Adopting Augmented Reality to Avoid Underground Utilities Strikes During Excavation

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Abstract

The construction industry constantly pursues innovative methods to improve safety, enhance productivity, and reduce costs and project durations. Augmented Reality (AR) is a promising technology, potentially bringing about transformative changes in construction. AR is a promising technology for visualising data in construction sites and preventing clashes and accidents. One of its promising applications is in the excavation sector, where accidental strikes on underground utilities pose serious safety risks, delays, and costly damages. However, while AR has gained increasing attention in recent years, its integration into construction practice remains limited.

To address this limitation, this research investigates the potential of AR to facilitate identifying underground utility locations through a systematic review, industry engagement, and user-centred experimentation. Initially, a systematic literature review was conducted to explore the current applications of AR in construction safety. This review identified the safety purposes of AR across three project phases: pre-event (e.g., training, safety inspections, hazard alerting, enhanced visualisation), during-event (e.g., pinpointing hazards), and post-event (e.g., safety estimation). However, the review also revealed a notable lack of studies focused on AR applications in excavation activities, particularly for underground utility strike prevention.

In response, a study was undertaken to understand the needs, expectations, and challenges associated with adopting AR in the excavation sector. 31 professionals from the excavation industry participated in the within-subject experiment, interacting with two AR prototypes, delivered via Optical See-Through (OST) and Video See-Through (VST) devices. The findings indicated a clear preference for AR over traditional methods such as paper-based drawings. Participants showed a preference for VST rather than OST, given their familiarity with VST devices such as tablets. Further, accessibility emerged as the primary barrier to adopting AR within the excavation industry.

Building on the literature and industry insights, an experimental study was designed to evaluate the effectiveness of different AR visualisation methods in underground utility detection. A within-subject experiment involving 60 participants was conducted to compare four of the most cited visualisation techniques for underground utilities: X-Ray, Shadow, Cross-Sectional, and a newly developed Combination method. Drawing on the Theory of Affordances and Task Load analysis, the study found that the Combination and X-Ray visualisation methods perform superior to the Shadow. These results provide empirical support for the user-centred design of AR visualisation techniques in excavation practice.

This research contributes to the fields of human-computer interaction, construction safety, and digital technology adoption by advancing the use of AR for underground utility strike prevention. The study shifts the focus of AR from general safety training to real-time, spatial visualisation for excavation, offering both theoretical insights and practical applications. Methodologically, it follows a structured mixed-methods approach, combining literature review, industry engagement, and experimental testing. Practically, it identifies user preferences, visualisation methods, and key adoption factors such as usability and accessibility. Overall, this thesis fills the gap between emerging AR technologies and their integration into safer excavation practices.

Dedication

To my father, for his endless wisdom and encouragement,

To my mother, for her unwavering love and support.

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The successful completion of this research has been greatly facilitated by the assistance and support of numerous individuals, friends, and organisations I have encountered and collaborated with throughout this journey.

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Abbreviations and Acronyms

AI: Artificial Intelligence

AR: Augmented Reality

BIM: Building Information Modelling

GIS: Geographical Information Systems

GPR: Ground Penetration Radar

HCI: Human-Computer Interaction

IoT: Internet of Things

OST: Optical-See-Through

PPE: Personal Protective Equipment

VR: Virtual Reality

VST: Video-See-Through

Chapter 1: Introduction

The construction industry is inherently high-risk, with accident rates nearly double those in other sectors (Le *et al.*, 2015). This is largely due to the dynamic and constantly changing nature of construction sites, frequent use of heavy equipment, and the presence of multiple workers performing varied tasks in close proximity. Although safety plans such as regular inspections, training programmes, and risk monitoring are widely implemented, incident rates on construction sites remain high (Zhou *et al.*, 2013; Guo *et al.*, 2017b). These accidents endanger workers, disrupt project timelines, and incur substantial costs for contractors, project owners, and insurance providers. In particular, safety management strategies have not always yielded the desired outcomes, even with PPE, regulations, and hazard awareness campaigns. One reason for this shortfall is that safety measures are not always followed consistently on site, often because of tight project deadlines or limited staff and equipment. Additionally, workers may lose interest in following safety protocols when they are too repetitive or do not address the actual risks present on a specific site (Harvey *et al.*, 2001; Coglianese *et al.*, 2003). Emerging technologies such as AR have been introduced into construction safety practices to address this gap, offering new ways to visualise critical information (Hou *et al.*, 2014; Asadzadeh *et al.*, 2020).

