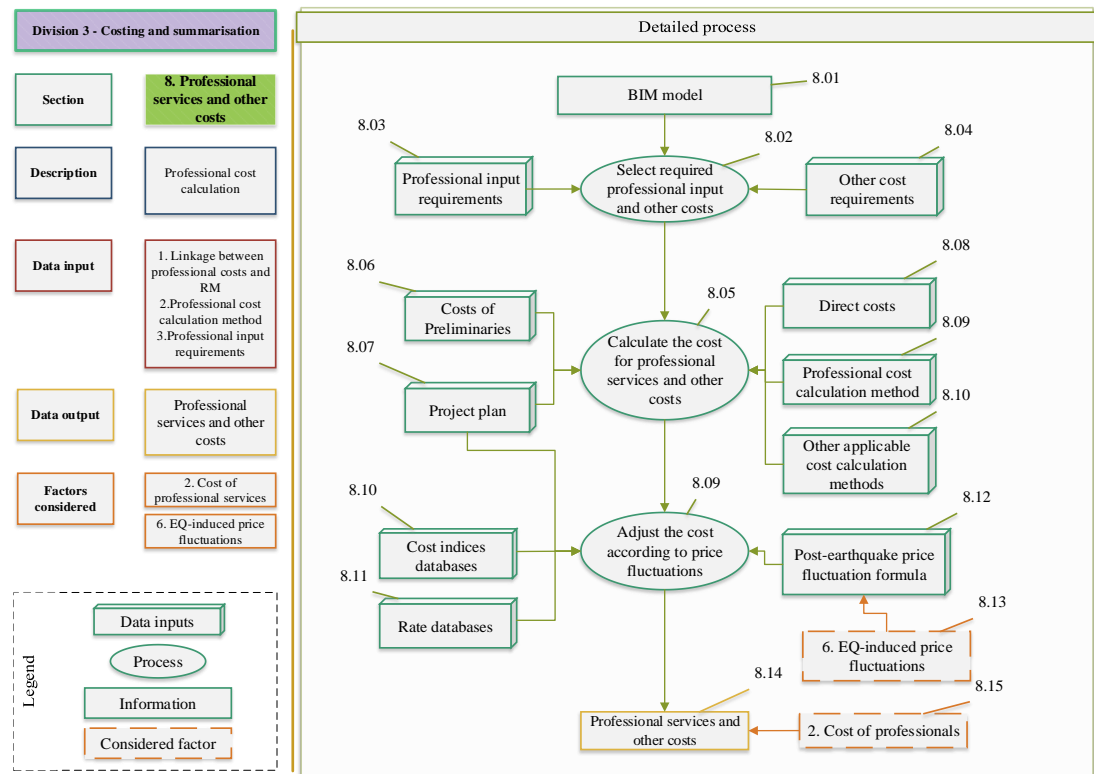
changes to the type of contract (7.03) is included through the rate development process (7.05) whereby profit and overhead percentages are included.

Next, the total direct cost of work items (7.08) is produced, using the rates and quantities. A similar process is used for costing the preliminary items (7.09). The costs of total direct costs (7.08) and preliminary items (7.09) are added together to produce a BOQ with total construction costs (7.10). This total does not reflect the impact of price fluctuations.

Projected price fluctuations that might occur during post-earthquake repair work are calculated with the use of a preload formula (7.15) included in the model. Calculations from this formula includes earthquake-induced price fluctuations (7.16), another key factor identified in the research. The price fluctuation formula operates on information provided by the construction cost indices (7.13), project plan (7.12), and rate databases (7.14). In this instance, the project plan (7.12) is used to identify the start date and duration of each work item. The output of the section (7.17) is an estimate of the total construction costs adjusted according to price fluctuations.

6.5.3.8 Professional services and other costs (Section 8)

Figure 6.16 - Professional services and other costs (Section 8)



Process of the professional services and other costs section (8)

The eighth section of the model calculates the cost of professional services and other costs (refer to Figure 6.16). The process starts with the selection of professional services and other costs required for total repair work (8.02). An inbuilt selection mechanism is included to link damage details to required professional services (8.03) and other costs (8.04). Details required for this function are: damaged element type, size of the element, location of the element, size of the damage, damage severity, damage location and required professional services for each type of damage. The required damage details are extracted from the BIM model (8.01).

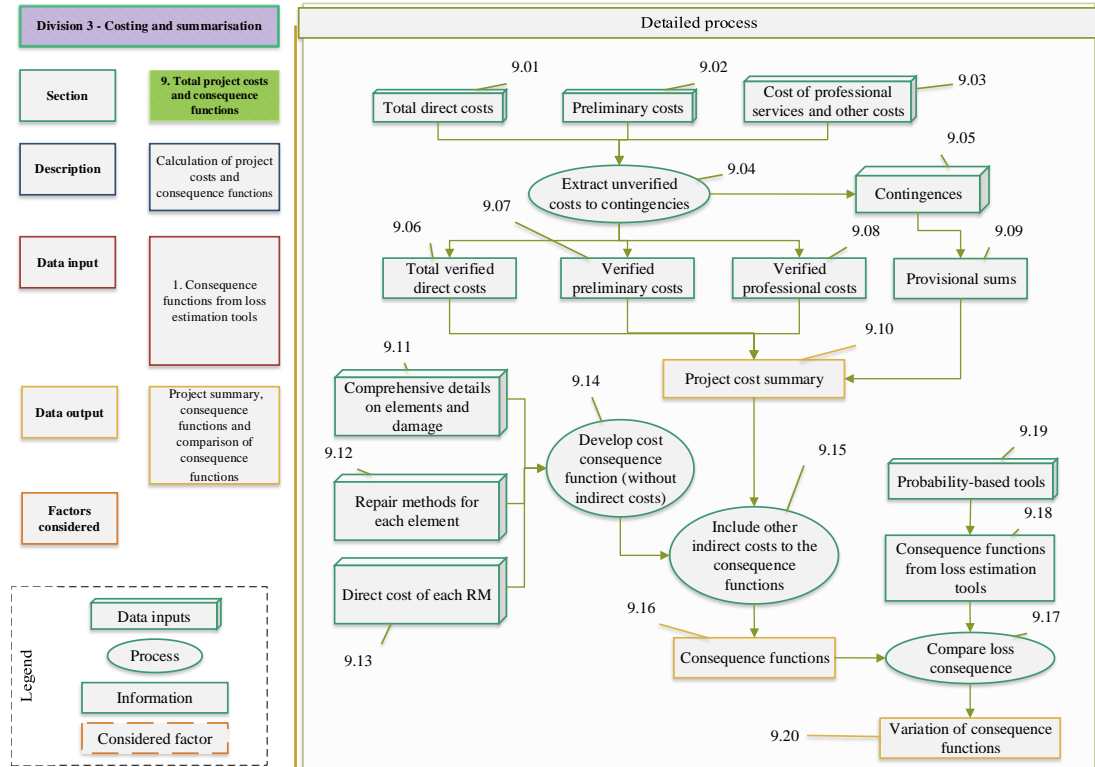
Several project details are used to calculate the cost of professional services and other costs (8.04): recommended professional services and costs; project start date and duration, extracted from the project plan (8.07); cost of preliminaries (8.06); and direct costs (8.08). Separate formulas are included in the model to calculate the professional service costs (8.09) and other costs (8.10).

Next, the costs of professional services and other costs are adjusted according to projected price fluctuations (8.09). As per section 7, a preloaded post-earthquake price fluctuation formula (8.14) is used to calculate the projected price fluctuations, which include earthquake-induced price fluctuations (8.15). As per the previous section, inputs for the price fluctuation formula are the construction cost indices (8.10), the project start date, the project duration and rate databases (8.11).

The project plan is used in this instance to identify the start date and duration of each professional service required and other costs in order to establish a professional cost calculation method (8.09). The final output of section 8 is the total cost of professional services and other costs (8.14), and includes another key factor identified in the research: cost of professional services (8.15).

6.5.3.9 Total project costs and consequential functions (Section 9)

Figure 6.17 - Total project costs and consequential functions (Section 9)



Process of the total project costs and consequential functions section (9)

The ninth and final section of the model focuses on combining all the previously-calculated costs to produce the total cost of the project (refer Figure 6.17). Additionally, this section develops consequence functions and compares them with previous versions. The developed consequence functions can be used in the pre-earthquake loss estimation tools that were identified in the literature section.

The total cost of the project contains total direct costs (9.01), costs of preliminaries (9.02) and professional services and other costs (9.03). The total cost of the project is based on both actual damage and projected probable damage. The costs associated with repairing actual damage are extracted into the total verified direct cost (9.06),

verified costs of preliminaries (9.07) and verified professional costs (9.08). Costs derived from probable damage are included in the contingencies (9.05). Since the model adopts the ANZSMM 2018 standard, costs of contingency items (9.05) are included in the provisional sums (9.09).

Then, the total verified direct costs (9.06), verified preliminaries costs (9.07), verified professional costs (9.08) and provisional sums (9.09) are summarised in the summary sheet to produce the total project cost summary (9.10).

The next step of the process is to produce consequence functions (9.15). As explained in the literature review, consequence functions link different damage states of building elements to the appropriate repair costs. The first step of the consequence function development process is to link the damage states of the building elements to the appropriate direct costs (9.14) and then develop consequence functions. The information used in this linking process are the repair methods details (9.12), the direct costs of the repair methods (9.13) and the damage states of the elements (9.11). Then, the remaining project costs are added to the consequence functions. A summary of the total project cost (9.10) will be divided and allocated proportionately to the remaining costs for each consequence (9.16). These costs are: the cost of preliminaries, the cost of professional services and other costs (9.15). This process produces the consequence functions for each damage state of all building elements.

Finally, the consequence functions developed from the C-DREEM (9.16) are compared with previously developed consequence functions (9.17), which include data extracted from loss-estimation (9.18) and probability-based (9.19) tools. The comparison functions as a feedback procedure for future modifications to C-DREEM. This process follows Principle 28 of the TRIZ methodology.

6.5.4 Key improvements achieved by the C-DREEM

The C-DREEM was designed to improve the current cost estimation process used for earthquake damage repair work. Mainly, the model focuses on including the impact of the factors affecting CEEDRW that were identified by this study. Different methodologies and sections were used to include the impact of these 11 factors into the CEEDRW process. These methods and relevant sections are summarised in Table 6.5

Table 6.5 - Methods and sections of C-DREEM used to include the impact of key factors identified in the study

Factor no.	Factor	Considered section	Method of coverage (including the model reference numbers)
1	Consequential damage repair	Repair method identification (Section 3)	The repair method and its selection process includes the identification of impacts from consequential damage (3.05)
		Quantification of repair work (Section 4)	The quantity calculation process quantifies the impact of consequential damage (4.04)
2	The cost of professional services	Professional services and other costs (Section 8)	The main output of this section is the cost of professional services (8.16)
3	Type of contract	Costing (Section 7)	Profit and overhead percentages in rates are adjusted according to the type of contract (7.05)
4	Restrictions during repair work	Repair method identification (Section 3)	'Other influences' evaluation process considers incorporates the impact of restrictions on the repair method (3.09)
		Quantification of repair work (Section 4)	The quantity calculation and duplication deduction process quantify the impact of restrictions during repair work (4.04 and 4.06)
		Quantification of duration and start date (Section 5)	'Other influences' evaluation process considers the impact of restrictions on start date and duration (5.05)
		Quantification of preliminaries (Section 6)	'Other influences' evaluation process considers the impact of restrictions on preliminary items (6.04 and 6.06)

Factor no.	Factor	Considered section	Method of coverage (including the model reference numbers)
5	Aftershocks, earthquake-induced hazards and weather conditions	Post-earthquake state identification (Section 2)	Probable damage data gives partial indication of aftershocks and earthquake-induced hazards. Probability-based loss estimation tools will be used to extract the data (2.03).
			Details from damage inspection reports will be used to extract and include actual damage information (2.06).
6	Earthquake-induced high rates and price fluctuations	Costing (Section 7)	Calculated costs are adjusted according to EQ-induced price fluctuations, which include the impacts of start date and duration (7.11 and 7.15)
		Professional services and other costs (Section 8)	Calculated professional services and other costs are adjusted according to EQ-induced price fluctuations, which include the impact of start date and duration (8.09 and 8.12)
7	Repair time	Quantification of duration and start date (Section 5)	The main purpose and final product of this section is to calculate the impact of the repair time through the calculation of the start date and project duration (5.19)
		Quantification of preliminaries (Section 6)	The impact of the repair time (6.08) will be considered when quantifying the preliminary items that are impacted by repair time (6.07)
8	Initially unforeseen damage	Post-earthquake state identification (Section 2)	Probable damage data gives a partial indication of initially unforeseen damage. Probability-based loss estimation tools will be used to extract the data (2.04).
9	Changes to the required final state of the building	Repair method identification (Section 3)	'Other influences' evaluation process considers the impact of changes to the required final repair state on the repair method (3.08) (e.g., changes in regulations)
		Quantification of duration and start date (Section 5)	'Other influences' evaluation process considers the impact of changes to the required final repair state on the start date and duration (5.05)
		Quantification of preliminaries (Section 6)	'Other influences' evaluation process considers the impact of changes to the required final repair state on preliminary items (6.04 and 6.06)
10	Pre-earthquake state of the building	Pre-earthquake state identification (Section 1)	The post-earthquake survey and 3D point cloud will cover some of the variations between the as-built drawings and the pre-earthquake state. This will lead to the identification of pre-earthquake damage (1.02 and 1.03)
11	Substandard repair work	Pre-earthquake state identification (Section 1)	The relevant building regulations are compared with the current condition of the building to identify substandard repair work (1.10).

The C-DREEM also introduces new methodologies that were not used in traditional CEEDRW in New Zealand. In the damage identification process, traditional CEEDRW only considers damage that has been identified by DDE reports or site investigations. The C-DREEM improves this process by combining probable damage information, probability-based loss estimation tools and actual damage information to improve the accuracy of estimations. Furthermore, the C-DREEM also develops consequence functions that can be directly used by P-58 methodology-based pre-earthquake loss estimation tools. These consequence functions enable the C-DREEM to create a feedback loop whereby the consequence function outputs of C-DREEM can be checked against the consequence functions included in P-58 methodology-based tools. This verification process further increases the accuracy of both C-DREEM and P-58 tools through the continuous monitoring of the outputs.

Another drawback to traditional cost estimation is that ad-hoc rates are used for repair work-related costs, and quantities are calculated manually. In order to improve this process, the C-DREEM introduces a standardised set of micro rates. This minimises the need to develop new rates. Based on these standardised micro rates, the cost of relevant quantities calculated using 3D models can be calculated through an automated process. This process improves the speed of cost estimation and reduces error by minimising the need for human intervention. Section 9 monitors the final output of the standardised process and will indicate if there is an error.

A number of components of the C-DREEM require quantitative studies to be done within the construction industry where the model will be employed. These include: the building regulation and current building state comparison process (item 1.10 in section 1 of the C-DREEM); the impact of other influences on repair work (item 3.09 in section 3 of the C-DREEM); the impact of external factors on start dates and start date

calculation methods (item 5.13 in section 5 of the C-DREEM); the practical process of repair method sequencing (item 5.03 in section 5 of the C-DREEM); and earthquake-induced price fluctuation calculation formulae (item 7.15 in section 7 of the C-DREEM). Further research would lead to the full realisation of the internal process of these components.

6.6 C-DREEM development and validation

C-DREEM was developed to improve the current process used for CEEDRW. The aim of C-DREEM was to incorporate the identified factors that affected CEEDRW while increasing the speed and accuracy of the estimates. In order to achieve these aims, a four-step process was used, which included model development, model improvement, focus group process validation and focus group interviews. Contributions from each of these methods to the development and validation of the C-DREEM are discussed in detail in the following sections.

6.6.1 Validation of the C-DREEM development process

For the first part of the model development process, the TRIZ methodology was used as a systematic method of innovation and problem solving (refer to section 6.1 and methodology). The process identified the six most suitable innovative principles to improve the CEEDRW process while maintaining its current advantages. This TRIZ evaluation process revealed that key innovative principles could improve the CEEDRW process and incorporate the key factors identified in the research that affected CEEDRW. However, complexity and difficulty in use were identified as drawbacks. According to TRIZ methodology, such drawbacks were acceptable, as they

would not stop the model from achieving its intended goal. According to the literature review, the TRIZ process is a proven innovation method developed from an analysis of past patents to identify ways to create optimum solutions. Therefore, it can be agreed upon that the outputs of the TRIZ process, as applied to the development of the C-DREEM, are reliable and valid.

Once the innovative principle to be used had been identified, the initial model of the C-DREEM was developed using the information acquired from the literature review, interview data analysis, questionnaire data analysis, document analysis and inputs from builder and quantity surveyors. In other words, the developed model was based on both current knowledge gained from literature and practical insights gained from professional input. Therefore, it can be concluded that the C-DREEM model was built on a valid foundation in its initial development process.

6.6.2 Validity of model improvement sessions through expert discussions

For the C-DREEM to be valid and reliable, the evaluation process had to be valid and reliable. Nine professionals with experience in CEEDRW evaluated the drawbacks of each iteration of the C-DREEM and made upgrades. The upgrade process continued until a final model had been developed. Any model developed for a practical purpose should be validated by professionals with knowledge of current processes and their drawbacks. Since professionals with experience in cost estimation were used for the model iteration validation process, it can be agreed that the C-DREEM developed by this process is valid.

6.6.3 Validity of the focus group process validation

Once the model was developed, the C-DREEM was evaluated using a focus group interview. The literature shows that a focus group method can be used as an effective method for model evaluation (Caillaud & Flick, 2017). This study conducted separate sessions with a process validation team to evaluate the focus group interview process and the questionnaire used. The process validation team included the nine quantity surveyors involved in the model development process and two additional quantity surveyors in academia. Therefore, knowledge from professionals involved in the construction industry and academia was applied to in the focus group process validation.

6.6.4 Validity of the focus group process

Finally, the C-DREEM was evaluated using a different team of nine professionals consisting of quantity surveyors and an engineer. All members of this team had not been involved in previous stages of the model development process. Thus, participants held no bias towards the C-DREEM. Additionally, members of this validation team had an average of 26.1 years of experience in the construction industry and an average of 6.9 years of experience with CEEDRW. Participants involved in the validation process had experience working for a variety of organisations, government, private, client, consultancy, construction, insurance, and supply. Hence, the focus group participants can be considered to be experts in the field of cost estimation for earthquake damage repair work in New Zealand, and the results of their focus group evaluation process can be considered valid, up to date and reliable.

6.7 Validation of the C-DREEM model

The aim of the process of validating the C-DREEM is to verify and improve the suitability of the proposed model for estimating the cost of repairing earthquake-damaged buildings. The validation process focused on the following sections of the model.

1. Clarity of the framework
2. Basic concept
3. Categorisation of rates
4. Repair method classification
5. Automation
6. Overall system

6.7.1 Validation approach

As explained in detail in the methodology section, the study used a three-step process to validate the C-DREEM: model improvement sessions through expert discussions, focus group process validation and focus group interview. First, during the development stage of the model, different iterations of the model were validated continuously with nine expert participants. The participants of the improvement team were volunteers, of which, only three participants had been involved in previous data collections.

The second step of this validation process was the focus group process validation. An 11-member team was involved in the focus group process validation. This step of the validation process refined the content and process to be used in the subsequent focus

group interview in terms of required participants, the structure of the C-DREEM model, and examples used for explaining the C-DREEM and its system mechanics, and the questionnaire used for validation. The focus group process validation sought to refine the content, clarity, information flow and understandability of the model.