AR, which overlays digital content onto real-world views, enables intuitive, real-time interaction with virtual information (Stanton *et al.*, 2013). It is increasingly recognised as a key component of the fourth wave of technological innovation in construction—called Construction 4.0—alongside Building Information Modelling (BIM), Virtual Reality (VR), robotics, Artificial Intelligence (AI), the cloud, and the Internet of things (IoT) (El Jazzar *et al.*, 2020; Newman *et al.*, 2020). Among these, AR is particularly suited to improving construction safety by providing workers with spatial awareness, hazard recognition, and training tools

(Wang and Dunston, 2007; Guo *et al.*, 2017a). Recent advancements in AR have made it technically feasible to apply AR in various field conditions, but practical implementation remains sparse in construction (Park and Kim, 2013; Behzadan *et al.*, 2015; Chi *et al.*, 2022). Furthermore, integrating AR into safety workflows requires intuitive visualisation methods that match construction workers' cognitive and physical demands (Zhou *et al.*, 2017).

One area where the adoption of AR remains underexplored is in preventing underground utility strikes during excavation. Underground utilities such as sewage systems, telecommunication lines, and electricity, water, and gas distribution networks are fundamental to modern infrastructure (Fenais et al. 2018; Wu et al., 2021). However, their concealment underground leaves them vulnerable to accidental strikes during excavation. An incident in August 2020 in Baltimore, Maryland, a contractor struck a gas line, resulting in an explosion that killed one person, injured others, and destroyed multiple homes (Li, 2020). Such events highlight the urgency of adopting more effective technologies to mitigate excavation-related risks. Beyond explosions, excavation-related incidents span urban utilities, transport corridors, industrial plants, and tunnelling, with consequences including fatalities, mass electricity outages, gas releases and chemical exposure (Crowley, 2025; Corso et al., 2003).

According to the Common Ground Alliance (2022), the U.S. alone reported over 500,000 utility damage incidents in a single year, indicating that current practices are insufficient to prevent these accidents on a global scale. Similar issues are observed in countries like the UK, Canada, and Australia, where efforts to centralise utility maps have not resolved challenges in field accuracy, timeliness, and usability (Abebe and Tesfamariam, 2020; Muthalif *et al.*, 2022a).

Current utility locating techniques, including Ground Penetrating Radar, electromagnetic locators, and manual digging, face a range of limitations, from poor visibility in certain soil conditions to operator-dependent accuracy (Uslu et al., 2016; Muthalif et al., 2022). Two-dimensional drawings and marking systems, such as flags and spray paint, are still commonly used, but these can be lost once excavation begins (Talmaki and Kamat, 2014). Services like BeforeUDig in New Zealand and One-Call in the United States aim to streamline communication between asset owners and contractors. Still, data coverage remains incomplete, especially when utility owners are not registered participants in these services (Fenais et al. 2020). Moreover, these systems lack integration with dynamic on-site visualisation tools.

In contrast, AR offers the potential to fill this information gap by visualisation of underground utilities before and during excavation. These visualisations can reduce uncertainty and improve decision-making on-site (Muthalif et al., 2022; Khorrami Shad et al., 2022). AR systems, such as OST and VST, enable workers to see digital representations of utility networks overlaid onto the real environment. Such overlays have been successfully applied in other areas of construction, including progress tracking (Lee and Akin, 2011), hazard avoidance (Kim et al., 2017), equipment training (Yang et al., 2021), and quality assurance (Sidani et al., 2021). Despite promising studies in these domains, AR use in excavation remains in an experimental phase, lacking empirical evaluations on usability, accuracy, or user trust in live excavation contexts (Fenais *et al.*, 2018b).

Despite these capabilities, the adoption of AR to avoid underground utility strikes remains limited. Industry hesitancy, technical complexity, and unclear cost-benefit outcomes have prevented AR from being widely implemented in excavation practices (Makkonen et al., 2016; Khorrami Shad et al., 2022). These challenges highlight a clear research gap in understanding how AR can be effectively and practically integrated into real-world construction workflows. As construction environments are often complex, time-sensitive, and involve multidisciplinary teams, any proposed AR solution must address user expectations, device limitations, training needs, and environmental constraints (Behzadan and Kamat, 2007). Together, these factors highlight the need for a comprehensive study that considers the technological feasibility of AR and its usability from an HCI perspective.

This thesis addresses that gap by systematically investigating the potential of AR to support utility strike prevention during excavation. It adopts a multi-phase approach, involving a literature review, industry engagement through interviews, and controlled experimental studies. This thesis aims to contribute theoretical insights and practical recommendations for using AR to avoid underground utility strikes during excavation. It identifies user preferences, adoption barriers, and visualisation effectiveness, thus informing both academia and industry professionals on how AR technologies can be effectively adopted for excavation. By integrating the Theory of Affordances and Task Load into experimental testing, the study evaluates AR technologies based on performance as well as analyses user experience, cognitive demand, and spatial awareness in excavation contexts. The findings aim to serve as a foundation for the next generation of user-centred AR tools in construction safety.

1.1 Research Problems and Questions

AR has emerged as a promising technology in the construction industry, offering new possibilities for enhancing safety, improving communication, and supporting real-time decision-making (Dunston and Wang, 2005; Guo *et al.*, 2012; Chi *et al.*, 2013; Li *et al.*, 2018). While various studies have explored the application of AR for construction tasks, such as training and hazard recognition (Kim *et al.*, 2017; Baek and Choi, 2020), AR for preventing underground utility strikes during excavation remains underexplored. Existing literature focuses on surface-level hazards and safety communication, with limited attention to the challenges posed by hidden infrastructure. Unlike above-ground risks, underground utilities are often unmapped, inaccurately marked, or inaccessible through traditional detection methods, making real-time spatial visualisation crucial. This gap indicates a critical need for research that tests AR's effectiveness in underground scenarios and explores its usability, reliability, and industry acceptance for utility strike prevention.

Underground utility strikes continue to pose serious risks to construction safety and project outcomes, often resulting in worker injuries, fatalities, equipment damage, costly repairs, and significant delays (Fenais *et al.*, 2018a; Fenais *et al.*, 2018b; Abebe and Tesfamariam, 2020). These incidents are disruptive and have long-term legal and financial consequences for contractors and asset owners. Although a range of utility locating tools, such as GPR, electromagnetic sensors, and utility mapping services, are commonly used, their effectiveness is frequently limited by various technical and environmental factors (Anchuela *et al.*, 2009; Uslu *et al.*, 2016; Muthalif *et al.*, 2022b; Su *et al.*, 2023a). GPR, for example, can be significantly affected by soil type, moisture content, and the depth or material of the utility being scanned, reducing its reliability in certain site conditions. Similarly, electromagnetic locators require conductive materials and skilled operators, making them less effective in complex or heterogeneous environments.

Furthermore, the industry relies heavily on outdated as-built drawings and surface markers such as spray paint or stakes, which can be lost or become inaccurate during ongoing site work (Talmaki and Kamat, 2014; Maree *et al.*, 2021). The outdated drawing is particularly problematic in urban areas with congested subsurface infrastructure, where overlapping utilities and undocumented assets increase the likelihood of accidental strikes. These challenges demonstrate the urgent need for more robust, real-time, and spatially intuitive methods to support safer excavation practices.

AR has demonstrated significant potential in addressing challenges associated with underground utility strikes by overlaying digital information directly onto the physical environment. This capability allows for more intuitive and spatially aware visualisation of underground utilities, enhancing the accuracy and efficiency of excavation activities (Zhou *et al.*, 2017).

However, the existing body of literature lacks comprehensive studies examining the practical adoption of AR technologies by excavation professionals. While early research has established the technical feasibility of AR systems in controlled environments, there is a lack of empirical studies focusing on user perceptions, effectiveness, and the practical barriers to widespread adoption in real-world construction settings.

To develop AR systems that effectively meet the needs of construction professionals, it is essential to evaluate how these technologies are perceived by end-users, how they compare to traditional utility detection methods, and which visualisation techniques offer the most effective support for locating underground utilities. Studies suggest that user-friendly interfaces, accurate spatial registration, and context-aware information delivery are critical factors influencing the successful adoption of AR in construction (Wang and Dunston, 2007). Furthermore, comparative analyses of different AR visualisation methods are necessary to determine their effectiveness in an outdoor scenario (Behzadan and Kamat, 2007).