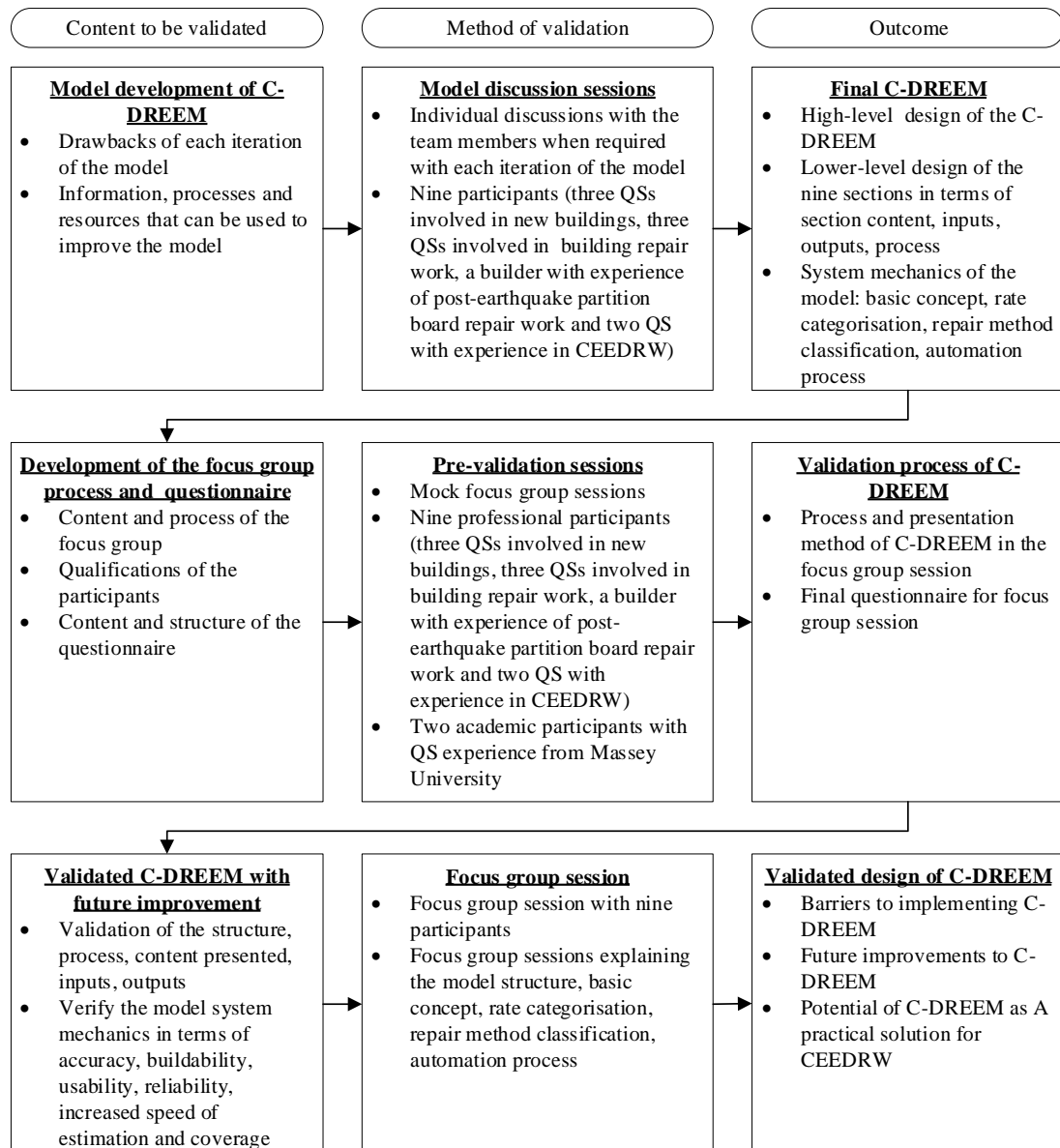
A focus group interview was conducted as the final validation step. Eight professionals with experience in CEEDRW and one engineer with experience in earthquake-related research participated in the focus group interview. These participants were selected from those who had responded to the survey and had not been involved in the model development process. Details of the experience, expert area and position of the participants in this focus group interview are included in Table 6.6. Further specific details of these participants are included in Appendix 8.

Table 6.6 - Focus group interview: participant profiles

Participant	Expert area	Position in the current organisation	Years of experience in the construction industry	Years of experience in CEEDRW
FR01	Quantity surveyor	Managing director	40	10
FR02	Quantity surveyor	Quantity surveyor	20	7
FR03	Project manager, Quantity surveyor	Consultant	63	6
FR04	Quantity surveyor	Director	20	10
FR05	Quantity surveyor	Quantity surveyor	17	4
FR06	Project manager, Quantity surveyor, Builder, Estimator	Building surveyor	39	10
FR07	Engineer	Research engineer	0	0
FR08	Quantity surveyor	Senior quantity surveyor	24	6
FR09	Quantity surveyor	Quantity surveying manager	12	9

The detailed methodological approach of the validation process is included in the methodology chapter and summarised in Figure 6.18.

Figure 6.18 - C-DREEM development and validation map



The following sections elaborate on the findings from the questionnaires that were completed by the nine participants involved in the focus group session.

6.7.2 C-DREEM validation results

Participants of the focus group were asked to comment and evaluate on the following aspects of C-DREEM:

1. Clarity of the framework
2. Basic concept
3. Categorisation of rates
4. Repair method classification
5. Automation
6. Overall system

6.7.2.1 Validation of C-DREEM framework

The participants were asked to consider specific statements regarding the ‘clarity of the framework’ and rate them according to their level of agreement. The framework relates to the functions of each section of C-DREEM. The rating scale ranged from 1 (Strongly Disagree) to 5 (Strongly Agree). Results from the questionnaire are shown in Table 6.7. More than two-thirds of the participants agreed or strongly agreed that the framework was clear in terms of structure, process, content, input requirements and output requirements. Additionally, two-thirds of the participants agreed that the C-DREEM could increase the speed of estimation and adequately cover all necessary variables required for CEEDRW.

Table 6.7 - Validation of the clarity of the framework (Participant views)

	1 Strongly Disagree	2 Disagree	3 Neither Agree / Disagree	4 Agree	5 Strongly Agree
The structure of the model is clear				5	4
				(56%)	(44%)
The model process is clear			1	5	3
			(11%)	(56%)	(33%)
The content presented in the model is clear			1	4	4
			(11%)	(44%)	(44%)

The input requirements for the model are clear		1	2	4	2
		(11%)	(22%)	(44%)	(22%)
The outputs of the model are clear			1	5	3
			(11%)	(56%)	(33%)
The model can increase the speed of estimation			3	3	3
			(33%)	(33%)	(33%)
The model adequately covers all necessary variables required for CEEDRW			3	6	
			(33%)	(67%)	

Participants were then asked to give reasons why they rated any of the above statements 1, 2 or 3. One participant (FR01) noted that further clarification was required regarding the allocation of responsibility for 3D model development, the process of initial assessments and the method to manage “...*conflicts of information in different engineering assessments*”. Another participant (FR05) added that homeowners need to be assured that the costing process used by the model is understandable and dependable, in order to “...*instil some trust*”. Two participants commented that “...*the system is complex*” (FR03) and that the C-DREEM process might take too long to estimate the costs of new projects (FR07).

Based on the previously mentioned drawbacks, the participants were given the opportunity to suggest methods that could be used to improve the model framework. Participants (FR03 and F07) stated that the process should be standardised, holistic and understood by everyone in order to reap the benefits of the framework. Other participants suggested additional features that the model should have. They wanted to see the C-DREEM as a tool that is usable “... *from a device in the field*” (FR04), developed on an online platform for information-sharing (FR06) and able to consider the impact from each new aftershock (FR05).

6.7.2.2 Validation of the basic concept of the C-DREEM

Next, the participants were asked to consider specific statements regarding the ‘basic concept’ of the C-DREEM and rate them according to their level of agreement. The rating scale ranged from 1 (Strongly Disagree) to 5 (Strongly Agree). Results from the questionnaire are shown in Table 6.8. Over three-quarters of the participants agreed or strongly agreed that the basic concept was clear, accurate, buildable, usable and reliable. Additionally, all participants agreed or strongly agreed that the basic concept can increase the speed of estimation. Two-thirds of participants also agreed or strongly agreed the basic concept adequately covers all necessary variables required for CEEDRW.

Table 6.8 - Validation of the basic concept of the C-DREEM (Participant views)

	1 Strongly Disagree	2 Disagree	3 Neither Agree / Disagree	4 Agree	5 Strongly Agree
The basic concept of the model is clear				5 (56%)	4 (44%)
The basic concept of the model is accurate			1 (11%)	2 (22%)	6 (67%)
The basic concept of the model is buildable			1 (11%)	5 (56%)	3 (33%)
The basic concept of the model is usable				6 (67%)	3 (33%)
The basic concept of the model is reliable			2 (22%)	3 (33%)	4 (44%)
The basic concept of the model can increase the speed of estimation				5 (56%)	4 (44%)
The basic concept of the model adequately covers all necessary variables required for CEEDRW			3 (33%)	4 (44%)	2 (22%)

Participants were then asked to give reasons why they rated any of the above statements as 1, 2 or 3 regarding the ‘basic concept’ of the C-DREEM. One participant (FR01) stated that there might be smaller work items like “...trims” that should be considered. Another participant added that there might be novel work items that are not captured by the model and that these items should be “*identified and costed accordingly*” (FR03).

Based on the stated drawbacks, the participants were given the opportunity to suggest methods that could be used to improve the ‘basic concept’. Participants did not mention any methods that could further improve the ‘basic concept’ of the C-DREEM.

6.7.2.3 Validation of the rate categorisation introduced in the C-DREEM

The participants were asked to consider specific statements regarding the ‘rate categorisation method’ used in the C-DREEM system mechanics and rate them according to their level of agreement. The rating scale ranged from 1 (Strongly Disagree) to 5 (Strongly Agree). According to Table 6.9, most of the participants (eight out of nine) agreed or strongly agreed that the rate categorisation was clear, accurate, buildable, usable and reliable. Additionally, three-quarters of the participants also agreed or strongly agreed that the rate categorisation adequately covers all necessary variables required for CEEDRW. All participants agreed or strongly agreed that the rate categorisation used in the system mechanics could increase the speed of estimation.

Table 6.9 - Validation of the rate categorisation method in the C-DREEM (Participant views)

	1 Strongly Disagree	2 Disagree	3 Neither Agree / Disagree	4 Agree	5 Strongly Agree
The categorisation of rates is clear				7	2
				(78%)	(22%)
The categorisation of rates is accurate			1	6	2
			(11%)	(67%)	(22%)
The categorisation of rates is buildable			1	5	3
			(11%)	(56%)	(33%)
The categorisation of rates is usable			1	5	3
			(11%)	(56%)	(33%)
The categorisation of rates is reliable			1	5	3
			(11%)	(56%)	(33%)
The categorisation of rates can increase the speed of estimation				4	5
				(44%)	(56%)
The categorisation of rates adequately covers all necessary variables required for CEEDRW			2	3	4
			(22%)	(33%)	(44%)

Participants were requested to give reasons if they rated any of the above statements regarding the ‘rate categorisation’ between 1 and 3. One participant (FR01) stated three actions that need to be taken as part of the rate development process: update the rates regularly, include an amount for allowances in the rates to cover smaller costs and use a generic rate to develop the specific rates to avoid major variations.

Based on the stated drawbacks, the participants were given the opportunity to suggest methods that could be used to improve the ‘rate categorisation’. One participant stated that repair methods considered in the model should “...comply with the minimum code requirements” (FR03).

6.7.2.4 Validation of the repair method classification adopted in the C-DREEM

Regarding ‘the repair method classification’ adopted in C-DREEM, the participants were asked to consider specific statements and rate them according to their level of agreement. The rating scale ranged from 1 (Strongly Disagree) to 5 (Strongly Agree). Most of the participants (eight out of nine) agreed or strongly agreed that the ‘repair method classification’ was clear, accurate, buildable, usable and reliable (refer to Table 6.10). Additionally, all participants agreed or strongly agreed that the ‘repair method classification’ adequately covers all necessary variables required for CEEDRW and can increase the speed of estimation.

Table 6.10 - Validation of the repair method classification adopted in C-DREEM (Participant views)

	1 Strongly Disagree	2 Disagree	3 Neither Agree / Disagree	4 Agree	5 Strongly Agree
The repair methods classification used in the model is clear				7 (78%)	2 (22%)
The repair methods classification used in the model is accurate			1 (11%)	4 (44%)	4 (44%)
The repair methods classification used in the model is buildable			1 (11%)	7 (78%)	1 (11%)
The repair methods classification used in the model is usable			1 (11%)	7 (78%)	1 (11%)
The repair methods classification used in the model is reliable			1 (11%)	6 (67%)	2 (22%)
The repair methods classification used in the model can increase the speed of estimation				5 (56%)	4 (44%)
The repair methods classification used in the model adequately covers all necessary variables required for CEEDRW				6 (67%)	3 (33%)

Participants noted reasons for rating statements from 1 to 3. One participant (FR01) stated that the builder might change the repair method to suit them. According to an example given by the participant (FR01), builders might rebuild a damaged partition wall rather than “...*patching up the repairs.*”

The participants were asked for procedures that could be used to improve the rate categorisation. One participant (FR06) stated that the repair method classification would improve with time following inputs from professionals. Another participant (FR09) suggested that the model should adopt standard repair methodologies that are used by the construction industry and will reduce the changes required. The aforementioned participant further added that these methodologies should be updated according to recommendations from “...*MBIE and other professional bodies*”.

6.7.2.5 Validation of the automation process in the C-DREEM

As the final step in the validation of the system mechanics of the model, the focus group participants were given statements regarding the ‘automation process’ designed for the C-DREEM and were asked to rate each statement according to their own level of agreement. The rating scale ranged from 1 (Strongly Disagree) to 5 (Strongly Agree). Over three-quarters of the participants agreed or strongly agreed that the ‘automation process’ was clear, accurate, buildable, usable and reliable (refer to Table 6.11). Additionally, most of the participants (eight out of nine) agreed or strongly agreed that the automation process adequately covers all necessary variables required for CEEDRW and can increase the speed of estimation.

Table 6.11 - Validation of the automation process developed for the C-DREEM (Participant views)

	1 Strongly Disagree	2 Disagree	3 Neither Agree / Disagree	4 Agree	5 Strongly Agree
The automation process of the model is clear			1	4	4
			(11%)	(44%)	(44%)
The automation process of the model is accurate			2	4	3
			(22%)	(44%)	(33%)
The automation process of the model is buildable			1	5	3
			(11%)	(56%)	(33%)
The automation process of the model is usable			1	4	4
			(11%)	(44%)	(44%)
The automation process of the model is reliable			2	4	3
			(22%)	(44%)	(33%)
The automation process of the model can increase the speed of estimation				5	4
				(56%)	(44%)
The automation process of the model adequately covers all necessary requirements for CEEDRW			1	4	4
			(11%)	(44%)	(44%)

Participants were asked to give reasons why they rated the above statements from 1 to 3. One participant (FR01) stated that the accuracy of the automation process totally depends on the accuracy of the inputs.

Based on the stated drawbacks, the participants were given the opportunity to suggest methods that could be used to improve the automation process. Participants mentioned that the automation process should not be, for example, “...*too cumbersome or involved*” (FR03). Another participant (FR08) stated that “*there will always be scenarios that do not match exactly*” and the model should consider the “... *individual parameters*” of each project.

6.7.2.6 Validation of the overall system of the C-DREEM

Once the total system had been explained, participants were asked about their opinion on the overall design of the C-DREEM. They were asked to rate statements using a rating scale that ranged from 1 (Strongly Disagree) to 5 (Strongly Agree) (refer to Table 6.12). More than half of the participants agreed or strongly agreed that the C-DREEM was user-friendly. Furthermore, all participants agreed or strongly agreed that the model will be useful in improving CEEDRW and that they would like to use a C-DREEM tool.

Table 6.12 - Validation of the overall system of the C-DREEM

	1 Strongly Disagree	2 Disagree	3 Neither Agree / Disagree	4 Agree	5 Strongly Agree
The model is user-friendly			4	3	2
			(44%)	(33%)	(22%)
The model will be useful in improving CEEDRW				8	1
				(89%)	(11%)
I would like to use a tool based on the proposed model				5	4
				(56%)	(44%)

Based on the overall system, a number of participants identified the following barriers to the implementation of the C-DREEM: the time and cost required for the software development process (FR08 and FR09) and the complexity of the model (FR04, FR06 and FR09). Another participant (FR03) stated that the usage of the model might drastically increase consultant fees.

The same focus group participants also offered the following suggestions to address these barriers: make the model readily available (FR01); develop the model into a software package (FR01); keep the model simple (FR03 and FR08); develop a user

manual (FR06); make the model even more ‘user-friendly’ (FR08); and actively solicit continuous feedback from the industry to keep the model up to date (FR09). Another participant (FR03) stated that, because the model is very detailed, it should be introduced in stages. This participant also suggested the use of a checklist to first establish the model and then develop the model using an “*ongoing working template*”.

Participants were then asked for their general opinion on the model and whether the model fulfilled their expectations. Two-thirds of the participants agreed that it fulfilled their expectations. Some of the comments given by the participants were: it makes an “*overall good impression and will improve when people use it*” (FR01), “*I think it has potential and will be useful for future situations*” (FR08) and “*It was probably better than what I had expected but it will be good to see it in a finished (software) state*” (FR09).

Finally, participants were asked if the proposed model could be a potentially practical solution suitable for commercialisation. Almost all the participants (eight of nine) stated that it should be commercialised. The remaining participant did not comment on the question. Additionally, two participants reiterated that the model should be developed into a software package (FR03 and FR09). However, one participant also added that methods used in the model should align with the current costing practices used in industry, saying:

“As an engineer, it comes down to its adoptability with the QS, especially how their current system and procedure aligns with the proposed developed model. Having a digital model could be another problem. However, technology is vastly changing.” (FR07)

Since the model was validated by experienced cost estimators, these remarks demonstrate the practical validity of the sections of C-DREEM, its internal components and overall design.

6.7.3 Suggested enhancements covered by improvements, further research and the software tool

Participants mentioned many enhancements that could be used to improve the C-DREEM. These suggestions can be divided into the topic areas of ‘improvements to the model’, ‘items that will be covered by the software development process’ and ‘future research’. These are summarised and expressed in Table 6.13. Limitations identified by the researcher are also included.

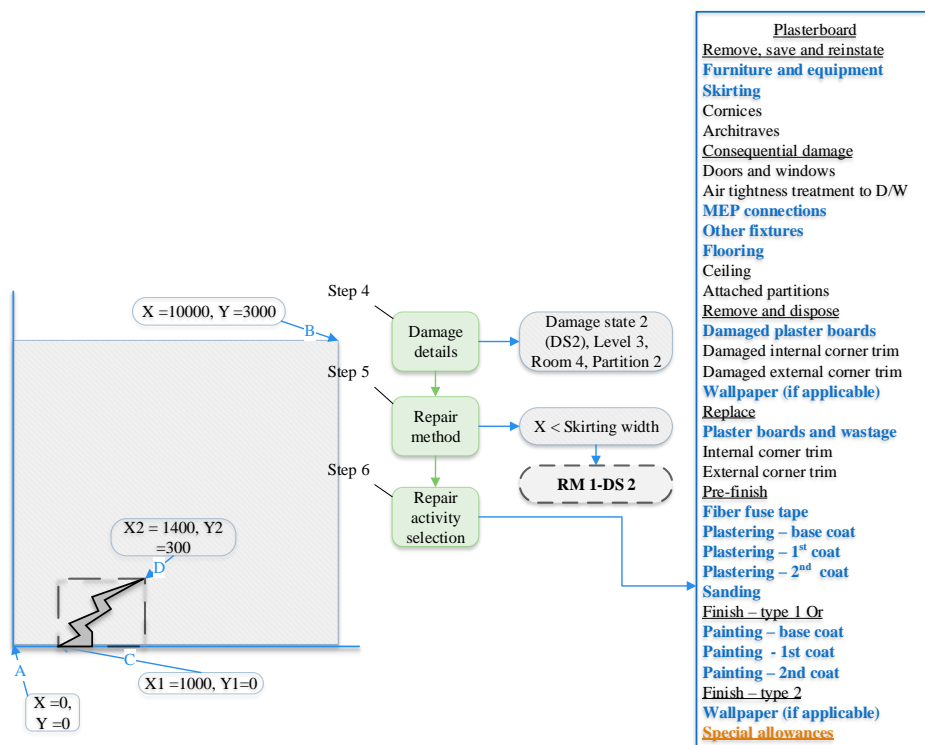
Table 6.13 - Suggestions for improvements, the software tool and further research

Method of coverage	Suggested enhancements
Improvements made to the model	The model has the ability to consider all items related to damage repair work. However, include an item for allowances to incorporate costs that are too small to calculate.
Software tool features	Simplify the process to make it easier to understand.
	Develop a holistic standardised procedure.
	Design model to be usable in the field.
	Include damage from aftershocks as they occur.
	Continuously update repair methods according to inputs from the construction industry and government bodies.
	Regularly update rates.
	Design so it is able to add ad-hoc rate breakdowns and repair methods which are not originally included in the model.
	Reduce the complexity of the model through better / more understandable software.
	Develop and provide a user manual.
	Plan a development process of manageable cost and duration.
Introduce the model in iterations, starting with a checklist.	

Method of coverage	Suggested enhancements
Further research	Predict and include the ad-hoc changes made by builders to repair methods so that the predictions made by the model are more realistic.
	Clearly define the 3D model development, and identify who is responsible for damage assessment and information verification.
	Develop methods to quantify changes to building regulations and include the impact of these changes in the model (item 1.10 in C-DREEM section 1)
	Identify and quantify other influences that impact the repair work (item 3.09 in C-DREEM section 3)
	Identify and quantify other influences impacting start date and start date calculation method (item 5.13 in C-DREEM section 5),
	Develop a practical process of repair method sequencing (item 5.03 in C-DREEM section 5)
	Develop an earthquake-induced price fluctuation calculation formula (item 7.15 in C-DREEM section 7)

One suggestion from the participants included above, that the C-DREEM should have an item to allow for items that are too small to cost has already been used to improve the model. The C-DREEM now includes a new item for ‘special allowances’ in its set of rates. This update is shown in orange in Figure 6.19.

Figure 6.19 - Updated automation process



Some suggestions made by participants will be covered by the software package to be developed to use the C-DREEM. The C-DREEM was identified as a complex system by a participant and from the perspective of TRIZ methodology (refer to Table 6.1 - TRIZ methodology-based approach for identifying innovative methods for CEEDRW). However, to achieve the intended goal, complexity was considered in the development process as an acceptable drawback that should be addressed in the development of the software package and user manuals. In particular, the resulting software should have the following characteristics: be easy to understand through a simplified process; have a holistic standardised procedure; be usable in field; include different types of damage (like aftershocks and earthquake-induced hazards) when they occur; allow for the continuous update of repair methodology according to changing industry standards; include regularly updated rates; and have the ability add ad-hoc rate breakdowns and repair methodologies that are not originally included in the model. Participants noted that a large amount of investment in money and time would be required for the software development process. Therefore, a cost-effective and time-efficient method should be identified for software development. Furthermore, the developed model should be introduced as an iteration so that the construction industry has the time to adapt and use the model without undue effort.

Some of the suggestions made by the participants cannot be currently implemented in the development of the model or software tool. These should be further researched. For example, participants gave a low rating for the clarity of input requirements of the framework. They stated that, in order to clarify a general understanding of the input requirements, they require the 3D model development process to be explained in greater detail. They also sought a clear indication of who is responsible for damage assessment and information filtration as conflicts between different sources of

information occur. As mentioned in the literature, 3D scanning technology is at an experimental stage as regards building damage evaluation (Jiao et al., 2019). In terms of responsibility for damage assessment and information filtration, this should be defined by the professionals involved in repair work or through a standard document. However, the researcher believes that these details are for further research and not part of the scope of this study.

As outlined in section 6.5.4, there are other functions that would benefit from further research that would result in the development of fully-realised internal processes to address these functions: the building regulation and current building state comparison process (item 1.10 in C-DREEM section 1); the impact of other influences on repair work (item 3.09 in C-DREEM section 3); the impact of external factors on start dates and start date calculation methods (item 5.13 in C-DREEM section 5); a practical process of repair method sequencing (item 5.03 in C-DREEM section 5); and earthquake-induced price fluctuation calculation formulae (item 7.15 in C-DREEM section 7).

6.8 Summary

In this chapter, processes used to develop and validate a C-DREEM process have been examined. The chapter describes the C-DREEM in detail, in terms of the system mechanics of the model and example processes, a high-level overview of the model and a complete description of its lower-level design. The improvements introduced by the C-DREEM were also discussed.

The overall feedback on the model framework and system mechanics was positive in terms of its clarity, accuracy, buildability, usability, reliability, coverage of necessary

variables required for CEEDRW and the potential to increase the speed of estimation. None of the comments identified errors in the framework of the model, its basic concept, its method of rate categorisation, the classifications used to identify repair methods or the automation process. However, the results of the validation process identified key ways to improve the model further, by developing the model into a software package, developing a guide, making the model user-friendly, introducing the model to the industry in stages, keeping the model simple, and continuously updating the model by soliciting and using feedback from the industry. The feedback from the participants was used to make immediate improvements to the C-DREEM, enhance future development of a software package and identify areas for future research.

Ultimately, the prevailing impressions of the model were positive. Additionally, results showed that the model does have the potential to be commercially viable and that the construction industry would strongly benefit from a software package based on the C-DREEM.

The next chapter discusses the research findings as they relate to the literature review.

7

DISCUSSION**7.1 Introduction**

The aim of this chapter is to present a discussion around the themes emerging from the research. Initially, this chapter discusses the current cost estimation processes used in NZ after the Canterbury earthquake sequence. The chapter then leads to an exploration of the 11 factors identified by the research in terms of current usage, significance and future usage methods. The dialogue also focuses on supporting the factors identified in the qualitative and quantitative research, using the literature review data and comparing the research results with the literature findings.

Thereafter, the processes of C-DREEM model development and validation are explored in terms of their contributions to achieving the intended aim of the model. The section flows to an examination of the DREEM model validation results regarding the six sections considered in the validation process.

The final section of the chapter focuses on the suggestions made by the participants to improve the model. The recommendations made by participants and researcher propositions are discussed and categorised into three sections: improvements to be made to the model, items to be covered in the development of the software package

and items for future research. The section concludes with a conversation on the importance of the model.

7.2 Current post-earthquake cost estimation models for earthquake damage repair work

The cost estimation process for earthquake damage repair work can differ by location, country, or era. This study mainly focused on the CEEDRW conducted after the CEQS in New Zealand. The detailed interviews were conducted with professionals who were involved in the earthquake damage repair work related to the CEQS. The analysis of the data revealed the characteristics of the cost estimation process used during that period.

The damage evaluation process started with rapid building assessments (RBA). The literature review reveals that the main objective of the RBA was to assess a building's safety for occupancy. According to the participants in the study, RBA reports were mostly used as checklists that provided a summarised output of building characteristics and inflicted damage (Ministry of Business Innovation and Employment, 2015). Results further revealed that RBA could not be used effectively for CEEDRW because the RBA was vague and simple by design, allowing for inspections to be conducted on a high volume of buildings in a short time. However, suppose the RBA can be improved to contain the information required for cost estimation while maintaining its core objectives. In that case, the RBA could be used as the initial source of information for CEEDRW.

Because the RBA was found unsuitable, the initial information source used for CEEDRW was the detailed damage evaluation (DDE). According to the literature

review, damage evaluations associated with the CEQS resulted in DDE, which was then used to develop CEEDRW (Wellington City Council, 2017). The results of this study revealed that the DDE was an initial point of information used for the cost estimation process during the CEQS. However, the DDE did not contain all the information required for CEEDRW. Therefore, contractors and clients conducted joint site investigations, which were used as the primary source of information for CEEDRW (refer to section 4.3). These site investigations were conducted after the detailed evaluations, and contractor selection process had been completed. This meant that the collection of this information required more time and additional professional input, prolonging the date by which a detailed cost estimate could be produced.

The interview data analysis also revealed that there was no standard damage evaluation method or process that contained all the information required for CEEDRW. Therefore, damage evaluations conducted by different professionals resulted in a range of outcomes. According to the participants, this process added considerable cost and was identified as one of the probable reasons that the earthquake damage repair work continued even until 2019. Therefore, this research revealed the need for a standard damage evaluation process. A standard process will be able to reduce the time required for damage evaluation by reducing errors and preventing the need for secondary evaluations. A standard process should also cater to the objectives of the RBA and DDE. However, such a process should be inter-connected, systematic and provide reliable information. The final aim of the process should be to provide the reliable information essential for CEEDRW and damage repair work.

7.3 Factors affecting estimated costs

In addition to the drawbacks associated with the information used for CEEDRW, 11 factors that had an impact on the CEEDRW were identified during the participant interview process in this study. The factors identified by the participants were verified using a literature review. The impacts of these factors are discussed as follows.

It is also important to understand the context of the cost estimation process in which these factors occur. The cost estimation process occurs after an earthquake where an earthquake damages the building through shaking and other earthquake-induced methods. Earthquake is also one of the unique types of natural hazard, as explained in section 2.3.10. Furthermore, the damaged buildings are not newly constructed, and the ageing buildings can range from 0 to 50 years or even more. Furthermore, the sudden demand created by the need to repair damaged buildings had overwhelmed the professionals in the construction industry and led to more professionals coming from other industries and countries was identified through the interview data analysis in sections 4.4.6 and 4.4.11. The New Zealand construction industry and its professionals did not have much experience in earthquake damage repair work and cost estimation. These factors were created as a compound effect that generated these novel variables, which include the requirement of construction methods different from new construction, the hidden nature of information required for estimation and difficulty in acquiring the required information. Based on this context, the following factors impacted the cost estimation process.

7.3.1 Consequential damage repair (F 01)

According to the participants, consequential damage to building elements was observed after the CEQS. Damage to other building elements caused by repair work on a particular building element is considered ‘consequential damage’. Additionally, damage to one building element can indicate damage done to other building elements. Consequential damage was not directly identified as a factor affecting cost estimations in section 2.5.3. However, it can be considered under the factor ‘project scope and complexity of design and construction’.

It has been noted in the literature that, during the CEQS, loose, broken and unstable brick chimneys, hot water chambers and heavy parapet walls damaged other elements, including electrical services, plumbing services, floors, roofs and other building elements (BRANZ, 2012; Dhakal, 2010). It is important to identify consequential damage because repairing some types of damage will require initially undamaged building elements to be repaired or replaced. Consequential damage associated costs might not be detected during initial damage inspections. However, once these costs are identified, scope and quantity variations can occur, resulting in an increase in costs. Therefore, the impact of consequential damage must be included in CEEDRW. This is a particularly important factor to consider. According to the survey questionnaire data, more than nine-tenths of the participants considered ‘consequential damage’ in past CEEDRW and wanted to consider that factor in future CEEDRW. Furthermore, upon statistical analysis, the ‘consequential damage’ factor also demonstrated a substantial weighted average of above four for its significance. These results indicate that consequential damage is a significant factor that was strongly considered in previous CEEDRW and should be included in models created for post-earthquake

CEEDRW, particularly because P-58 methodology-based tools do not directly consider them.

Despite the importance of consequential damage, interview data revealed that consequential damage was not included in CEEDRW at the initial stages because this type of damage was not identified at that stage. However, when the damage was identified, the cost of consequential damage repair work was included in estimates as a variation. According to the standard contracts used in New Zealand, the cost of variations can be estimated using agreed rates, adjusted agreed rates or by building up rates using actual costs, overheads and profit using a cost breakdown (Standards New Zealand, 2013).

Consequential damage might not be easily detected by tools based on the P-58 methodology, as such tools assess individual building elements to predict damage without considering inter-elemental impact (Applied Technology Council, 2018d). However, if the probabilistic model of a typical P-58 tool incorporated 3D modelling with virtual repair process simulations, consequential damage could be predicted and included in the cost estimation process.

It is important to note that survey questionnaire results indicate that consequential damage repair should be included in ‘contingencies’ or as a lump sum amount. The New Zealand standard contract 3910:2013 specifies that unknown expenditures should be included in the project cost as contingencies (Standards New Zealand, 2013). According to data from interviews and questionnaire responses, the cost of consequential damage repair work was substantial but could not be accurately predicted at the initial stages. This is a possible reason that many participants would choose to include these costs in contingencies. The other method specified, using a

lump sum amount, is a standard method used in cost estimation to estimate the cost of an item, therefore, in line with current practices (New Zealand Institute of Quantity Surveyors, 2018).

7.3.2 Cost of professional services (F 02)

Construction projects require input from building and associated professionals, in particular, those in design, architecture and engineering (DAE). Additionally, in instances where disputes can occur, legal and dispute resolution advice might be required.

The cost of professional services can become a significant share of total construction costs. A study conducted by Feldmann et al. (2008) in the USA expressed that the mean cost of architectural and engineering services associated with new construction can vary between seven and fifteen percent of the total project cost. According to a study in New Zealand on housing construction costs, the cost of professional services varies between three and four percent (Collins & Bealing, 2015). However, the analysis of the factors affecting traditional cost estimation did not identify the cost of professional service as a critical factor affecting cost estimations in section 2.5.3. Furthermore, section 2.5.3 did identify the ‘contract disputes’ factor, which directly relates to the cost of legal and dispute resolution services.

These costs of professional services associated with repair work can have a substantial impact on the total cost of such work compared with new construction. One reason could be that repair work generally requires additional professional inputs from geological engineers, structural engineers and lawyers to assess damage repair work and facilitate dispute resolution processes as part of the settling of insurance claims.

A study of 5,575 buildings conducted in Italy by Di Ludovico et al. (2017) on the reconstruction process after the L'Aquila earthquake revealed that the cost of DAE services could be between sixteen and seventeen percent of the total cost; this did not include the cost of legal services. In New Zealand, the *Paul Geoffrey Myall Vs Tower Insurance* high court case also considered the cost of professional services. In this case, the High Court ruled that an acceptable percentage to attribute to the cost of DAE services is, at most, fifteen percent. This percentage can be reduced to around seven based on increased project size (Paul Geoffrey Myall Vs Tower Insurance Ltd, 2017).

Analysis of the interview data showed that the cost of professional services associated with the CEQS was substantial. According to the participants, there were instances in which the total costs of professional services were around 30 percent of the total project cost. Participants added that, other than DAE services, legal services also amounted to a major portion of final repair costs. When compared to the percentage costs of professional services in new construction, this represents a major variation. Therefore, the cost of professional services should be included in CEEDRW.

Based on the analysis of survey questionnaire data, the extent to which the cost of professional services was considered in past CEEDRW was rated differently for each professional service. The cost of structural, geotechnical, architectural and quantity surveying services was considered by more than three-quarters of participants in past CEEDRW, and more than nine-tenths of participants indicated that these costs should be included in future CEEDRW. Under statistical analysis, these costs also obtained a high weighted average of above 3.2. These results indicate that structural, geotechnical, architectural, and quantity surveying services represented significant costs that were considered in previous CEEDRW and should be included in future CEEDRW.

Alternatively, less than a quarter of the participants considered the cost of legal and dispute resolution services in past CEEDRW. Statistically, responses relevant to these professions obtained a weighted average below 3. These ratings indicate that these costs were not considered by most in past CEEDRW and have less significance. However, the majority of participants indicated that these costs should be included in future CEEDRW.

One of the main reasons given for the lower ratings for these professions is that legal and dispute resolution services were only required for situations which were not typical for all repair work. For example, legal services would only be required when parties needed to claim their rights, and dispute resolution services were required when two parties disagreed about a claim and had reached a deadlock. These types of situations would typically occur during negotiations between the insurance companies and clients. As per the analysis of the interview data, the insurance companies would aim to reduce the payment amount as much as reasonably possible, while clients would aim to repair their houses to the highest possible standards. Additionally, disputes can arise due to the difficulty of separating pre-earthquake damage from earthquake damage. Substandard repair work might also require clients to hire legal services to claim funds for re-correction work. Therefore, legal services are likely to be highly involved as an essential service in the completion of earthquake-damaged building repair work. This could explain why most participants (60%) indicated that these costs should be considered in future CEEDRW. Therefore, we can conclude that all costs associated with professional services should be considered in a model developed for CEEDRW.

According to the literature, current methods calculate DAE services (F 02) as a lump sum amount, a percentage of total cost or a time-based rate (Association of Consulting

Engineers Engineering et al., 2017; New Zealand Institute of Architects Incorporated, 2018; New Zealand Institute of Quantity Surveyors, 2018). Current methods calculate legal services at an hourly rate, as a fixed amount or as a percentage of the settlement costs (New Zealand law society, 2020). According to the New Zealand International Arbitration Centre (2021) and the International Chamber of Commerce (2021), arbitration costs are calculated using the disputed amount, the number of arbitrators and the cost of administration. However, New Zealand elemental cost analysis standards and ANSMM 2018 deem that costs of DAE professional services should be included under ‘other development costs’ and should not be included in construction cost estimates, because these costs are not part of the project construction scope of work (New Zealand Institute of Quantity Surveyors, 2017; NZIQS et al., 2018). Additionally, the cost of legal and arbitration services is generally not included in an estimate because these costs are not common and occur only when the services are required. Furthermore, the analysis of tools based on the P-58 methodology revealed that the impact of the cost of professional services is not considered in loss estimation processes (Applied Technology Council, 2018d; Bradley, 2009).

Responses to the questionnaire in this study suggest the cost of professional DAE services should be included in CEEDRW as a lump sum amount or as a percentage of the total project cost, due to the substantial impact of such costs on post-earthquake damage repair work. These methods are in line with methods currently used to estimate the cost of professional DAE services.

Survey questionnaire results further indicate that cost of legal and dispute resolution services should be included as a lump sum amount or as a percentage of the total cost, which are similar to the methods used in current CEEDRW processes. Notably, participants also suggested including the cost in contingencies. This suggestion could

be based on the high probability of occurrence but unpredictable nature of legal and arbitration costs, which are, in some instances, calculated using the size of the dispute and the time required (New Zealand International Arbitration Centre, 2021; New Zealand law society, 2020).

7.3.3 Type of contract (F 03)

A construction project can engage in a fixed-price, remeasurement or cost-reimbursement contract (Cartlidge, 2017). These different types of contracts assign different levels of risk to the client or contractor.

In a fixed-price contract, the construction cost is fixed, and the contractor bears the risk of quantity variations. In remeasurement contracts, the quantity variation risk is borne by the client while the builder bears the variations of unit rates. Finally, in a cost-reimbursement contract, the client bears the rate and quantity variations (Ashworth & Perera, 2015; Brook, 2017; Cartlidge, 2017). According to the literature review on factors affecting cost estimation in section 2.5.3, 'type of contract' was also identified as a critical factor affecting cost estimation.

The profit percentage allocated to mark-ups can vary depending on the project risk, and thus can change the construction costs (Edyta Plebankiewicz & Leśniak, 2013). According to the aforementioned New Zealand court case, *Paul Geoffrey Myall Vs Tower Insurance Ltd* (2017), the maximum acceptable profit margin for repair work after the CEQS is deemed to be ten percent. This amount was allowed to change to accommodate variations associated with the need to engage specialised skills (Duncan Cotterill, 2017; *Paul Geoffrey Myall Vs Tower Insurance Ltd*, 2017).