This thesis addresses the following research questions:

> **RQ1:** What are the main applications and safety-related purposes of AR in the construction literature?
>
> **RQ2:** What are the perceptions, expectations, and challenges of excavation professionals toward adopting AR technology for preventing underground utility strikes while excavating?

RQ3: How do different AR devices compare for excavation tasks?

RQ4: How do different AR visualisation methods compare in visualising underground utilities?

RQ5: What design and implementation recommendations can be developed to guide the creation of AR systems suited to underground utility strike prevention?

1.2 Research Aim and Objectives

In response to the research problems identified in Section 1.1, this study aims to investigate how AR can be effectively adopted to prevent underground utility strikes during excavation activities. The applied importance of these objectives is underscored by industry statistics: in the UK, there are roughly 60,000 accidental strikes on buried pipes and cables each year, as per the UK Government's Geospatial Commission (2021) total economic costs of about £2.4 billion annually; similar datasets in North America report hundreds of thousands of damages per year (Fenais *et al.,* 2020a). These figures highlight the potential value of tools that reduce misinterpretation at the trench. This research contributes to the body of knowledge by providing empirical insights into the usability, perception, and effectiveness of AR technologies in the excavation sector, with a particular focus on AR visualisation methods and user experience. Specifically, the study examines how users interact with different AR visualisation methods regarding sensory, cognitive, functional affordances, task load, and spatial understanding. The study also aims to offer practical recommendations to support the design and implementation of AR systems suited to utility strike prevention.

Therefore, the following research objectives are formulated to guide this study:

O1: To explore the existing academic literature on AR applications in construction safety, with a focus on utility-related tasks.

O2: To identify the perceived needs, expectations, and challenges of excavation professionals regarding the adoption of AR technologies in utility strike prevention.

O3: To evaluate and compare different AR display devices (OST and VST) regarding task load and user preference.

O4: To evaluate and compare different AR visualisation methods for underground utilities based on system affordances and task load.

O5: To provide user-centred design and implementation recommendations for AR systems to prevent underground utility strikes.

1.3 Thesis Outline

This thesis consists of six chapters. This section provides an overview of the content and purpose of each chapter.

Chapter 1: This chapter introduces the research problem, outlines the research questions, and presents the aim and objectives of the study.

Chapter 2: This chapter describes the overall research method, covering research stages and strategies.

Chapter 3: This chapter presents an overview of AR applications in construction safety. The chapter includes a synthesis and interpretation of existing studies, and a discussion of key technical components, including AR display technologies, tracking methods, and HCI. This chapter establishes the research foundation and identifies knowledge gaps in the context of AR for construction safety. This chapter addresses research objective 1.

Chapter 4: This chapter provides a background on current utility locating practices, describes the AR systems tested by participants, and presents their feedback on usability, preferences, required features, and perceived barriers to adoption. The results inform the practical needs and limitations of AR in real-world excavation scenarios. This chapter addresses research objectives 2 and 3.

Chapter 5: This chapter presents the design and findings of a controlled experimental study that evaluates four AR visualisation methods (X-Ray, Shadow, Cross-Sectional, and Combination). The experiment assesses each method based on user perception, affordances (sensory, cognitive, functional), task load, and error analysis. Quantitative and qualitative results are analysed to determine which visualisation methods are most effective and user-friendly for visualising underground utilities. This chapter addresses research objectives 4 and 5.

Chapter 6: This chapter provides a discussion of the findings across all chapters, linking them back to the research questions and objectives. It outlines the key theoretical and practical contributions of the research, highlights its limitations, and proposes directions for future studies aimed at enhancing the adoption and effectiveness of AR in preventing underground utility strikes.

1.4 Summary

Construction remains a high-risk industry with incident rates that persist despite inspections, training, PPE, and hazard campaigns. A critical, under-addressed problem is accidental strikes to underground utilities during excavation. Current practices are constrained by soil and weather conditions, operator dependence, incomplete or outdated records, and the cognitive effort required to interpret plans in situ. AR offers a way to visualise verified subsurface information in context, potentially improving spatial understanding and on-site decision-making; however, practical adoption for utility strike prevention remains limited and insufficiently evaluated in real settings.