According to the analysis of the interview data, different types of contracts were used in repair work related to the CEQS. The comments from the questionnaire further verified that the mark-ups used during the CEQS varied according to the type of contract. As an example, lump-sum contracts were said to involve a higher risk and higher mark-up. According to participants, contractors favoured cost-plus contracts because they had a lower risk for the contractor. Since even one percent added to the cost of a construction project can have a significant effect, the impact associated with costs depending on the type of contract should be considered in the CEEDRW process.

Responses to the survey questionnaire revealed that most of the participants had considered the 'type of contract' factor in their past CEEDRW (64%) and that they wanted to consider this factor in future CEEDRW (67%). However, statistically, the factor obtained a weighted average below 3 for its significance. As mentioned above, court rulings in NZ had already limited the maximum allowable margin and most projects selected contractors through non-competitive processes. These can be reasons for the low significance rating of this factor. However, these reasons were specific to the CEQS, and it must be noted that other situations may differ. Therefore, the impact on costs associated with changes in contract type should be included in the CEEDRW process.

While repair costs can be impacted by changes in contract type and type of contract was considered by post-earthquake CEEDRW, the analysis of P-58 methodology-based tools revealed that changes in mark-up are not considered by these tools (Applied Technology Council, 2018d; Bradley, 2009). However, survey questionnaire results indicate that profit margins should change according to the type of contract. This finding is consistent with findings in the literature, which confirm that different

types of contracts (F 03) resulted in different mark-up percentages (Dziadosz et al., 2015).

7.3.4 Restrictions during repair work (F 04)

Participants in the interview sessions revealed that restrictions like building occupancy during repair work were a common occurrence after the CEQS. Occupancy of a building can impact the repair work process (Applied Technology Council, 2018c). According to Ward et al. (2017), the time and cost required to repair a building while it is occupied can be higher. Additionally, precautionary measures might have to be taken for damaged buildings, due to health and safety issues that require access restrictions (Applied Technology Council, 2018c). Even though this factor was not directly identified in in section 2.5.3 under factors affecting traditional cost estimation, it can be considered under the ‘method of construction and construction technique’ factor.

Interview participants supported these findings by revealing that project costs and duration increased due to these restrictions. Participants stated that, in some instances, the duration of a project increased by 50 percent due to building occupancy. The repair work cost also increased due to additional preliminary and general items being required and durations of projects being prolong. Restrictions during repair work including occupancy and hazards were also identified by probabilistic loss estimation tools (Applied Technology Council, 2018c). Therefore, CEEDRW should consider the impact of restrictions during repair work.

According to the survey questionnaire, the majority of participants (68%) included the impact of restrictions during repair into their past CEEDRW, and, statistically, this

factor obtained a high weighted average of 3.70 for its significance to CEEDRW. Additionally, more than three-quarters of participants (78%) indicated that the impact of restrictions during repair should be included in future CEEDRW. This high significance level, inclusion in past CEEDRW by the majority of participants and an intention to consider this factor in future usage indicate that the restrictions during repair should be considered by a model developed for CEEDRW.

The traditional CEEDRW process did include the impact of restrictions during repair work, but only when it was identified as a variation. Variations were calculated using agreed rates, adjusted agreed rates or by building up rates using actual costs, overheads and profit using a cost breakdown (Standards New Zealand, 2013). The impact of restrictions during repair work were identified by P-58 methodology-based tools (Applied Technology Council, 2018d). However, these P-58 methodology-based tools required manual input of data to calculate the impact of restrictions. Results from the survey questionnaire indicated that restrictions during repair work (F04) should be calculated using the unit rate method or a lump sum amount. According to ANSMM 2018, the use of the unit rate method or a lump sum amount is the most common method used to estimate construction costs (NZIQS et al., 2018).

7.3.5 Aftershocks, earthquake-induced hazards and weather conditions (F 05)

Interview data analysis revealed that damage from aftershocks, earthquake-induced hazards and weather conditions was observed after the CEQS. A review of the literature verified the above findings and indicated that many incidences of post-earthquake damage resulted from liquefaction and aftershocks (Potter et al., 2015), fire (G. B. Baker et al., 2012) and flooding (Davis et al., 2015) detected after the CEQS. Even though damage from aftershocks, earthquake-induced hazards and weather

conditions are not typical in traditional construction and thus not identified in section 2.5.3, the impact of these factors could be attributed to ‘likely scope changes’ and ‘ground and site conditions’ factors.

According to interview data, liquefaction was considered as earthquake damage and included in the CEQS related CEEDRW processes. However, according to the *Tower Insurance Ltd v Earthquake Commission New Zealand* high court case (2011) and analysis of interview data, aftershocks, fire and inundation damage required secondary evaluations. Secondary evaluations were conducted to identify whether an earthquake had, in fact, directly caused the damage.

Additionally, the review of the literature revealed that internal elements of a building with external fabric compromised by an earthquake could be damaged by typical weather conditions like snow, wind and rain (Inland Marine Underwriters Association, 2001). Prolonged exposure to weather conditions can easily damage building elements such as electrical services, electrical equipment, internal plasterboards and furniture.

Data from interviews and the survey questionnaire supported this notion and further demonstrated that these types of damage complicated the CEEDRW process. As examples, these types of damage required additional work like temporary covering, were considered as separate claims, created continuous damage to buildings and required re-evaluating the building after each occurrence. Therefore, aftershocks, earthquake-induced hazards and weather conditions had a significant impact on post-earthquake repair cost and time.

The survey questionnaire indicated that damage from fire, floods and weather conditions was considered by most participants (at 60%, 68% and 64%, respectively) in past CEEDRW, and nearly half of participants considered the damage from

aftershocks (45%) in past CEEDRW. Statistically, these damage types obtained a low weighted average for their significance on CEEDRW, with all below 3. The following research findings can be used to elucidate the reasons for the low usage and significance rating of the aforementioned types of damage in cost estimations. The literature review, interview data and survey questionnaire data all demonstrated that damage from aftershocks, fire, floods and weather conditions were considered as new earthquake events. This is clearly evident from the *Tower Insurance Ltd v Earthquake Commission New Zealand* high court case (*Tower Insurance Ltd v Earthquake Commission*, 2011). Hence, the damage created by these types of earthquake-induced damages had to be re-evaluated and re-estimated. Therefore, cost estimators might not consider the impacts of types of damages in CEEDRW, as these events can be considered as variations after they have occurred.

Despite this, the majority of the participants indicated that damage from aftershocks (60%), fire (65%), floods (64%) and weather conditions (66%) should be included in future CEEDRW. The substantial impact observed from these types of damage can be a reason for this. Therefore, the impact of these factors should clearly also be included in future models used for CEEDRW.

Analysis of P-58 methodology-based models indicated that the impact of main shocks and aftershocks was considered by P-58 methodology-based tools. As mentioned above, traditional CEEDRW included the impact of these types of damage as separate events only when they were identified. When identified, these costs were calculated according to a standard method of measurement (SMM) and conditions in the contract as variations using agreed rates, building up rates using current rates or building up actual costs using cost breakdowns (Standards New Zealand, 2013). Similarly, the survey questionnaire results suggest including the impact of these types of damage into

CEEDRW using a unit rate method similar to methods used in post-earthquake CEEDRW. The results also suggested including the cost impact of the factor in contingencies. One of the reasons participants suggested including this cost in contingencies could be the substantial impact on CEEDRW by such damage, and CEEDRW should have an indication of this impact.

7.3.6 Earthquake-induced high rates and price fluctuations (F 06)

According to the interview participants, increased rates and abnormal price fluctuations were evident after the CEQS, resulting in wide variations in cost estimates. The sudden disparity between supply and demand caused by an earthquake can create corresponding sudden growth in construction costs, defined as a demand surge (Döhrmann et al., 2017).

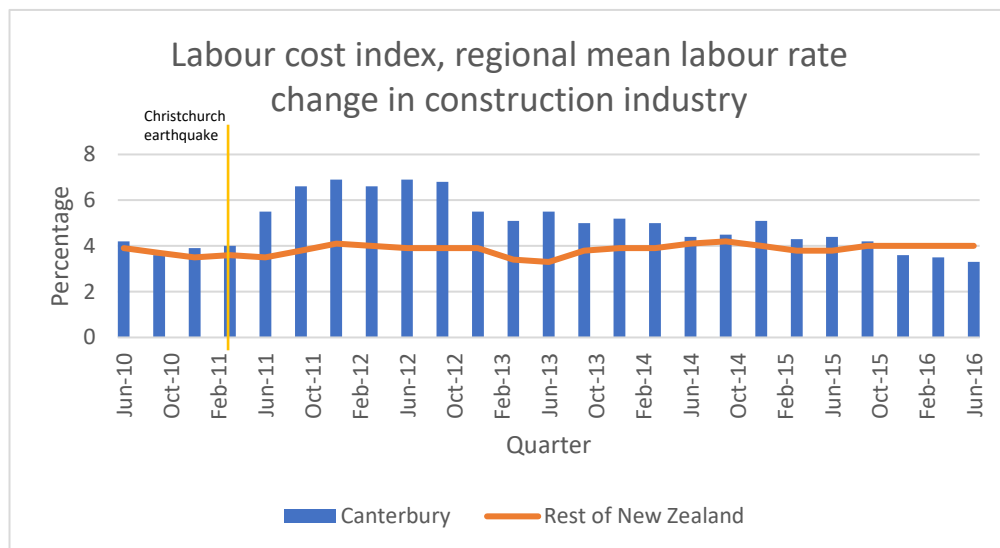
The client or the builder has to bear the risk of a surge in demand. When the builder bears the impact of such a surge, their cost estimation should include the impact of these variations. If the client bears the risk of price fluctuations, the construction price can be adjusted according to the changes in market prices. While previous research on models that can estimate price fluctuations caused by disasters exists (Ahmadi & Shahandashti, 2018; Khodahemmati & Shahandashti, 2020; Olsen & Porter, 2013), examples for the practical usage of the models studied were not identified through the literature review.

A surge in demand after disasters was witnessed after the Wenchuan earthquake in China (Chang et al., 2012) and the CEQS in New Zealand (Statistics New Zealand, 2018); such surges are also associated with weather-related disasters in the USA (Ahmadi & Shahandashti, 2018). According to Olsen and Porter (2013), 50 and 20

percent increases in costs were observed after the 2006 Cyclone Larry in Australia and the 1994 Northridge earthquake in the USA, respectively. In section 2.5.3 relating to factors affecting traditional cost estimation, earthquake-induced high rates and price fluctuations could be attributed to ‘price fluctuations’ and ‘quality, prices, and availability of resources’ critical factors.

Data from Statistics New Zealand (2021) revealed a sudden increase in labour rates in the construction sector after the CEQS (Figure 7.1). Stephenson (2013) states that labour cost escalation can be attributed to the deviations in demand compared to the labour supply, buyers' preparedness to pay higher costs and higher wages required to attract skilled labour from other regions.

Figure 7.1 - Labour cost index showing regional mean labour rate change in the construction industry in Christchurch and rest of the New Zealand (Statistics New Zealand, 2021)



Interview data supported the findings in the literature, offering examples of labour cost escalation related to the CEQS arising from specific circumstances, such as the lack of availability of qualified, skilled labourers and the recruitment by government

organisations of professionals from other regions like the North Island of New Zealand and from other countries like the UK and Ireland.

Additional reasons for increased rates for repair work were identified through the analysis of interview and survey questionnaire data. Participants attributed higher labour costs to: unjustified arbitrary rates used by contractors, the higher level of difficulty of post-earthquake repair work, economies of scale increasing the cost of the repair of work items with small quantities, the high wastage of resources during repair work, the additional time required to understand suitable repair procedures, the lack of repeatable work procedures and the increased professional inputs required. Interview data analysis further revealed that there was a 20 to 30 percent increase in housing repair construction costs after the CEQS. Therefore, earthquake-induced high rates and price fluctuations have a substantial impact and should be included in CEEDRW.

This is particularly true, given that price fluctuations are intertwined with the determination of a project's start date. The project start date sets the agreed rates related to construction costs. This can then be affected by anything that prevents the start of repair work, such as the need for: specialised equipment that requires a long lead time to procure, building damage inspections, finance acquisition, DAE input, building and planning permits and the selection of a contractor (Almufti & Willford, 2013).

Analysis of the interview and survey questionnaire data also revealed reasons that delayed the start dates of projects, including: unavailability of contractors, delays to required policy changes, delays in vacating the building, re-evaluation required after major aftershocks and delays to the approval of funds. Participants noted that a

project's start date could vary from the estimated date and that cost estimates can, in turn, be vulnerable to any price fluctuations.

Furthermore, according to the survey questionnaire data, earthquake-induced high rates and price fluctuations had been considered by more than three-quarters of the participants in past CEEDRW, and the vast majority of participants (87%) suggested the factor be considered in future CEEDRW. Statistically, this factor also obtained a high significance rating of above 3.5, indicating that earthquake-induced high rates and price fluctuations were highly considered in previous CEEDRW. An increase in the rating to include future CEEDRW further supports this notion. Therefore, earthquake-induced price fluctuations should be included in models created for post-earthquake CEEDRW.

Regarding the price fluctuations (F 06), the construction contract would determine the method used to include its impact. In the New Zealand standard contracts, price fluctuations can be excluded, adjusted according to published indices or adjusted according to ad-hoc methods (Standards New Zealand, 2013). Indices published by Statistics New Zealand (2021) are issued quarterly and published according to market changes. Therefore, any unforeseeable price fluctuations will be adjusted only after they have made an impact. Furthermore, interview data show that earthquake-induced high rates and price fluctuations were controlled during the CEQS using a schedule of rates during the tender evaluation stages. According to the analysis of P-58 methodology-based tools, earthquake-induced price fluctuations were not considered in cost-estimation processes (Applied Technology Council, 2018d; Bradley, 2009). However, the analysis of survey questionnaire data indicates that the most suitable methods to include the impact of earthquake-induced price fluctuations are to allow price variations according to published price indices or to change costs according to

market rates. These suggestions are similar to the methods suggested by the literature. The deviation questionnaire results and the methods employed after CEQS, which controlled the price fluctuations, could be due to the unpredictable nature of earthquake-induced price fluctuations.

7.3.7 Repair time (F 07)

Repair time is directly related to repair costs and comprises the start date and repair duration. The start date is directly affected by price fluctuations (discussed under F06); a change in start date can lead to a significant change in total cost. Repair duration has a direct impact on preliminary items that are related to the overall project, and can be increased due to restrictions during repair (Applied Technology Council, 2018c). Section 2.5.3 also identified repair time as a factor affecting traditional cost estimation.

Analysis of the interview data indicated that the vast majority of housing repair projects conducted after the CEQS were not completed within the estimated durations due to: scope changes during construction, contractor inexperience and inability, delays in professional inputs and delays in approvals. Since time-related costs depend on the duration of a project, it is vital to consider and accurately estimate the project's duration in the CEEDRW.

According to the survey questionnaire results, the vast majority of participants indicated that they had considered the duration of repair work in past CEEDRW (88%) and that this should be considered in future CEEDRW (92%). Statistically, this factor can be considered significant because it obtained a high weighted average (3.84). This high significance rating, inclusion in past CEEDRW by most participants, and

identification of usefulness in future usage indicate that a model developed for CEEDRW should consider the duration of the repair.

According to the literature, different methods can be used to estimate the duration of a construction project. These include Bromilow's time and cost model (Bromilow, 1969), the critical path method (Newitt, 2009; Project Management Institute, 2014), the program evaluation and review technique (PERT) (E. Plebankiewicz et al., 2015; United States Bureau of Naval Weapons Special Projects Office, 1958) and Monte Carlo simulations (Kwak & Ingall, 2009; Project Management Institute, 2014). Of the aforementioned methods, the critical path method is the most commonly used in construction projects to estimate duration. Analysis of P-58 methodology-based tools revealed that these tools estimated the duration of repair work, but did not consider the impact of repair time in the cost estimation process (Applied Technology Council, 2018d; Bradley, 2009; Haselton Baker Risk Group, 2020).

Alternatively, interview data analysis revealed that different methods were used to estimate the duration of the repair work project after the CEQS, including the total project cost, total labour hours and professional experience. However, the results of the survey questionnaire data suggest that professional experience and the total anticipated number of repair hours should be used to estimate repair time in CEEDRW. These results are similar to those found in the analysis of interview data but deviate from literature findings, perhaps because the methods presented in the literature are not practically usable in repair work due to the nature of repair activities.

7.3.8 Initially unforeseen damages (F 08)

Earthquake damage to building elements can be hidden. This initially unforeseen, or concealed damage is usually discovered through destructive testing or during repair work (Clifton et al., 2011; Galloway & Hare, 2012). The literature has shown that the identification of new damage and resulting changes in cost estimation were evident during rehabilitation work after the CEQS (Robertson & Woods, 2019). The analysis of the factors affecting traditional cost estimation in section 2.5.3, did not directly identify the initially unforeseen damages as factors. However, it can be attributed to the factors; ‘quality of assumptions used in preparing the estimate’, ‘clear and detailed project documentation’ and ‘project scope and complexity of design and construction’.

Analysis of the interview data also revealed evidence of initially unforeseen damage after the CEQS, with descriptions of cost variations of 100 to 150 percent observed in some instances. Therefore, it is necessary to predict and include the impact of unforeseen damage in CEEDRW.

According to statistical analysis of the survey questionnaire data, initially unforeseen damage obtained a noteworthy weighted average of 4.22 for its significance on CEEDRW. Furthermore, the vast majority of participants indicated that initial unforeseen damage was considered in past earthquakes (86%) and was deemed worth including in future CEEDRW (84%). It is interesting to note this two percent difference in the percentage of participants who advocated the usage of this factor in future cost estimation when compared to past inclusions in CEEDRW. According to the New Zealand standard conditions of contract for buildings, initially unforeseen damage (F08) is typically not included in cost estimation (Standards New Zealand, 2013). When identified, this type of damage is included as variations, claims or scope

changes, which would be calculated using agreed rates or adjusted agreed rates, or by building up actual costs. These costs also include claims for additional time, overheads and profits. This could be a reason for the reduction in the number of participants intending to include initially unforeseen damage in future estimations. Regardless, it is clear that initial unforeseen damage should be included in a model built for CEEDRW.

In terms of how to incorporate these costs, results from survey questionnaire data suggest that unforeseen damage should be included using contingencies, as a percentage of the total cost or a lump-sum amount. The high likelihood of occurrence and the impact of initially unforeseen damage could be one reason for including it in CEEDRW. Including this factor in contingencies could address the lack of detail in damage observation at preliminary stages while having an indication of potential impact. Given further details, a percentage of the total cost or a lump-sum amount can be used to include estimations of unforeseen damage with higher accuracy.

The literature shows that P-58 methodology-based models consider probabilistic damage using past and experimental data (Applied Technology Council, 2018c), which could capture initially unforeseen damage. However, outputs from P-58 methodology-based models can differ from the actual damage. That noted, when compared to the process used to identify initially unforeseen damage in the CEQS, the use of probabilistic damage estimation methods can be advantageous. Therefore, probabilistic damage estimates from P-58 tools could well be used to include the impact of initially unforeseen damage in contingencies until verified.

7.3.9 Changes to the required final state of the building (F 09)

The cost of construction is highly dependent on the final output required. Changes in the final required state or design may affect final repair costs (Doloi et al., 2012; Gebrehiwet & Luo, 2017; Kim et al., 2018; Sohu et al., 2017). Interview data analysis revealed two main causes for such changes in repair costs associated with the CEQS: changes to the building code and stakeholder influence. Changes in government regulations was directly identified as a factor affecting cost estimations in section 2.5.3. Even though both owner and insurer influence are not directly identified, the factors ‘type of client’ and ‘financial capability of the owner’ can relate to the impact of this factor.

Previous studies have identified that changes to building codes, which define how repair work should be conducted in a country, can impact the cost estimation of buildings (Doloi et al., 2012; Shash & Ibrahim, 2005). The expected lifetime of a building is 50 years (Faqih et al., 2020; New Zealand Building Act, No. 72, 2004). During the lifetime of a building, the building code can change, and an earthquake can occur at any stage of that building’s expected life span. If the current building codes are different from the building codes used in the construction process, it can result in changes to the final repair state required to meet the codes. For example, in New Zealand, between 1992 and 2019, the B1 (structure) section and the B2 (durability) section of the building code changed 16 and 12 times, respectively (Ministry of Business Innovation and Employment, 2019a, 2019b). Therefore, it is likely that building codes will continue to change and impact the CEEDRW process. Previous research also expressed that building regulations had a major impact on building demolitions after the CEQS (Marquis et al., 2017). Results from the analysis of the

interview data gave further examples of buildings (or parts of buildings) required to be repaired in accordance with the most current NZ building code.

The likelihood of changes to building codes will require the CEEDRW process to compare as-built construction standards and current construction standards to select the most rational repair methodologies applicable. Additionally, the survey questionnaire data further revealed participants' predictions that fewer changes would be required if repair work was conducted immediately after an earthquake because building code changes tend to be implemented after the earthquake's impact has been analysed. It is important to note that insurance policies generally did not include a betterment clause, so like was to be replaced with like. However, modern construction practices that may require an engineered design will dictate the final code-compliant repair strategy to meet current building code requirements.

Analysis of the interview data revealed many examples in which the stakeholders had a significant effect on CEEDRW. In these examples, the influence of funding agents and building owners changed the repair methods. The literature review also revealed the influence of stakeholders on construction work (Doloi et al., 2012; Luo et al., 2017; Memon et al., 2010; Sohu et al., 2017). The influence of insurers, in particular, after the CEQS was also identified by previous research which demonstrated that insurer requirements had a major impact on building demolitions after the CEQS (Marquis et al., 2017). Therefore, it is evident that changes to the final expected repair state can substantially impact the CEEDRW and will require specific cost breakdowns and cost estimation methods.

This factor, 'changes required to final repair state to meet statutory compliance', was considered by 95 percent of survey questionnaire respondents for both past and future

CEEDRW and, statistically, obtained a weighted average of 4.45 for its significance to CEEDRW. This factor was the highest-ranked factor for past and future consideration in CEEDRW and the second-highest ranked factor in significance. Therefore, changes required to the final repair state to meet statutory compliance should certainly be considered by a model built for CEEDRW.

Interestingly, the factor, ‘changes required to final repair state to meet stakeholder requirements, was considered by almost half of participants (55%) in past CEEDRW and a majority of participants (66%) indicated that it should be included in future CEEDRW. It also had a low significance rating, with a weighted average below 3. Minor changes made by stakeholders within the scope of work would be considered as variations and major changes would be considered as scope changes. These changes have typically been included in CEEDRW only when they have occurred. This could be a reason for the low rating of the factor when compared to ‘changes required to final repair state to meet statutory compliance’. However, as explained previously, changes made by stakeholders do have a significant impact on CEEDRW. Furthermore, as per the aforementioned results, a majority of participants considered the factor in past cost estimation, and the increase in the number considering it for the future indicates its importance. Therefore, changes required to the final repair state should also be considered in a model built for post-earthquake CEEDRW.

According to the standard conditions of contract NZS 3910, changes required to the final repair state (F 09) can be considered as a variation, a claim or scope change when identified (Standards New Zealand, 2013). According to the standard conditions of NZS 3910, these changes can be calculated using agreed rates, adjusted agreed rates or by building up actual costs. However, these changes were not captured by the P-58 methodology-based tools, as they only focus on the as-built conditions of the building

(Applied Technology Council, 2018d; Bradley, 2009; Haselton Baker Risk Group, 2020). Alternatively, research participants suggested the use of a unit rate built by cost breakdowns or a lump sum amount in CEEDRW, similar to the current methods used in the traditional cost estimation process.

7.3.10 Pre-earthquake state of the building (F 10)

During its life span, a building can deviate from its as-built conditions. Such deviations can occur due to poor maintenance, external weather, wear and tear and user abuse (Faqih et al., 2020; Wahida et al., 2012). However, these defects and damaged items also generally need to be repaired to meet statutory requirements during the earthquake damage repair process. Pre-earthquake damage might also need to be considered separately in CEEDRW, as insurance policies do not cover pre-earthquake damage (Chawynski, 2019). The incidence and cost of insurance-funded repair work were substantial during the CEQS, where the number of cumulated insurance claims was NZ \$21 billion, representing 52 percent of the total loss (Insurance Council of New Zealand, 2019).

Interview data analysis showed that pre-earthquake damage significantly impacted the CEEDRW because such damage was not repaired under the earthquake damage claims, which covered a substantial number of the building repair projects after the CEQS. Therefore, damage identification efforts initiated by insurance and government funds require that earthquake damage be differentiated from pre-earthquake defects and damage.

According to the analysis of the interview data, it was difficult to differentiate between earthquake and pre-earthquake damage. The difficulty was, in part, attributed to the

fact that the indicators typically used to identify historical damage (e.g. moss) and earthquake damage (e.g. cracks) could be misleading or covered up by temporary repair works. Due to its impact on repair work, the pre-earthquake state of the building should be considered in the cost estimation process. Even though the pre-earthquake state of the building is not typical in traditional construction and thus not identified in section 2.5.3, the impact of these factors could be attributed to ‘likely scope changes’, ‘project scope and complexity of design and construction’ and ‘ground and site conditions’ factors.

According to the survey questionnaire, the pre-earthquake state of the building was considered by three-quarters of the participants in past CEEDRW and obtained a high weighted average (3.67) for its significance in CEEDRW. These ratings indicated that pre-earthquake damage has a high impact on CEEDRW. The majority of participants also indicated that this factor should be included in future CEEDRW. However, data revealed a 16 percent reduction in future usage rating when compared to past usage. The pre-earthquake state is typically not considered by insurers as a part of earthquake damage repairs. Therefore, the cost estimator would exclude pre-earthquake state in cases in which an insurance claim funded the repair work. This could be one of the main reasons participants indicated they would be less likely to consider this factor in the future. However, the majority of participants did indicate that a building’s pre-earthquake state should be included in future estimations. Therefore, the post-earthquake cost estimation model should consider the pre-earthquake state in the CEEDRW process.

According to an analysis of the interview data, pre-earthquake damage is typically not included in cost estimates funded by insurers because an earthquake did not cause these damages. P-58 methodology-based models also did not consider the impact of

the pre-earthquake state of the building (Applied Technology Council, 2018d). However, building owners are expected to meet statutory requirements when the building is repaired. Therefore, this pre-earthquake damage requires a separate cost estimation. According to ANZSMM and NRM 2 standards, the separate cost estimation of pre-earthquake damage can be calculated using a unit rate method (NZIQS et al., 2018; Royal Institution of Chartered Surveyors, 2009). Analysis of the questionnaire data revealed support for a unit rate method or a lump sum amount, standard methods used in cost estimation (NZIQS et al., 2018), to include the impact of pre-earthquake damage repair costs.

7.3.11 Substandard repair work (F 11)

Substandard construction work has been identified as an impactful factor on cost estimations related to new construction (Alumbugu et al., 2014; Hatamleh et al., 2018; Shash & Ibrahim, 2005). The repair work conducted after an earthquake may also not be up to the required standard. According to Cretney (2019) and Price and Peters (Price & Peters, 2015), substandard repair work was identified in the repair work conducted after the CEQS. These substandard repairs required secondary damage identification and a revised repair work process.

Analysis of the interview data supported this notion. Participants mentioned that it was not uncommon for a second round of repair work to be conducted after the CEQS. Reasons for substandard repair work included differential and incorrect input from professionals, weaknesses of contractor capabilities and incapability of supervisors. Secondary repair works added cost and time, as evidenced by interview and survey questionnaire data analysis. As an example, participants described cases in which initial repair work hid the actual damage indicators such that additional destructive

testing was required to identify the original damage. Section 2.5.3 did not identify the impact of the substandard repair work from the literature review of factors affecting cost estimation. However, ‘capability and capacity of the consultants/estimators’, ‘capability and capacity of the contractor’ and ‘ground and site conditions’ factors could partially cover the impact of substandard repair work.

According to the survey questionnaire, substandard repair work was considered by 65 percent of the participants in past CEEDRW, and 75 percent of the participants indicated that it should be included in future CEEDRW. Statistically, the factor obtained a weighted average of 3.71 for its significance on CEEDRW. Typically, the cost estimate does not consider substandard repair work because it is circumstantial. However, the post-earthquake repair work era created a unique environment in which high volumes of difficult and unique repair work were conducted in a short period of time, and in which the aforementioned influences could lead to substandard repair work being done. In the light of this experience, the significance of substandard repair work on CEEDRW, the majority of participants considering the factor in past CEEDRW and the 10 percent increase in the number of those planning to consider this factor in the future, it is clear that substandard repair work should be included in CEEDRW. Therefore, a model built for post-earthquake CEEDRW should include the impact of substandard repair work.

A review of the P-58 methodology-based models revealed that these models did not consider substandard repair work (Applied Technology Council, 2018d, 2018b; Haselton Baker Risk Group, 2020). However, interview data revealed that substandard initial repair work resulted in secondary repair after CEQS and that this secondary repair was considered as a separate event, when identified. According to standard cost estimation practices, these costs were evaluated using an SMM, which typically uses

a unit rate method or, in some instances, a lump sum amount, to evaluate the total cost (NZIQS et al., 2018). Similarly, analysis of the survey questionnaire data also revealed that a unit rate method or a lump sum amount would be the most suitable methods for including the impact of substandard repair work.

7.4 Impact of the factors on the policy and practice in the New Zealand context

There are some implications of the identification of the above critical factors on policy and practice in New Zealand. Due to the uncertainty of identifying the impact of the factors affecting CEEDRW, now placed limitation of the percentage of contingencies might need to be removed. This is because the impact of these factors can go well beyond the limits placed by the New Zealand high court (Paul Geoffrey Myall Vs Tower Insurance Ltd, 2017).

Furthermore, insurance companies' policies need to consider the impact of these factors in the cost estimation process in the instance of earthquake damage repair work. Therefore, the policies should either consider the impact of the factors in their costing process or exclude the impact of these factors.

The government can also revise their damage identification standards such as the rapid building assessment, to include the impact of the factors affecting cost estimation (Ministry of Business Innovation and Employment, 2015). The rapid building assessment standard can be upgraded to give an indication of the impact of the aforementioned factors. Furthermore, the detailed damage identification process should be upgraded to identify the indicators of revealing the impact of the above factors.

The interview data and questionnaire survey show that the cost estimators did not consistently consider the above-identified factors. Therefore, the cost estimators should upgrade their practice to include the impact of the aforementioned factors.

7.5 Validity of the final C-DREEM

As mentioned in section 6.7.2, the final model validation process focused on six main sections: clarity of the framework, basic concept, categorisation of rates, repair method classification, automation and overall system. Results from each of these sections are discussed below.

7.5.1 Clarity of the framework

The clarity of the framework was evaluated across five key sections: structure, process, content, input requirements and output requirements. Other than one disagreement on the clarity of inputs, more than two-thirds of the final validation team voted in agreement on the clarity of these sections. Additionally, most participants agreed that the model increased the speed of estimation and covered the necessary variables. Therefore, we can conclude that the developed framework and its aspects are clear, increase the speed of CEEDRW and cover the necessary variables.

Participants gave their opinions on methods for improving the framework. Results show that the model should have a clearer definition of the 3D model development process, how responsibilities are allocated in the damage assessment process and the correct information selection process. These features are covered in part by the scope of this study but would benefit from further research.

Results also identified the following drawbacks of the model: the model is complex, it needs to be easily understandable to gain trust, and it might require a long time to estimate initial projects. These drawbacks do not challenge the framework itself, and can be overcome by developing the software package to be simple and easily understandable. Additionally, the results indicate that the model should operate according to a holistic and standardised procedure, be usable in the field, operate on an online platform for information-sharing and accommodate the input of damage from aftershocks as they occur. These features can be included when the C-DREEM software package is developed.

7.5.2 Validity of the basic concept, categorisation of rates, repair method classification, and automation

Criteria that were different from the previous sections were used to evaluate the four sections of the model associated with system mechanics: the basic concept, categorisation of rates, repair method classification and automation. Focused on the ability of the sections to achieve the intended aims of the C-DREEM, the criteria were: clarity, accuracy, buildability, usability, reliability, ability to increase the speed of estimation and coverage of factors affecting CEEDRW. The majority of votes (more than 66 percent) were given in support of all criteria being met. Additionally, none of the participants disagreed or strongly disagreed with any of the criteria statements. Therefore, it can be concluded that the basic concept, categorisation of rates, repair method classification and automation associated with the C-DREEM are valid, reliable and achieved their intended aims.

Focus group participants also gave their opinions on ways to improve the model. These comments did not mention any specific drawbacks associated with these sections, and

instead focused on the software model operation process. They suggested using a standard method, simplifying the process, continuously updating repair methodology according to construction industry practices, regularly updating rates and allowing provisions in the model to add project-specific costing methods that were not currently included in the model.

The participants also stated that there might be very small items associated with repair work, and noted that these items could be covered by adding an item for allowances into the set of rates. In response to participants' suggestions, an item for allowances was included in the C-DREEM to cover costs too small to calculate.

Participants also mentioned that builders might rebuild or replace an element that could otherwise be repaired. As a result, a criterion could be developed by observing ad-hoc changes made by builders during repair work. Analysis and inclusion of such changes in the model can generate more accurate estimates. This is not a part of this project and should be the subject of further research.

7.5.3 Validity of the overall system of C-DREEM.

Finally, based on the overall presentation and system, the C-DREEM was evaluated in terms of user-friendliness, usefulness in improving CEEDRW and participants' willingness to use a software package based on the model. When asked about the model's user-friendliness, a few participants (four out of nine) voted 'neither agree/disagree', perhaps because the model was not yet operative as a practical software tool. However, most participants (five out of nine) agreed or strongly agreed that the model was user-friendly. These results show that the C-DREEM model itself did have a positive impact on many of the participants.

All participants agreed or strongly agreed that the C-DREEM would be useful in improving CEEDRW, and that they would like to use it. Two-thirds of participants also stated that the model fulfilled their expectations, and almost all the participants (eight out of nine) stated that it should be commercialised. One participant (FR09) stated, "*It was probably better than what I had expected*". These feedbacks suggest that the model had achieved the intended goal of improving CEEDRW and that professionals working in the construction industry would be willing to use it.

Participants also suggested characteristics that would improve the overall model. These were: ready availability, simplified usability, a user manual, and increased user-friendliness. Additionally, participants noted that, as the C-DREEM model is a digital model that differs from current manual processes, in the short term, the cost of professional services associated with earthquake repair work might increase as the professionals respond to the challenge of learning a new system. One participant suggested that the C-DREEM-based software package should be introduced in stages, starting as a checklist and progressively being upgraded as people get accustomed to each software iteration.

Participants also identified complexity, cost and time required for software development as barriers to the development of the C-DREEM. Therefore, the C-DREEM must be developed and maintained at a manageable cost and allow for reasonable durations as part of the development process.

7.6 Importance of the C-DREEM

The importance of the C-DREEM can be identified when it is compared with the traditional CEEDRW process and P-58 methodology-based models. Therefore, a

comparison was conducted between the C-DREEM, the traditional post-earthquake cost estimation for earthquake damage repair work (PEQ-CEEDRW) process and probability-based models, as expressed in Table 7.1.

Table 7.1 - Difference between P-58 methodology-based models, PEQ-CEEDRW and the C-DREEM

Characteristics	P-58 methodology-based models	PEQ-CEEDRW	C-DREEM
Speed of cost estimation	Highest due to the lower number of inputs required.	Lowest due to the length of time required for manual estimation.	Better than the current cost estimation process according to validation results. Lower than P-58 methodology-based models due to the greater number of inputs required.
Accuracy of outputs from CEEDRW	Lowest due to the use of probability information and minimum use of building-specific details and factors considered.	Better than P-58 due to the use of actual damage. Lower than C-DREEM because of non-consideration of probable future damage and a smaller number of factors affecting CEEDRW	Higher than all other methods due to the use of both probability predictions and actual damage and a standard CEEDRW process. Considers all of the factors affecting CEEDRW
Complexity	Requires users to identify the function of fragility curves and consequence functions.	Lowest due to the use of the simple theory of rates multiplied by quantity equals cost.	Highest. Due to the use of automation processes and other integrated functions.
Provides a standardised process to include the impact of key factors	No	No	Yes
Can be used for post-earthquake CEEDRW	No	Yes	Yes

The main differences between the methods are related to the innovations introduced to the C-DREEM system by the TRIZ methodology. The innovations were introduced to increase the cost estimation process's speed and consider all key factors affecting

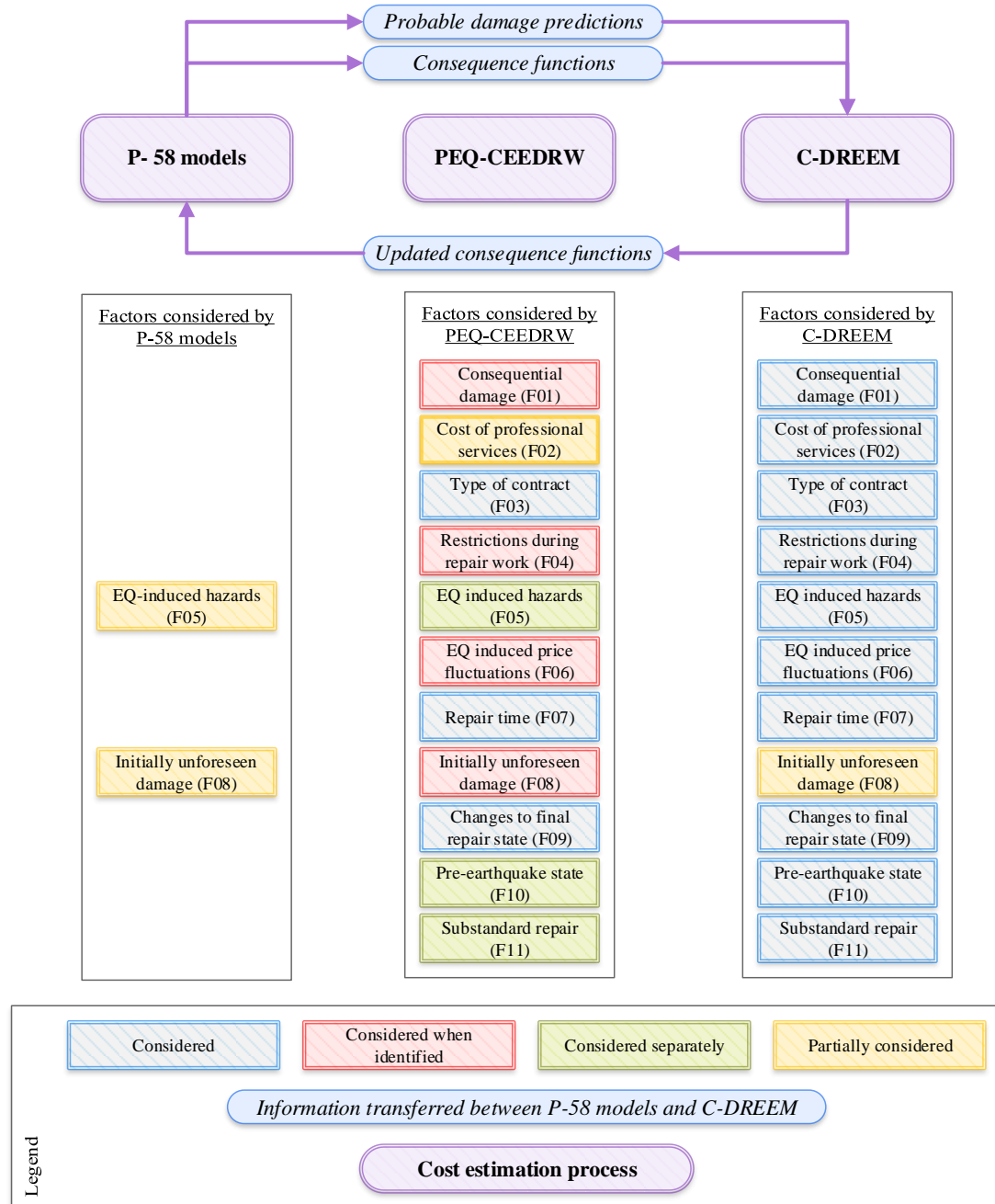
CEEDRW. With regard to speed of estimation, the C-DREEM was developed with automated: (i) damage identification; (ii) repair method selection; and (iii) cost estimation processes. Validation results confirmed that the C-DREEM would be faster than PEQ-CEEDRW. According to the analysis of P-58 methodology-based models, these models do not consider the details of building elements, repair methodology and all factors related to CEEDRW to the same extent as the C-DREEM (Applied Technology Council, 2018d). Because of the greater number of calculation stages used in the C-DREEM, this system would be slower than a P-58 methodology-based model in similar hardware settings.