This thesis investigates how AR can support safer excavation through a user-centred HCI. It combines a literature review with industry engagement interviews and a controlled experiment that compares AR devices and four visualisation methods. The studies examine usability, perceived task load, affordances, error, with attention to barriers such as accessibility, integration with existing workflows, and environmental constraints. The research questions and objectives focus on current AR applications in construction safety, practitioner needs and adoption challenges, device preferences, the comparative effectiveness of visualisations for underground utilities, and the development of practical, user-centred recommendations for implementing AR to reduce underground utility strikes.

Chapter 2: Research Methodology

This chapter discusses the research methodology and methods used to achieve the project aim: adopting AR to reduce underground utility strikes during excavation. This section begins with a general introduction to the philosophical perspective of research that guided this research and then describes the research approaches in this area. Then, the selection of the approach adopted for this research study is discussed. The section presents the research design and method, the development of the sample selection and the data collection procedures.

2.1 Research Philosophy

Recognising the philosophical stance of a research study is a crucial initial step, as it fundamentally influences the research process (Saunders, 2014; Creswell and Creswell, 2017). In technology adoption studies, this is particularly important because the chosen philosophical position shapes the selection of methods, the interpretation of data, and how user input is understood. A researcher's view of the world and their beliefs about knowledge and reality naturally shape how they frame their research questions and structure their study (Kumar, 2018). These beliefs, known as a research philosophy, guide the methods for collecting, analysing, and generating data, often described through "ontology" and "epistemology" (Sutrisna, 2009). Ontology refers to the assertions and assumptions about the nature of reality, including its existence, appearance, and interactions (Guba and Lincoln, 1994). Objectivism and constructivism are the most commonly discussed distinctions in ontological positions (Sutrisna, 2009). In contrast, epistemology concerns the nature of knowledge and how scholars understand reality, with positivism and interpretivism being its two major branches.

This research aims to investigate how AR can be adopted to reduce underground utility strikes during excavation, with particular attention to the role of HCI in shaping its effectiveness. The researcher believes that HCI significantly influence AR adoption and shape the research objectives. Creswell and Creswell (2017) associate positivism with a conventional approach, where a theory is tested and refined through data collection to build knowledge. Bell *et al.* (2022) add that positivism relies on observable facts, like natural sciences. In contrast, interpretivism emphasises the importance of understanding human interactions to interpret social reality, rather than relying solely on scientific methods (Bell *et al.*, 2022).

Furthermore, Bell *et al.* (2022) differentiate between objectivism, which holds that social phenomena and their meanings exist independently of human perception, and constructivism, which asserts that social realities are constructed through human interaction. Positivism is based on Objectivism, which holds that there is a single objective reality that all people perceive. Interpretivism relies on Constructivism to understand reality, which individuals construct and understand differently (Sutrisna, 2009).

This research aims to investigate how AR can be effectively adopted to prevent underground utility strikes during excavation. It is recognised that HCI, along with various devices and systems involved in the process. The study focuses on a specific context where, although the integration process may appear as an objective reality, it is essential to understand the perspectives and interpretations of the AR users, devices and systems involved. This study does not adopt a strictly positivist or interpretivist stance, allowing for a more flexible approach to address the research problem.

Instead of prioritising one view, the study focuses on identifying the most appropriate methods and approaches to address the research problems. The literature supports the use of "*pragmatism*", the idea that what works best is most important for addressing research questions (Murphy and Murphy, 1990; Tashakkori, 2010; Saunders, 2014). According to pragmatism, research begins with a problem and aims to provide practical solutions to inform future practices (Saunders, 2014). Regardless of the methods used, researchers should focus on the research problem and employ all necessary approaches to fully understand its challenges and solutions (Creswell and Creswell, 2017).

2.2 Research Approach

The development of theory plays a pivotal role in determining a suitable research design, as it is influenced by the extent to which the theoretical framework is defined (Saunders, 2014). Irrespective of the research type, theory remains a fundamental element, explaining patterns observed (Bryman, 2016). In the research process, the collection and analysis of data are aimed at generating knowledge (Bello *et al.*, 2024). The interaction between theory and research is shaped by two principal considerations: first, the type of theory being addressed, and second, whether the research seeks to test existing theories or to generate new ones (Saunders, 2014; Gray, 2021).