Regarding output accuracy of CEEDRW, the C-DREEM would have the upper hand. The C-DREEM uses both probability-based damage estimation and actual damage assessment in its process. In comparison, P-58 methodology-based models only use probable damage, and PEQ-CEEDRW only uses actual damage. Because the C-DREEM considers both types of information, it can also evaluate its results alongside past data to identify any deviations. Furthermore, C-DREEM also considers all of the factors affecting CEEDRW. Therefore, the C-DREEM would estimate with higher accuracy than other methods. It is worth noting that P-58 methodology-based models use probable damage, which contains fewer details, while PEQ-CEEDRW uses actual damage, which provides more details and considers most of the factors affecting CEEDRW. Therefore, estimates created by PEQ-CEEDRW will be more accurate than outputs generated by P-58 methodology-based models.

The complexity of the process is also a key characteristic that needs to be considered as part of the evaluation process of the C-DREEM. The PEQ-CEEDRW method would have the lowest level of complexity, as its calculations are based on the simple theory of rates multiplied by quantity equals cost. Next, the P-58 methodology-based model

will have a higher level of complexity as it uses fragility curves and consequence functions for the estimation process (Applied Technology Council, 2018d; Bradley, 2009; Haselton Baker Risk Group, 2020). The C-DREEM model would be the most complex system, as its processes include: fragility curves for probable damage information, consequence functions for estimation evaluations, automation for damage identification and cost estimation processes and real-time updated prices using cost databases.

Figure 7.2 - Comparison between P-58 methodology-based models, PEQ-CEEDRW and C-DREEM in terms of factor coverage and information sharing



Further describing the factors considered by the models, the C-DREEM also considers all the key factors that impact CEEDRW, based on the information available, as explained in chapter 6 (refer to Figure 7.2). In comparison, P-58 models consider

earthquake-induced hazards (F 05.1) and the impact of initially unforeseen damage (F 08). However, these models only include the impacts of aftershocks and initially unforeseen damage. Initially unforeseen damage is only considered from probability-based damage estimation methods, and aftershocks are only one part of earthquake-induced hazards. Therefore, the impact of earthquake-induced hazards and unforeseen damage are, in fact, only partially considered by these models.

PEQ-CEEDRW considers the factors that are identifiable at the cost estimation stage, including the impact of types of contract (F 03), repair time (F 07), and changes required to the final repair state (F 09). However, as demonstrated during the CEQS, some other factors were considered at the latter stages of the project, when information became available. These factors were: consequential damage repair (F 01); restrictions during repair work (F 04); earthquake-induced high rates and price fluctuations (F 06); and initially unforeseen damage (F 08). Some factors that were identified at the latter stages of the project were considered separate events: earthquake-induced hazards and weather conditions (F 05), the pre-earthquake state of the building (F 10) and sub-standard repair work (F 11). The cost of legal services was also not considered during the CEQS, since these costs were not part of the construction costs. Therefore, the total costs of professional services (F02) were not fully considered.

A key feature of the C-DREEM is that it creates an information cycle with P-58 methodology-based models (refer to Figure 7.2). The C-DREEM uses the probability-based predictions and consequence functions produced by P-58 methodology-based models in its process. Probability-based predictions are used to identify damage to building elements, and consequence functions are used to evaluate the outputs of the C-DREEM. In turn, C-DREEM produces updated consequence functions that can be used to update the P-58 methodology-based models. This information cycle can

improve the outputs of both the C-DREEM and P-58-based models. Another benefit of the C-DREEM is that it offers a standard method to incorporate the impact of key factors and defines the standard procedure in which the impact should be included. Therefore, the C-DREEM provides a standardised method cost estimation process.

In comparison, the C-DREEM model is more complex than other cost estimation processes and has a lower speed of cost estimation than P-58 methodology-based models. However, the C-DREEM will produce estimates of greater accuracy than other methods and cover all key factors at a higher speed than PEQ-CEEDRW methods. As mentioned above, the C-DREEM also creates an information cycle with the P-58 methodology-based models to improve the outputs of both models and provides a standard process to incorporate the factors into the CEEDRW process. Additionally, the C-DREEM is designed to fulfil the needs of the post-earthquake cost estimation processes identified through extensive research. It can be concluded that the C-DREEM achieves its intended purpose of incorporating all key factors affecting CEEDRW into a standardised process and of increasing the accuracy and speed of the post-earthquake cost of estimation for earthquake damage repair work.

7.7 Impact of C-DREEM on the policy and practice in the New

Zealand context

As discussed in section 7.4, eleven critical factors have a major impact on CEEDRW and should be included in the cost estimation process. Since all factors are not fully considered in the CEEDRW process, C-DREEM provides the methodology to include the impact of the factors in the CEEDRW process. C-DREEM framework provides a

detailed sequence that cost estimation practices in New Zealand can adopt, thus changing the current practice.

Interview data analysis and literature show that there are separate cost estimation practices used in the traditional CEEDRW process and pre-earthquake loss estimation tools. However, these tools are not linked together. C-DREEM provides the method that can combine these two mechanisms together and complement each other. Insurance companies can use C-DREEM in their policy creation process for both, premium calculations and claim amount estimations while complimenting each other.

P-58 methodology-based tools like PACT, SLAT and SP3 creators will also benefit as they will have a steady mechanism to upgrade the consequence functions automatically and then a testing process to check their accuracy.

New Zealand government can create their own global disaster damage prediction and damage claim processing tool using the C-DREEM tool as a basis. The database created can be used to predict future earthquake-related disasters.

7.8 Summary

Chapter 7 presents a discussion on themes recognised from the research. The research identified that the initial conducted rapid building assessments (RBA) after CEQS did not contribute to CEEDRW, however, RBA could be a source of information for CEEDRW if upgraded. The main source of information used for CEEDRW was identified as the detailed damage evaluations (DDE). The discussion further revealed that DDE had given different outcomes for the same property. Therefore, it was identified that a standard damage evaluation process was needed to produce consistent cost estimations.

The next section of the chapter addresses the 11 factors identified during the research in terms of reference in literature, importance, usage and significance. The existence of these 11 factors was supported by the literature and, while all were noted to have a substantial impact on CEEDRW, only some of these factors were considered pre-earthquake in the cost estimation model. Some of the non-considered factors were: consequential damage repair, cost of professional services, type of contract, earthquake-induced high rates and price fluctuations. Results of the research also show that the majority of participants consider these factors in the traditional CEEDRW process, but some were considered only when identified. However, the majority of participants indicated that all factors should be considered in future cost estimations. Results further revealed methods that could be used to incorporate the impact of the factors into CEEDRW, most of which were similar to the methods used in the traditional CEEDRW process.

Next, the C-DREEM model validation results were discussed. The discussion showed that the model was reliable and valid. Improvement suggestions given for the models were categorised into three categories: improvements to the model, improvements to the software package and considerations for future research. The suggestions given by the participants resulted in one minor upgrade to the model to include an item for allowances to cover minor cost items. This model is now valid, reliable and fit for its purpose.

Finally, the C-DREEM, the current cost estimation method, and the P-58 methodology were discussed and compared. This comparison revealed that the C-DREEM is suitable for post-earthquake cost estimation for earthquake damage repair work and archives intended purposes.

The next chapter concludes the study by summarising the findings and providing recommendations.

8

CONCLUSION AND RECOMMENDATIONS

8.1 Introduction

This chapter presents the conclusion and recommendations of the research. The first section of the chapter provides a description of the aims and objectives of this study and the methods used to answer them. Subsequently, the key contributions of the research are presented. Then, the limitations of the research are described. Finally, the chapter suggests recommendations that can be adopted by the research community, policymakers and practitioners specialising in the cost estimation of earthquake damage repair work.

8.2 Conclusions and fulfilment of the research aim and objectives

The aim of this study was to develop a post-earthquake cost estimation model for earthquake damage repair work. In this regard, four objectives were cultivated to achieve the aim. The accomplishment of each objective of the study is discussed in the following sections.

8.2.1 Fulfilment of the first objective

The first objective of the study was to examine earthquake characteristics, damage to buildings, damage identification methods and cost estimation methods. A review of the literature review was used to identify the behaviour of earthquakes, their impact and cost estimation practices such as the use of pre-earthquake damage prediction models. It was identified that the drawbacks of the pre-earthquake models made them unsuitable for post-earthquake cost estimation.

The literature review revealed the complexities related to earthquakes and earthquake damage and the drawbacks of current cost estimation tools. Additionally, the literature review exposed that no significant research had been conducted to develop a post-earthquake cost estimation model for earthquake damage repair work. This knowledge gap illuminated the need to investigate current post-earthquake cost estimation processes and build a new model.

The key findings of this examination were the drawbacks of the probability-based loss estimation tools that made them unsuitable as post-earthquake loss estimation tools. The main reasons for unsuitability were that these models did not provide the required cost breakdowns and did not cover requirements related to cost estimation of earthquake repair work.

8.2.2 Fulfilment of the second objective

The study's second objective was to examine the current practices of cost estimation conducted after an earthquake in New Zealand to identify the processes used. The

semi-structured interviews were used to meet this objective, and interviews were conducted with professionals involved in the Canterbury earthquake sequence.

Analysis of the interview data and literature review revealed that detailed damage evaluation reports were considered to be the main information source for cost estimation. Interview data also revealed that rapid building evaluation reports were not suitable for CEEDRW; this was supported by literature findings. The key finding was that there was no standard method for post-earthquake damage evaluation and cost estimation for earthquake damage repair work.

The analysed interview data revealed the methods used for earthquake damage identification and cost estimation, drawbacks of the current methods and significant factors that have an impact on the process.

8.2.3 Fulfilment of the third objective

The third objective of the study was to identify the factors that have an impact on cost variations, examine the usage and significance of the identified factors and explore potential methods of incorporating them into a post-earthquake damage estimation process. Interview data of current cost estimation practices revealed key factors affecting CEEDRW. Thereafter, a survey questionnaire was conducted to collect the opinions of professionals with experience in CEEDRW regarding the aforementioned factors.

Analysis of the interview data identified 11 factors that need to be considered in CEEDRW. The literature review findings supported the consideration of these as key factors and further revealed the substantial impact they have on CEEDRW.

The survey questionnaire results revealed that professionals inconsistently included the aforementioned factors in CEEDRW. Factors like changes required to the final repair state, consequential damage repair to meet statutory compliance, duration of repair work and initially unforeseen damage were included in CEEDRW by most of the professionals. However, factors like the cost of dispute resolution services, cost of legal services and damage from aftershocks were considered by a minority of the professionals. Inconsistent consideration of the aforementioned factors could be one of the reasons for cost variations in current cost estimation practice. According to the literature findings and analysis of the interview data, some factors were considered as separate events requiring new damage evaluations and were either only included when identified as a variation or not considered as part of the building construction costs.

Variations in the statistical significance of the aforementioned factors were identified from the analysis of the questionnaire data. Some factors, like the cost of structural and geotechnical engineering services (part of F 02), initially unforeseen damage (F 08) and changes required to the final repair state (F 09), obtained high significance ratings, while the cost of dispute resolution services (part of F 02), cost of legal services and damage from fire, flood, weather conditions and aftershocks (F 05) achieved scores indicating low significance. Less-significant factors were those whose impact was likely to be included as variations or whose impact was only considered when identified. The literature review and interview data analysis identified that, even factors with low significance ratings could have a significant impact when they occur. The significance of these lower-ranked factors was further supported by the increased inclinations of the cost estimators to consider them in future cost estimates prepared for earthquake damage repair work.

Findings also led to suitable methods of incorporating these factors into the cost estimate. A comparison was made between the suggested estimation methods and current methods. It revealed that, in current practice, consequential damage repair (F 01), restrictions during repair work (F 04), earthquake-induced hazards (F 05), earthquake-induced high rates and price fluctuations (F 06), initially unforeseen damage (F 08), changes required to final repair state (F 09), pre-earthquake damage (f 10) and substandard initial repair work (F 11) were initially not included in CEEDRW until identified, and that pre-earthquake damage was typically not included in CEEDRW. When the impacts of such factors were identified, they were included as variations and considered as separate events. However, the survey questionnaire indicated that all 11 key factors identified in the semi-structured interview should be included in CEEDRW. Therefore, the identification of these 11 factors, the assessment of their significance and selection methods of incorporation to CEEDRW fulfilled the third objective.

8.2.4 Fulfilment of the fourth objective

The first part of the fourth and final objective of the research was to develop and validate a model that incorporates the identified factors into a standardised earthquake damage cost estimation process and improves the accuracy and speed of such estimation process. In this regard, the C-DREEM model for post-earthquake cost estimation of earthquake damage repair work was developed. The C-DREEM was developed based on the ideas extracted from the TRIZ methodology, key findings from the research, a review of relevant documents and input from professionals.

The C-DREEM can be viewed from the perspectives of its system mechanics and its high and lower-level design. The system mechanics of the C-DREEM model provide

the underlying process of the model and is described in four parts: basic concept, rate categorisation, repair method classification and automation. The high-level design of C-DREEM contains three main divisions: identification, quantification, and costing and summarisation. These divisions are each further divided into three sections, for a total high-level design that includes nine sections. Taking each division to an analysis of its lower-level design reveals the first division, identification, focuses on the identification of building damage and repair methods through pre-earthquake state identification, post-earthquake state identification and repair method identification sections. The second division of the C-DREEM, quantification, calculates the quantities related to the C-DREEM in terms of repair work, duration, start date, and preliminaries. The costing and summarisation division of the model addresses costing, professional services and other costs, total project costs, and consequential functions. This division calculates the project's total cost and provides a summarised output. The final outputs to be generated by the C-DREEM are a final cost estimate of the project, updated consequence functions and a comparison between past and new consequence functions for corrective actions.

The next part of the fourth objective was to validate the C-DREEM model. The validation process of the C-DREEM was, as described above, conducted through a focus group interview. The focus group involved a team of experts in the fields of cost estimation for earthquake damage repair work in New Zealand. In order to obtain the final opinions of these professionals and fulfil the objectives of the validation process, a survey questionnaire with closed and open-ended questions was used. The validation process focused on the clarity of the framework (high and lower level design), the functions of the four parts of the system mechanics and the overall model. Overall results were positive and revealed that the model achieved its intended aim by

improving the accuracy and speed of cost estimation while considering impact of the 11 key factors identified in the research that affect cost. Only one suggestion focused on improving the model by adding an item for allowances. All other suggestions given by the participants focused on improving the software package in the next stage or were aspects to be considered in further research. Participants indicated their willingness to use the model when developed as a software package.

Validation was also established through a comparison conducted between the P-58 methodology-based models, the post-earthquake CEEDRW process used during the CEQS and the developed C-DREEM using literature review, data collection findings and validation results. The comparison revealed that, even though the C-DREEM was complex and slower to use than P-58 methodology-based models, it would be faster than the CEEDRW process in current use and more accurate than both CEEDRW and P-58 methodology-based models. The C-DREEM is deemed the most accurate due to its design, which incorporates probability predictions and actual damage, the standard CEEDRW process and all the key factors affecting CEEDRW. The results of this comparison confirm validation results. Therefore, it can be concluded that this research has built a standardised post-earthquake cost estimation model for earthquake damage repair work which is faster and more accurate than the current processes.

8.3 Contribution to knowledge

There are several knowledge contributions from this research that can be considered as original contributions to the body of knowledge. These are discussed in the following sections.

8.3.1 Contribution to theoretical understanding

The main contribution of this research project to the theoretical understanding is the identification of these critical factors affecting cost estimation of earthquake damage repair work and the determination of how to incorporate these into various models. The research explored the practical CEEDRW processes used in New Zealand during the CEQS and identified 11 unique factors that impact CEEDRW that should be included in future cost estimates. Although some of the factors were considered in cost estimation for new construction, there were no identifiable studies that combined and explored the impact of these factors specifically on post-earthquake CEEDRW.

The study further identified the most important factors, which were: the cost of structural engineering services, changes required to the final repair state to meet statutory requirements, the cost of geotechnical engineering services, initially unforeseen damage and consequential damage repair. Except for the factor changes required to the final repair state to meet statutory requirements, other factors were not directly identified as critical factors affecting cost in current international literature. These findings give these factors more value in the context of CEEDRW compared to traditional cost estimation.

The research also identified the most suitable methods that can be used to incorporate the impact of all 11 key factors into the CEEDRW process. The methods suggested by the research comply with the current methods used in new construction, for example, the use of unit rate breakdown and lump sum amount. However, this validation suggests that the methods used in cost estimation using the consequence function are not the most suitable for estimating the cost of earthquake damage repair work.

This research further improves current literature on cost estimation by the creation of a micro rate system for CEEDRW. The research suggests that any complex cost estimation for CEEDRW could be broken down into smaller rates and standardised. Excess work created could be solved through automated damage and repair method linking process.

8.3.2 Contribution to professional practice

The main contribution of the research to the professional practice of cost estimators is the C-DREEM model. The model has combined all the findings from the research, literature review, document review and input from professionals into one system. The novelty of C-DREEM is that it provides a singular model that can incorporate the impact of all the identified factors to be considered in the CEEDRW process.

The study also provides a framework from which to standardise and automate key aspects of the cost estimation process. The automation processes introduced for cost-based damage identification, rate development, rate selection and quantity calculation can improve the speed and accuracy of the CEEDRW process. The study also defines the circumstances in which factors should be included in the CEEDRW process. Further, this study made one of the first attempts to develop a set of standardised micro rates for repair work that covers all types of repairs to building elements. The novelty of these contributions is that they can transform the current ad-hoc and ambiguous CEEDRW process into a more standardised format similar to an SMM. Even though this system is more complex than traditional, and P-58 methodology-based loss estimation tools, the automated system reduces the workload imposed on the cost estimators.

The research also revealed that the integration of information from probability-based tools and the post-earthquake CEEDRW process could improve both systems and that damage predictions from probability-based loss estimation could be used to predict initially unforeseen damage. Initially unforeseen damage is difficult to identify in the post-earthquake CEEDRW process. Therefore, developing a system that can anticipate it can improve the post-earthquake costing process. Additionally, it was found that consequence functions used in pre-earthquake cost estimation tools can be used to cross-check the outputs of post-earthquake cost estimations. In turn, standardised post-earthquake cost estimations developed from tools like the C-DREEM can be used to update the consequence functions of loss estimation tools continuously.

The findings revealed that the information sources used in the current CEEDRW process could be further improved. The research discovered that an upgraded RBA report could provide the information required in the cost estimation process. This would increase the accuracy and speed of initial damage estimates even further. Additionally, the study pointed out the need for a standardised details damage evaluation process for earthquake damage buildings.

In addition, the C-DREEM model provides a methodology for cost-estimating practitioners to conduct the CEEDRW process in a standardised manner whereby unit rates can be developed for each repair job. The importance of the standardised unit rates is that standardisation allows the rate to be monitored and optimised for better cost control. The development of the C-DREEM has created the ability to establish a cost control loop through which the consequence functions developed for P-58 methodology-based models can be continuously updated from the C-DREEM, and the consequence functions used in P-58 methodology-based models can be used to monitor and update outputs from the C-DREEM.

For homeowners, more accurate cost predictions created by the cost estimation tools can be used for their negotiations with insurance companies and their decisions regarding the repair work and demolition. Additionally, the C-DREEM system will create more rapid cost estimations compared to the traditional CEEDRW process, which will reduce the repair duration (which starts from the occurrence of the earthquake and ends when the repair work is completed) and benefit the homeowners.

For insurance companies, the prediction tools will help accurately predict the cost of earthquake damage repair work compared to the traditional cost estimation process reducing the loss after an earthquake by adjusting insurance premium amounts. Based on identified factors, insurance company policies can be updated. The policies can select to include the impact of identified factors and increase the premium or exclude their impact from future insurance claims.

For the government, standard cost estimation practices should be upgraded to include the impact of the aforementioned factors and create an automated system incorporating the C-DREEM model. This would reduce the operating cost of the government organisations due to its automated mechanisms used for cost estimation. Government agencies can also take actions to reduce the impact of the elven factors before they occur during the post-earthquake stage and control island-wide cost variations.

8.4 Research limitations

The limitations of the research are mainly associated with the data collection methods. The initial data collection method used in the research was semi-structured interviews. The semi-structured interviews were conducted using face-to-face sessions, which were not infallible. As an example, in such an interview, the interviewer has the ability

to change the format of the questions, change the sequence of questions and add probing questions. Changes made to the interviews conducted were necessary to gain the required information. However, this semi-structured approach might have affected the experiences of the participants and influenced the answers given. Additionally, participants might not have given the absolute correct answers to the questions. These and other issues that could affect the quality of the research, such as low rapport between the participants and interviewer, low confidence among the participants regarding the level of security of the collected data and participant bias, were difficult to identify and exclude from the final collected data.

Additionally, the research used an exploratory sequential design. This meant that the qualitative data collected through the semi-structured interviews influenced the questions developed for the secondary data collection method, the survey questionnaire. Regarding the survey questionnaire, the questions themselves might have influenced the results of the questionnaire, even in cases when open-ended questions were provided to collect the independent opinions of the participants. Therefore, the results of the research are affected by such adverse methodological impacts.

The sample population selected for the qualitative data collection were cost estimators, engineers, technicians and builders with experience in earthquake damage repair work. The survey questionnaire focused on practitioners with experience in CEEDRW. Although the research aimed to draw the best and most appropriate contributors to the study, there were difficulties in acquiring the participants for interviews and the survey questionnaire. The geographical spread of suitable participants, the limited time frame of the study and limited resources all made the involvement of participants difficult.

Additionally, the results of the research might have been affected if the sampling frame was not similar to the population targeted.

The research was able to develop a C-DREEM for CEEDRW for the New Zealand context. The model was also validated with the opinions of participants with expert levels of experience using CEEDRW in New Zealand. Therefore, the findings might not be applicable and able to be generalised to a wider geographic area and a global context.

Additionally, the C-DREEM was evaluated as an overall theoretical concept that did not consider individual functional elements and data connection methods used in each section of the model using actual data. Therefore, further upgrades and data definitions will be required for the future development of a software package.

Finally, the results of this research are based on the philosophical stance and subsequent research method selected by the researcher. Therefore, the result might vary if the different research methods is used.

8.5 Recommendations

Based on the findings of the research, key recommendations can be made for construction industry practitioners and policy developers, as well as for further research.

8.5.1 Construction industry practitioners

The construction industry should consider the impact of the 11 factors identified in the study as part of its cost estimation process. Non-consideration of the impacts of these

factors has been seen to create inaccurate cost estimates. Measures can be taken to select suitable methods to quantify and incorporate the impact of these factors when an earthquake occurs. When these measures are taken, the construction industry will be better prepared to produce accurate cost estimates for post-earthquake construction.

The main result of this study was the creation of a cost estimation model that can accurately estimate the cost of repairing earthquake-damaged buildings. The proposed model can improve the speed and accuracy of cost estimation for earthquake damage repair work. Informed by this model, the construction industry will be in a better position to develop a software system focused on cost estimation. As specified in section 6.7.3, the software developed should be: easy to understand, contain simplified processes, be holistic, contain a standardised procedure, be usable in the field, including damage from aftershocks as they occur, be continuously upgraded according to industry changes, be up to date with current rates, able to add ad-hoc cost estimation methods that are not included in the model when needed, provide a user-friendly manual, be developed and maintained at a manageable cost and allow for reasonable durations as part of the development process.

8.5.2 Government and insurance policymakers

The major recommendations of this study are valuable to the government and insurance policymakers as they support the development of a standardised damage evaluation and cost estimation process for earthquake damage repair work. The recommended standardisation would reduce the duplication of work and the errors impacting damage identification, cost estimation and damage rectification processes. The proposed model can be used as the basis for the development of a standardised process for CEEDRW.

The research also identified 11 factors that impact the CEEDRW. Some of these factors, such as earthquake-induced hazards and substandard repair work, have regularly been excluded by cost-estimating practitioners in their final cost estimates until they have occurred. However, nationwide rehabilitation strategies developed for major earthquakes are influenced by the total estimated cost of repairing or rebuilding damaged buildings. Therefore, all 11 factors should be taken into consideration for such estimates.

Government and insurance policymakers can take active measures to minimise the impact of these 11 factors before and during the post-earthquake rehabilitation process. Specific impacts to minimise are associated with the following factors: substandard repair work, damage caused by weather conditions, cost of professional or legal services, price fluctuations due to demand surges and changes to the final repair state. For example, policy changes can be made to control cost fluctuations, take national precautionary actions to reduce damage caused by weather conditions and prevent the occurrence of potential substandard repair work. Policies can also be developed to prevent legal disputes using lessons learnt from past earthquakes. While the above-mentioned actions might not be applicable in every situation, policymakers can make great use of improved knowledge of these identified factors.

The study also highlighted the drawbacks of the current information sources related to cost estimation process. Specifically, the study pointed out the need for a standardised detailed damage evaluation report preparation process. Additionally, the research indicated that RBA reports did not provide the information required for the CEEDRW process. The research further suggested that RBA formatting should be updated to capture the information required for cost estimation without compromising its intended purpose of providing rapid building damage evaluations.

8.5.3 Further research

The findings and limitations of this research are based on data collected from New Zealand construction industry professionals with experience in earthquake damage repair work. Therefore, the results and C-DREEM model created is directly applicable to the New Zealand context. Further research may be done to quantify the impact of the 11 factors on CEEDRW in other parts of the world, identify the other factors that could have an impact on the cost estimation of earthquake damage repair work in other regions and validate the usability of the C-DREEM model in different regions. Based on the results of any further research, necessary changes should be made to the C-DREEM model.

The C-DREEM developed from this study should establish a theoretical concept for a more advanced CEEDRW process. In order to fully realise the validity of C-DREEM, a software package should be developed that includes actual cost data from previous earthquakes. Further research should be conducted to acquire the required information and validate the C-DREEM-based software package.

It is important to note that some parts of the proposed software package require further research. For the software to work most effectively, it must be able to incorporate: damage into a BIM model (item 2.02 and 2.05 in section 2 of C-DREEM); an earthquake-induced price fluctuation calculation formula (item 7.15 in section 7 of C-DREEM) and a practical process for repair method sequencing (item 5.03 in section 5 of C-DREEM). It also must be able to quantify: the impact of impeding factors and estimate the start date (item 5.14 in section 5 of C-DREEM); other influences that have an impact on the repair work (item 3.09 in section 3 of C-DREEM); and the impact of changes to building regulations (item 1.10 in section 1 of C-DREEM).

Additionally, the software should allow individual builders and professionals to make changes to accommodate unique project conditions. As such, this (software) form of the model should be open-sourced to enable multiple parties to update content and should also contain appropriate security protocols.

The model would be best served by the incorporation of a 3D model for damage evaluation purposes. However, the New Zealand construction industry currently does not use 3D modelling to process damage evaluation. Therefore, further research is required on practical methods of using 3D modelling for damage evaluation.

The discussion section also noted that it is difficult to detect consequential damage. Therefore, further research is required to identify consequential damage. As suggested, 3D modelling with virtual repair process simulations can be used to predict such damage.

According to this study, the prospects for an improved, fully-functioning, software-driven C- DREEM are high, and the time is ripe for further development in this field.

9

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10 APPENDICES

10.1 Appendix 1

Table 10.1 - Details of the interview participants

Participant	Years of experience in construction	Years of experience in construction related to EQ	Organisation	Profession
R.01	5	5	Contractor	Engineer
R.02	6	6	Government consultancy	Quantity surveyor
R.03	13	5	Earthquake damage assessment consultancy	Engineer
R.04	2	2	Earthquake damage assessment consultancy	Engineer
R.05	7	3	Earthquake damage assessment consultancy	Quantity surveyor
R.06	20	10	Contractor	Quantity surveyor
R.07	22	2	Contractor	Quantity surveyor
R.08	17	1	Contractor	Quantity surveyor
R.09	12	2	Contractor	Quantity surveyor
R.10	17	4	Earthquake damage assessment consultancy	Engineer
R.11	8	2	Contractor	Quantity surveyor
R.12	49	8	Earthquake damage assessment consultancy	Engineer

Participant	Years of experience in construction	Years of experience in construction related to EQ	Organisation	Profession
R.13	25	7	Earthquake damage assessment consultancy	Engineer
R.14	45	9	Earthquake damage assessment consultancy	Quantity surveyor
R.15	10	5	Earthquake damage assessment consultancy	Quantity surveyor
R.16	10	7	Earthquake damage assessment consultancy	Quantity surveyor
R.17	20	4	Government consultancy & contractor	Quantity surveyor
R.18	20	5	Earthquake damage assessment consultancy	Quantity surveyor
R.19	35	30	Contractor	Engineer

10.2 Appendix 2

10.2.1 Activities conducted in a site investigation for secondary repair work

1. Interview the claimant for the problems they thought about
2. Inspected problems identified by the claimant
3. Visually inspected the floor and walls
4. Inspected the walls by knocking and floors by moving about to hear creaking sounds
5. Inspect the floor levels
6. Inspect wall plumbness
7. Inspect door window plumbness
8. Inspected the visible foundation from the outside for cracks
9. Inspected the foundation from inside
 - a. Check the pile connections
 - b. Cracking on the inside of the perimeter (if the crack is in both inside and outside then it is earthquake-related)
 - c. Defective repair work
 - i. Cracking is only inside of the perimeter – contractor has only patched up the outside perimeter
 - ii. Packing of piles to level the floor
10. Where the perimeter foundation wall reinforced or not (From reinforcement identifier)
 - a. If reinforced – easy to repair – there is skeleton to fix the reinforcement
 - b. If unreinforced - might have to remove the total perimeter foundation

11. Roof inspection from the inside -

- a. Roof connections - tile and tile battens / Ridge lines - rafters
- b. Sunlight coming in – it's were its raining

10.3 Appendix 3

10.3.1 Interview template with probing questions

School of Engineering and Advanced Technology
 Massey University, Auckland (Oteha Rohe)
 Albany Highway
 Albany 0632
 Auckland, New Zealand

Post-earthquake repair cost estimation model for New Zealand

Background questions

Type of Organisation -

Current position -

Years of experience in construction industry -

Years of experience in earthquake rebuild / construction -

Brief description of experience based on earthquake rebuild -

Interview questions

Damage identification

1. What damage identification methods have you used? (e.g. rapid building evaluation, visual inspection)
 - a. Damage evaluation reports (probing question)
 - b. Site investigation methods (probing question)
 - c. Sources of information (probing question)
 - d. Damage states (probing question)
 - e. Difficulties faced (probing question)
2. From your experience, what was the proportion of multi-storey buildings that were insured for earthquake damage?

- a. How many were insured and how many non-insured? (probing question)
- b. Did insurance coverage (or lack of coverage) affect the damage repair process, cost and time? (probing question)

Cost estimation

1. According to your experience, what current sources of information are used in practice to enable a cost estimate for earthquake damage repair?
 - a. Documents referred (probing question)
 - b. Sources of information (probing question)
 - c. From whom (probing question)
 - d. The process followed (probing question)
 - e. How are the rates broken down (e.g. quotations, QV builder, Rawlinson's)? (probing question)
 - f. Commonly adopted contract methods – lump sum, re-measurement, cost reimbursement (probing question)
 - g. Standard method of measurement used (probing question)
 - h. Similar sources/practices for each damage state? (probing question)
 - i. Factors affecting cost estimation – location, price escalation, size of the repair work. How do you include them the cost estimation? (probing question)
2. Compared to new construction, what are the differences associated with earthquake damage estimation?
 - a. Different factors considered (probing question)
 - b. Rate breakdown (probing question)
3. Have any of your cost estimations included consequential damage? (e.g. water damage, flooding, fire)
4. What are the challenges you have faced? How did you overcome these?
5. Have you observed a common variation in the cost estimates? What percentage did these typically have?

Time estimation

1. According to your experience, what is the current process of time estimation for repairing earthquake damage?
 - a. Documents referred (probing question)
 - b. Source of information (probing question)
 - c. Rules of thumb (probing question)
 - d. Does the contract type affect time estimation? (probing question)
 - e. Scheduling methods used (probing question)
2. Has any of your time estimation included the effects of other repair work by other builders?
3. Compared to new construction, what are the differences in time estimation for repairing earthquake damage?
 - a. Factors considered (probing question)
4. Have you observed a common variation in the time estimates? What percentage did these typically have?
 - a. Are there any impeding factors that affect damage repair work (e.g. long lead time for equipment) (probing question)?

Any further thoughts?

10.4 Appendix 4

10.4.1 Survey questionnaire format

Figure 10.1 - Questionnaire survey format - part 1

9/24/21, 4:47 PM Factors affecting the repair costs of earthquake damaged buildings

Factors affecting the repair costs of earthquake damaged buildings

Please enter a valid email for unique coding purposes.

* Required

1. Email *

Project Description

This survey focuses on identifying the factors that affect the repair costs of earthquake damaged buildings. This survey forms part of my PhD research project that aims to develop a model to calculate repair costs of earthquake damaged buildings. The outcome of the research will help builders prepare more accurate cost estimates.

Project Procedures and Data Management

The survey will take around 10 minutes to complete. Data will be stored securely under strict access and password protection. Access to this information is only available to the researcher and supervisors. The data will be stored in a desktop computer and secure cloud storage. The project findings will be published in conferences and journals. The participants will be notified of the publications upon request.

Committee Approval Statement

This research has been reviewed and approved by the Massey University Human Ethics Committee: Northern, Application 4000017232. If you have any concerns about the conduct of this research, please contact A/Prof David Tappin, Chair, Massey University Human Ethics Committee: Northern, telephone 64 9 414 0800 x 43384, email humanethicsnorth@massey.ac.nz.

Participant consent

2. Do you wish to be a participant in this research? *

Mark only one oval.

Yes (which means you give consent to become a participant)

No

Brief overview of your experience

Please choose the most relevant response

<https://docs.google.com/forms/d/1i4jD3Ct68kBGyqoTgLRBFEIwkJyVUXtrOowBwul5k/edit>
1/11

Figure 10.2 - Questionnaire survey format - part 2

9/24/21, 4:47 PM Factors affecting the repair costs of earthquake damaged buildings

3. Do you have experience in assessing the repair cost of earthquake damaged buildings? *

Mark only one oval.

Yes

No

4. If yes, please state the years of experience in earthquake damage repair work estimation. *

Factors that affect the repair costs of earthquake damaged buildings

<https://docs.google.com/forms/d/1i4jD3Ct68kBGyqoTgLrBFEIwikGjVtUXtrOowBwul5k/edit> 2/11

Figure 10.3 - Questionnaire survey format - part 3

9/24/21, 4:47 PM Factors affecting the repair costs of earthquake damaged buildings

5. Please select from the following list the factors you considered when assessing the repair cost of earthquake damaged buildings. *

Mark only one oval per row.

	Yes	No
Price fluctuations due to change in demand for resources as a result of an earthquake (e.g. changes in Labour rates due to high demand)	<input type="radio"/>	<input type="radio"/>
Initially unforeseen damage (e.g. structural damage identified during construction)	<input type="radio"/>	<input type="radio"/>
Duration of repairs (e.g. preliminary and time related costs depend on repair duration)	<input type="radio"/>	<input type="radio"/>
Building being occupied during repair work (e.g. restriction on repair time and access)	<input type="radio"/>	<input type="radio"/>
Substandard initial repair work	<input type="radio"/>	<input type="radio"/>
Damage from aftershocks (e.g. tremors that occur after the earthquake might increase building damage)	<input type="radio"/>	<input type="radio"/>
Damage from weather conditions (e.g. rain, wind and snow can increase the damage of buildings)	<input type="radio"/>	<input type="radio"/>
Changes required in reconstruction to meet statutory compliance	<input type="radio"/>	<input type="radio"/>
Changes required in reconstruction to meet client requirements (e.g. improvements in the structure)	<input type="radio"/>	<input type="radio"/>
Pre-earthquake state of the building (e.g. damage that had occurred before the earthquake, ground subsidence)	<input type="radio"/>	<input type="radio"/>
Impact of a damaged building element on another adjoining building element (e.g. damage of a partition wall which is in contact with a ceiling and associated cornices)	<input type="radio"/>	<input type="radio"/>
Varying profit margins depending on the type of building contract (e.g. lump sum, cost plus margin etc.)	<input type="radio"/>	<input type="radio"/>

<https://docs.google.com/forms/d/1i4jD3Ct68kBGyqoTgLrBFElwkJVUXtrOowBwul5k/edit> 3/11

Figure 10.4 - Questionnaire survey format - part 4

9/24/21, 4:47 PM Factors affecting the repair costs of earthquake damaged buildings

Damage from earthquake induced hazards - flooding

Damage from earthquake induced hazards - fire

6. Did you include the costs of following professionals when assessing the repair cost of earthquake damaged buildings? *

Mark only one oval per row.

	Yes	No
Structural engineer	<input type="radio"/>	<input type="radio"/>
Architect	<input type="radio"/>	<input type="radio"/>
Quantity surveyor	<input type="radio"/>	<input type="radio"/>
Geo technical engineer	<input type="radio"/>	<input type="radio"/>
Land surveyor	<input type="radio"/>	<input type="radio"/>
Lawyer / Advocate	<input type="radio"/>	<input type="radio"/>
Dispute Resolution Facilitator / Dispute Resolver	<input type="radio"/>	<input type="radio"/>

7. Please state any other factors that you included in your cost estimates.

Impact of different factors on the repair costs of earthquake damaged buildings

<https://docs.google.com/forms/d/1i4jD3Ct68kBGyqoTgLfBEIwkJvUxtrOowBwul5k/edit>
4/11

Figure 10.5 - Questionnaire survey format - part 5

9/24/21, 4:47 PM Factors affecting the repair costs of earthquake damaged buildings

8. Please indicate significance of the following factors on accuracy of the repair cost estimates of earthquake damaged buildings. *

Mark only one oval per row.