Inductive and deductive reasoning represent two distinct research approaches, differing primarily in how they engage with existing knowledge and approach data collection. Deductive research begins with hypotheses derived from an existing body of knowledge. These hypotheses are then tested through data collection and analysis. This approach is closely associated with objectivism and positivism, which assume the existence of a single objective reality (Sutrisna, 2009). In contrast, inductive research emphasises the collection and analysis of data to generate findings, with existing knowledge used to inform analysis when needed. Inductive reasoning permits a logical gap between premises and conclusions, where conclusions are judged to be supported by the observations made (Ketokivi and Mantere, 2010). While inductive and deductive approaches are conceptually distinct, they are not mutually exclusive and can be integrated in research (Saunders and Tosey, 2012; Saunders, 2014). This integrative strategy, referred to as the abductive approach, enables researchers to use the strengths of both reasoning approaches (Gill and Johnson, 2010; Schoch, 2020).

Given the need to incorporate both objectivist and constructivist perspectives, this research necessitated the collection of data on current practices to support theory development and theory testing. An objectivist perspective was important to evaluate the performance of the AR system. In contrast, a constructivist perspective was necessary to understand the expectations of excavation professionals and how users interact with AR technology. Accordingly, a mixed approach was followed, integrating elements of both deductive and inductive reasoning. The study commenced with deductive reasoning, with a problem definition, followed by an inductive reasoning approach to generate a theory. The selection of this approach was informed by the nature of the research questions, the researcher's prior experiences, and the intended audience of the study (Creswell and Creswell, 2017).

This research focused on exploring how AR can be applied to prevent underground utility strikes during excavation. A conceptual understanding was initially developed by reviewing the existing literature, using a deductive approach to identify key themes such as AR safety applications in the construction sector, usability factors, and visualisation devices. This method helped shape the direction of the research and informed the development of research questions. Then, empirical data were gathered through interviews with industry professionals and a controlled experiment involving AR visualisation methods. These stages adopted the inductive reasoning approach, allowing the researcher to analyse user feedback and evaluate the performance of different AR visualisation methods. The combined use of deductive and inductive reasoning aligns with the methodological guidance of Saunders (2014), where data are collected to explore a phenomenon, identify themes, explain patterns, and modify or create new theories, which are then tested through further data collection.

2.3 Research Methods

At the data level, data can typically be divided into quantitative, qualitative, or mixed methods (Sutrisna, 2009; Saunders, 2014; Bell *et al.*, 2022). The differences reflect philosophical perspectives, preferred research strategies and the tools used for data collection and data analysis (Creswell and Creswell, 2017). Quantitative research is often related to a positivist perspective, which assumes that reality is objective and measurable. In contrast, qualitative research is typically based on an interpretivist perspective.

Quantitative research typically involves establishing a research aim, defining the population and sample, choosing appropriate data collection tools, and analysing the relationships between defined variables. A key focus in this process is ensuring that the measurements used are reliable and valid (Bell *et al.*, 2022). In contrast, qualitative methods explore the qualities of phenomena, acknowledging the subjective nature of reality (Sutrisna, 2009). The selection of research methods is typically informed by the overall research approach. In this study, both deductive and inductive reasoning were applied at different stages, leading to the adoption of a mixed methods approach.

Using qualitative and quantitative methods allows the research to reduce the limitations of relying on a single approach (Knight and Ruddock, 2009; Fellows and Liu, 2021). This mixed-methods strategy supported inductive reasoning to explore patterns emerging from the data and deductive reasoning to test theory-informed ideas.

While qualitative research is commonly associated with an interpretivist perspective, which seeks to understand individuals' subjective experiences (Knight and Ruddock, 2009), it is also aligned with pragmatism, where methodological choices are shaped by the research context and outcomes (Tashakkori, 2010; Saunders, 2014; Creswell and Creswell, 2017).

Qualitative research often follows an inductive approach, where patterns and themes emerging from the data contribute to developing or refining theory (Saunders, 2014; Gray, 2021). However, qualitative work can also involve deductive reasoning when the aim is to test or explore established theories in new contexts (Yin, 2012).

This study uses inductive and deductive reasoning to explore the research problem from different perspectives and contribute to theory development, following a similar approach used in earlier studies (Saunders and Tosey, 2012; Gray, 2021). This reasoning is reflected in the different phases of the study:

Objective 1 was achieved through a systematic literature review, using a deductive approach to classify safety AR applications in construction and identify research gaps.

Objective 2 was addressed using qualitative methods via semi-structured interviews with 31 excavation professionals. This inductive phase identified user needs, adoption barriers, and contextual challenges.

Objective 3 was achieved by comparing OST and VST devices using data collected from semi-structured interviews and qualitative and quantitative analyses.

Objective 4 was fulfilled by a within-subject experiment involving 60 participants. Quantitative data (e.g., affordance scores, task load, and error rates) and qualitative feedback were analysed to compare X-Ray, Shadow, Cross-Sectional, and Combination methods.

Objective 5 was accomplished by integrating findings from all prior stages to produce evidence-based, user-centred guidelines for adopting AR in excavation workflows. Figure 2.1 summarises the three-stage research methods, systematic literature review, industry interviews with AR exposure, and a controlled experiment, showing inputs, sample sizes, instruments, analyses, and outputs.

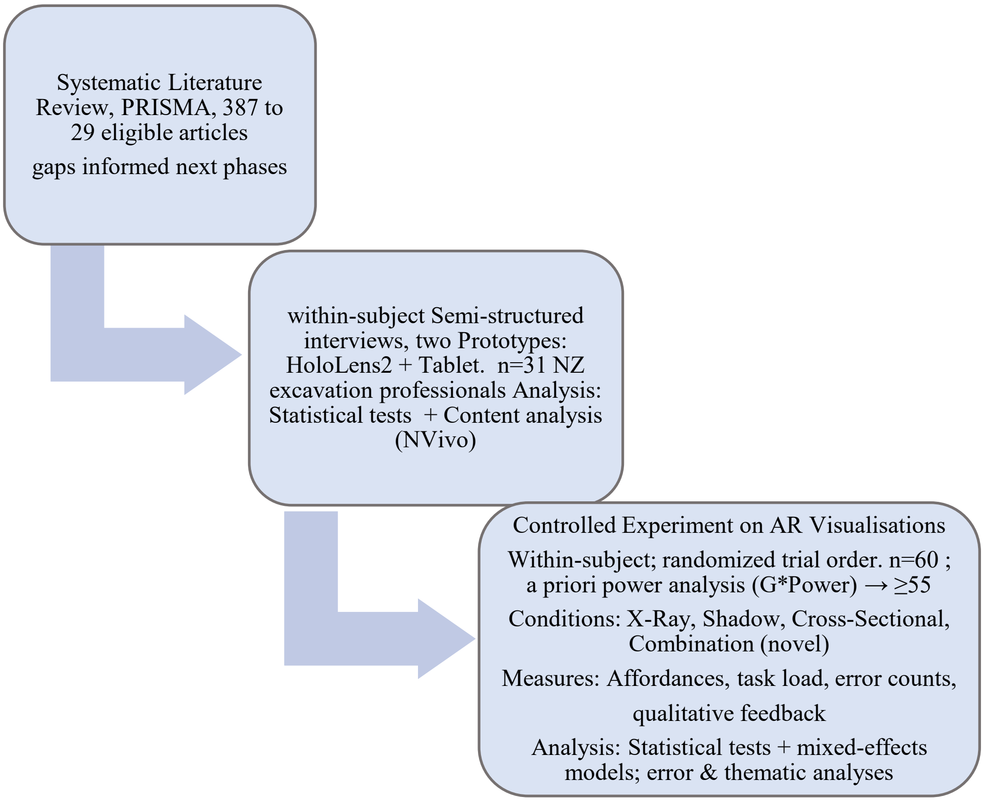


Figure 2.1: Overall research methodology

2.4 Conceptual and Research Frameworks

This doctoral research is structured across three main chapters (Chapters 3 to 5), each corresponding to one of the three key stages of the study: the systematic literature review, the industry engagement through semi-structured interviews, and the experimental evaluation of AR visualisation methods. This structure was designed to progressively build knowledge, starting with a broad review of the field, followed by direct insights from industry practitioners, and concluding with empirical testing. The relationships between the main concepts and variables explored throughout the research are outlined in the conceptual framework presented in Figure 2.2. This framework illustrates the logical flow of the investigation and demonstrates how each phase informs the next.