	Very Important	Important	Some importance	Slightly important	Not important at all
Price fluctuations as a result of post-earthquake demand	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Unforeseen damage	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Duration of works	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Building being occupied during repair work	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Varying profit margins depending on the type of building contract	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Damage as a result of aftershocks	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Damage as a result of flood	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Damage as a result of fire	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Damage as a result of rain, wind and snow	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Changes required in reconstruction to meet statutory compliance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Changes required in reconstruction to meet client requirements	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Pre-earthquake state of the building	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Impact of a damaged building element on another adjoining building element (e.g. damage of	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

<https://docs.google.com/forms/d/1i4JD3Ct68kBGyqoTgLRBFEIwikGjVtUXtrOowBwul5k/edit> 5/11

Figure 10.6 - Questionnaire survey format - part 6

9/24/21, 4:47 PM Factors affecting the repair costs of earthquake damaged buildings

a partition wall in contact with a ceiling and associated cornices)

Substandard initial repair work

9. Please indicate significance of the cost of professionals on the total repair cost of earthquake damaged buildings. *

Mark only one oval per row.

	Very Important	Important	Some importance	Slightly important	Not at all important
Structural Engineer	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Quantity Surveyor	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Architect	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Land Surveyor	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Geotech Engineer	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Lawyer / Advocate	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Dispute Resolution Facilitator / Dispute Resolver	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Most suitable method to estimate the repair costs of earthquake damaged buildings

<https://docs.google.com/forms/d/1i4jD3Ct68kBGyqoTgLRBFEIwikGjVtUXtrOowBwul5k/edit> 6/11

Figure 10.7 - Questionnaire survey format - part 7

9/24/21, 4:47 PM Factors affecting the repair costs of earthquake damaged buildings

10. Please select the most suitable method to include the following factors in the repair cost estimates of earthquake damaged buildings. *

Check all that apply.

	Don't include	Include using A unit rate built by cost break down	Include using As a percentage of total cost	Include using As a lump sum amount	Include using In contingencies	Include using Other method
Unforeseen damage	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Costs associated with the building being occupied during the repair work period	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Substandard initial repair work	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Damage as a result of aftershocks	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Damage as a result of flood	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Damage as a result of fire	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Damage as a result of rain, wind and snow	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Changes required to meet code	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Changes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

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Figure 10.8 - Questionnaire survey format - part 8

9/24/21, 4:47 PM Factors affecting the repair costs of earthquake damaged buildings

required to meet client requirements

Pre-earthquake state of the building

Impact of a damaged building element on another adjoining building element

11. Do you think contractors' margin should change based on the type of building contract (e.g. lump sum, cost plus)? *

Mark only one oval.

No

Yes

Other: _____

12. Please indicate the most suitable method to include impact of price fluctuations in repair cost estimations of earthquake damaged buildings. *

Mark only one oval.

Do not include the impact of price fluctuations

Use published price indices for price fluctuation calculations

Adjust according to your own calculations

Allow for actual price changes in the contract

Other: _____

<https://docs.google.com/forms/d/1i4jD3Ct68kBGyqoTgLRBFElwikGjVtUXtrOowBwul5k/edit> 8/11

Figure 10.9 - Questionnaire survey format - part 9

9/24/21, 4:47 PM Factors affecting the repair costs of earthquake damaged buildings

13. Please indicate the most suitable method to estimate total duration of repair work for cost estimation purposes. *

Mark only one oval.

Did not calculate duration for cost estimation purposes

Using a percentage of repair costs

Using experience

Using total repair hours

Other: _____

14. Please select the most suitable method to include the cost of professionals in the repair cost estimates of earthquake damaged buildings? *

Check all that apply.

	Don't include	A unit rate built by cost break down	Percentage of the total cost	A lump sum cost	In contingencies	Other method
Structural Engineer	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Quantity Surveyor	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Architect	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Land Surveyor	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Geotech Engineer	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Lawyer / Advocate	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Dispute Resolution Facilitator / Dispute Resolver	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

<https://docs.google.com/forms/d/1i4jD3Ct68kBGyqoTgLrBFEIwikGjvTUXtrOowBwul5k/edit> 9/11

Figure 10.10 - Questionnaire survey format - part 10

9/24/21, 4:47 PM Factors affecting the repair costs of earthquake damaged buildings

15. If you have mentioned other methods above, please specify them.

Further thoughts

16. Please add any additional comments you may have.

17. Would you like to know more about this research? *

Mark only one oval.

Yes (You will be asked to give your details) *Skip to question 18*

No

Your details (Saved confidentially)

18. Name *

19. Email *

<https://docs.google.com/forms/d/1i4jD3Ct68kBGyqoTgLrBFEIwikGjvTUXtrOowBwul5k/edit> 10/11

Figure 10.11 - Questionnaire survey format - part 11

9/24/21, 4:47 PM Factors affecting the repair costs of earthquake damaged buildings

20. Telephone no (optional)

Thank you for participating in this research. It is much appreciated.

This content is neither created nor endorsed by Google.

Google Forms

<https://docs.google.com/forms/d/1i4jD3Ct68kBGyqoTgLrBFEIwikGjVtUXtrOowBwul5k/edit> 11/11

10.5 Appendix 5

Table 10.2 - Questionnaire response time and years of experience

Respondent number	Timestamp	Years of experience in CEEDRW
RS01	2019/05/14 5:08:53 PM GMT+12	2
RS02	2019/05/21 4:48:36 PM GMT+12	3
RS03	2019/05/21 4:54:43 PM GMT+12	3
RS04	2019/05/22 11:52:07 AM GMT+12	1
RS05	2019/05/22 12:39:17 PM GMT+12	2
RS06	2019/05/22 7:14:50 PM GMT+12	9
RS07	2019/05/23 1:13:07 PM GMT+12	1
RS08	2019/05/23 11:38:45 AM GMT+12	4
RS09	2019/05/24 11:47:36 AM GMT+12	1
RS10	2019/05/27 10:51:32 PM GMT+12	5
RS11	2019/05/27 9:55:42 AM GMT+12	1
RS12	2019/06/13 10:55:52 AM GMT+12	6
RS13	2019/06/13 7:10:12 AM GMT+12	3
RS14	2019/06/14 4:07:37 PM GMT+12	7
RS15	2019/06/18 9:52:19 AM GMT+12	7
RS16	2019/06/28 2:41:37 PM GMT+12	2
RS17	2019/06/28 9:00:09 PM GMT+12	10
RS18	2019/07/01 12:55:19 PM GMT+12	9
RS19	2019/07/09 9:18:03 AM GMT+12	2
RS20	2019/07/10 11:16:37 AM GMT+12	2
RS21	2019/07/11 12:14:40 AM GMT+12	7
RS22	2019/07/12 2:59:31 PM GMT+12	8
RS23	2019/07/15 4:16:47 PM GMT+12	8
RS24	2019/07/17 2:39:49 PM GMT+12	1
RS25	2019/07/17 3:04:30 PM GMT+12	3
RS26	2019/07/17 3:35:27 PM GMT+12	2
RS27	2019/07/17 4:01:53 PM GMT+12	1
RS28	2019/07/17 6:37:05 PM GMT+12	8
RS29	2019/07/17 7:35:21 PM GMT+12	2
RS30	2019/07/17 7:41:33 PM GMT+12	2
RS31	2019/07/17 9:04:37 PM GMT+12	7
RS32	2019/07/18 1:22:53 PM GMT+12	8

Respondent number	Timestamp	Years of experience in CEEDRW
RS33	2019/07/18 1:48:50 PM GMT+12	4
RS34	2019/07/18 11:04:35 AM GMT+12	6
RS35	2019/07/18 12:26:50 PM GMT+12	7
RS36	2019/07/18 3:10:57 PM GMT+12	6
RS37	2019/07/18 4:27:35 PM GMT+12	3
RS38	2019/07/18 5:01:15 PM GMT+12	4
RS39	2019/07/18 9:27:41 AM GMT+12	3
RS40	2019/07/18 9:29:45 AM GMT+12	6
RS41	2019/07/19 10:09:40 AM GMT+12	5
RS42	2019/07/19 11:06:19 AM GMT+12	8
RS43	2019/07/19 12:14:06 PM GMT+12	5
RS44	2019/07/19 3:15:47 PM GMT+12	10
RS45	2019/07/19 3:59:02 PM GMT+12	1
RS46	2019/07/19 7:35:35 AM GMT+12	2
RS47	2019/07/19 7:43:21 AM GMT+12	5
RS48	2019/07/19 9:39:24 PM GMT+12	5
RS49	2019/07/20 3:04:40 PM GMT+12	9
RS50	2019/07/22 1:45:06 PM GMT+12	7
RS51	2019/07/22 5:09:59 PM GMT+12	1
RS52	2019/07/22 6:34:44 PM GMT+12	1
RS53	2019/07/22 7:42:14 PM GMT+12	2
RS54	2019/07/22 8:57:15 PM GMT+12	5
RS55	2019/07/23 1:13:09 PM GMT+12	3
RS56	2019/07/23 10:27:25 AM GMT+12	8
RS57	2019/07/23 10:50:05 AM GMT+12	2
RS58	2019/07/23 11:07:14 PM GMT+12	3
RS59	2019/07/23 11:48:22 PM GMT+12	5
RS60	2019/07/23 2:48:12 PM GMT+12	2
RS61	2019/07/23 2:52:49 PM GMT+12	7
RS62	2019/07/23 3:21:54 PM GMT+12	8
RS63	2019/07/23 3:43:54 PM GMT+12	3
RS64	2019/07/23 3:44:45 PM GMT+12	3
RS65	2019/07/23 4:29:53 PM GMT+12	1
RS66	2019/07/23 4:34:26 PM GMT+12	8
RS67	2019/07/23 4:36:44 PM GMT+12	9
RS68	2019/07/23 4:39:06 PM GMT+12	2
RS69	2019/07/23 4:58:57 PM GMT+12	8

Respondent number	Timestamp	Years of experience in CEEDRW
RS70	2019/07/23 4:59:58 PM GMT+12	6
RS71	2019/07/23 5:31:50 PM GMT+12	7
RS72	2019/07/23 8:15:50 AM GMT+12	5
RS73	2019/07/23 8:15:54 PM GMT+12	3
RS74	2019/07/23 8:31:23 AM GMT+12	5
RS75	2019/07/23 8:33:49 PM GMT+12	1
RS76	2019/07/24 2:58:58 AM GMT+12	4
RS77	2019/07/24 7:47:24 PM GMT+12	2
RS78	2019/07/24 9:08:54 AM GMT+12	8
RS79	2019/07/24 9:23:19 PM GMT+12	7
RS80	2019/07/30 10:33:52 PM GMT+12	4
RS81	2019/07/31 7:38:01 PM GMT+12	8
RS82	2019/08/05 11:25:17 AM GMT+12	7
RS83	2019/08/05 12:09:38 PM GMT+12	1
RS84	2019/08/05 3:35:38 PM GMT+12	2
RS85	2019/08/05 5:33:43 PM GMT+12	4
RS86	2019/08/06 1:25:08 PM GMT+12	7
RS87	2019/08/06 1:49:04 AM GMT+12	3
RS88	2019/08/06 12:43:13 PM GMT+12	5
RS89	2019/08/06 3:49:07 PM GMT+12	8
RS90	2019/08/14 2:54:26 AM GMT+12	2
RS91	2019/08/20 8:22:38 AM GMT+12	9
RS92	2019/09/13 9:50:36 AM GMT+12	8

10.6 Appendix 6

Table 10.3 - Linking rates and repair methods (RM)

No	Section	Item	RM 1		RM 2		RM 3		RM 4		RM 5		RM 6		RM 7		RM 8	RM 9	
			DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS2	DS3	
1	Remove, store and reinstate	Furnishing and Equipment	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	
		Architraves									✓	✓		✓				✓	✓
		Cornices			✓	✓		✓		✓								✓	✓
		Skirting	✓	✓				✓		✓	*	✓		✓				✓	✓
2	Consequential damage	Doors and windows										✓		✓				✓	
		Air tightness treatment for D/W										✓		✓					✓
		Electrical connections		*		*		*		*		*		*		*	*	*	*
		Water connections		*		*		*		*		*		*		*	*	*	*
		Gas connections		*		*		*		*		*		*		*	*	*	*
		Network connections		*		*		*		*		*		*		*	*	*	*

No	Section	Item	RM 1		RM 2		RM 3		RM 4		RM 5		RM 6		RM 7		RM 8	RM 9		
			DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS2	DS3
		Other attachments		*		*		*		*		*		*		*	*	*		
		Flooring	*	*													*	✓		
		Ceiling			*	*											*	✓		
		Attached partition(s)						✓		✓							✓	✓		
3	Remove	Damaged plaster boards		✓		✓		✓		✓		✓		✓		✓	✓	✓		
		Damaged internal corner trim								✓									✓	
		Damaged external corner trim						✓												✓
		Wallpaper (if applicable)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
4	Replace	Plaster boards and wastage		✓		✓		✓		✓		✓		✓		✓	✓	✓		
		Internal corner trim								✓								✓	✓	
		External corner trim						✓										✓	✓	
5	Pre-finish	Fibre fuse tape	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
		Plastering – base coat	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

No	Section	Item	RM 1		RM 2		RM 3		RM 4		RM 5		RM 6		RM 7		RM 8	RM 9
			DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS2	DS3
		Plastering – 1st coat	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Plastering – 2nd coat	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Sanding	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Wall preparation for wallpaper	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
6.1	Finish – type 1	Painting – base coat	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Painting - 1st coat	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Painting – 2nd coat	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
6.2	Finish – type 2	Wallpaper installation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Use if applicable	*					Rate will be required	✓									

10.7 Appendix 7

Table 10.4 - Linking repair methods (RM) and preliminary items

Preliminaries item type	Item	RM 1		RM 2		RM 3		RM 4		RM 5		RM 6		RM 7		RM 8	RM 9
		DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS2	DS3
Payments - Based on the total project cost	Payment of taxes by contractor	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Bonds and guarantees	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Notices and fees	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Insurance	CAR insurance	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Vehicle insurance	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Temporary Electrical Services	Metered installation. (includes inspection)		✓		✓		✓		✓		✓		✓		✓	✓	✓
	Extra over for Cabling		✓		✓		✓		✓		✓		✓		✓	✓	✓
	Extra over for connection material		✓		✓		✓		✓		✓		✓		✓	✓	✓
	Extra over for testing		✓		✓		✓		✓		✓		✓		✓	✓	✓
	Extra over for Works		✓		✓		✓		✓		✓		✓		✓	✓	✓

Preliminaries item type	Item	RM 1		RM 2		RM 3		RM 4		RM 5		RM 6		RM 7		RM 8	RM 9
		DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS2	DS3
Preliminaries	Power consumed - builder's tariff		✓		✓		✓		✓		✓		✓		✓	✓	✓
	Supply charge - builder's tariff		✓		✓		✓		✓		✓		✓		✓	✓	✓
Telephone Connection Fees	Allowance for call charges		✓		✓		✓		✓		✓		✓		✓	✓	✓
	Broadband modem/router		✓		✓		✓		✓		✓		✓		✓	✓	✓
	Internet service provider account		✓		✓		✓		✓		✓		✓		✓	✓	✓
Temporary Water Services	Metered installation includes inspection		✓		✓		✓		✓		✓		✓		✓	✓	✓
	Extra over for piping		✓		✓		✓		✓		✓		✓		✓	✓	✓
	Extra over for connection material		✓		✓		✓		✓		✓		✓		✓	✓	✓
	Extra over for testing		✓		✓		✓		✓		✓		✓		✓	✓	✓
	Extra over for Works		✓		✓		✓		✓		✓		✓		✓	✓	✓
	Water consumed - builder's tariff		✓		✓		✓		✓		✓		✓		✓	✓	✓
	Supply charge - builder's tariff		✓		✓		✓		✓		✓		✓		✓	✓	✓
Covering	Temporary fences	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Preliminaries item type	Item	RM 1		RM 2		RM 3		RM 4		RM 5		RM 6		RM 7		RM 8	RM 9
		DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS2	DS3
	Hoardings	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Floor covering	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Wall covering	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Door covering	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Health and Protection	General site safety – signs	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	General site safety – cones	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	General site safety – tapes and barricades	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	General site safety – safety nets	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Toilet	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Site shed	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Rubbish skips	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Site supplies	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Protective Clothing and Accessories	Hats	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Boots	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Safety vests	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Overalls	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Hearing Protection	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Preliminaries item type	Item	RM 1		RM 2		RM 3		RM 4		RM 5		RM 6		RM 7		RM 8	RM 9
		DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS1	DS2	DS2	DS3
	Eye protection / safety glasses	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Gloves	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Masks and respirators	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	First aid kits	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cleaning	Daily cleaning (If occupied)	*	✓	*	✓	*	✓	*	✓	*	✓	*	✓	*	✓	✓	✓
	Daily site clearance (If occupied)	*	✓	*	✓	*	✓	*	✓	*	✓	*	✓	*	✓	✓	✓
	Final clean	*	✓	*	✓	*	✓	*	✓	*	✓	*	✓	*	✓	✓	✓
Mould inspection and removal		✓		✓		✓		✓		✓		✓		✓	✓	✓	✓
Setting out		*	✓	*	✓	*	✓	*	✓	*	✓	*	✓	*	✓	✓	✓
Temporary access		*	✓	*	✓	*	✓	*	✓	*	✓	*	✓	*	✓	✓	✓
Attendance		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Use if applicable	*
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Rate will be required	✓
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10.8 Appendix 8

Table 10.5 - Detailed experience of the focus group participants

Participant	Expert area	Position in Organisation	Experience in construction (Years)	Experience in CEEDRW (Years)	Specific CEEDRW experience												
					In public companies						In private companies						
					Client	Consultant	Insurance	Builder	Supplier	Other	Client	Consultant	Insurance	Builder	Supplier	Other	
FR01	Quantity surveyor	Managing director	40	10	0	0	0	0	0	0	0	10	10	10	10	0	0
FR02	Quantity surveyor	Quantity surveyor	20	7	4	0	0	0	0	0	0	0	3	0	0	0	0
FR03	Project Manager, Quantity surveyor	Consultant	63	6	6	6	6	6	0	0	0	6	6	6	0	0	0
FR04	Quantity surveyor	Director	20	10	0	0	0	0	0	0	0	0	2	0	8	0	0
FR05	Quantity surveyor	Quantity surveyor	17	4	0	0	0	0	0	0	0	4	4	4	4	4	0
FR06	Project Manager, Quantity surveyor, Builder, Estimator	Building surveyor	39	10	0	0	10	0	0	0	0	0	0	0	0	0	0
FR07	Engineer	Research Engineer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR08	Quantity surveyor	Senior Quantity surveyor	24	6	0	0	0	0	0	0	0	0	4	0	2	0	0

Participant	Expert area	Position in Organisation	Experience in construction (Years)	Experience in CEEDRW (Years)	Specific CEEDRW experience											
					In public companies						In private companies					
					Client	Consultant	Insurance	Builder	Supplier	Other	Client	Consultant	Insurance	Builder	Supplier	Other
FR09	Quantity surveyor	Quantity surveying manager	12	9	0	0	9	0	0	0	0	0	0	0	0	0