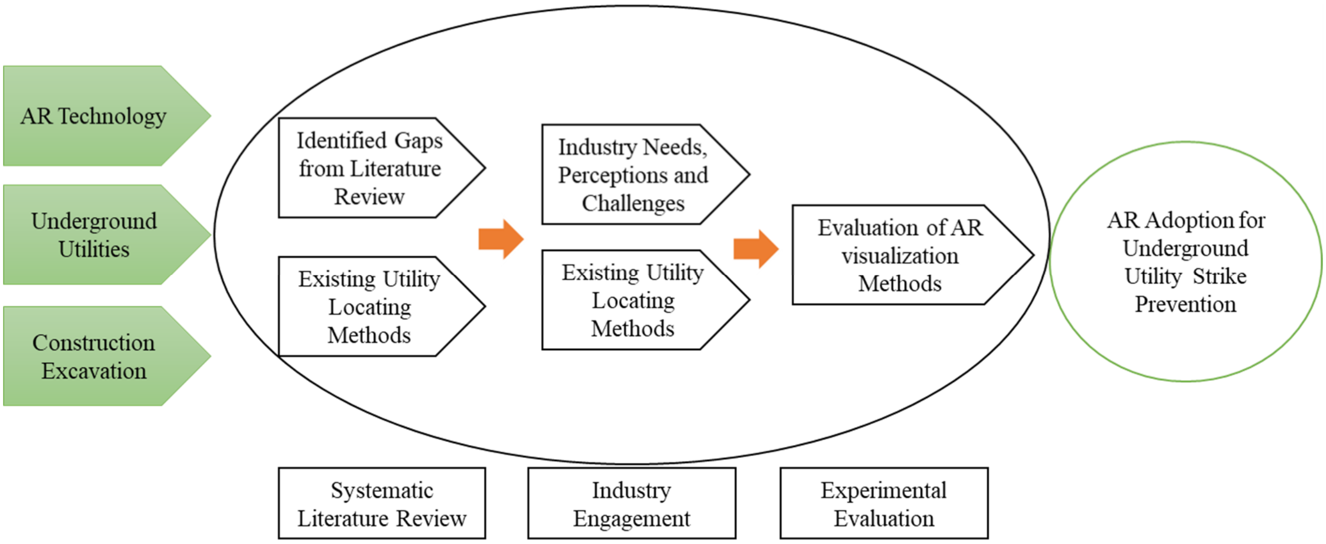


Figure 2.2: Conceptual Framework (Donaldson, 2001)

The conceptual framework presents the key elements shaping the adoption of AR to prevent underground utility strikes in excavation work. The framework is designed to provide a clear view of the research path, starting from identifying gaps in the literature, progressing through the investigation of industry perspectives, and evaluating AR visualisation methods. It begins with a systematic review to define the current landscape of AR in construction safety. It then incorporates findings from interviews with industry professionals to explore perceived barriers and practical needs. Finally, it integrates experimental data comparing different AR visualisation methods based on user experience. These stages are informed by both inductive and deductive reasoning.

2.5 Ethics

As this study involved human participants, obtaining ethics approval was essential to ensure the research was conducted responsibly and under ethical standards. The project has been evaluated by peer review and judged to be low risk. The research design incorporated several ethically sensitive components, including semi-structured interviews and an experimental study. Potential risks identified included participant discomfort when using unfamiliar AR devices, data privacy concerns, and the possibility of perceived pressure to participate, particularly among industry professionals. To mitigate these risks, participants were provided with clear and detailed information sheets outlining their rights, including the right to withdraw at any time without consequence. Informed consent was obtained prior to participation. During the experimental sessions, safety protocols were followed, and support was available in case of technical difficulties or user discomfort. All data were anonymised and securely stored to protect participant confidentiality. Ethics approval was granted under the notification number 4000026685, which remains valid for three years from 28 October 2022 (see Appendix 1).

2.6 Data Collection

This study employed multiple sets of data across different research stages, each used to address specific research questions. Following the initial literature review, qualitative data were collected through semi-structured interviews with 31 excavation professionals (see Appendix 4). This stage aimed to capture insights into current industry practices, user perceptions, and expectations regarding AR technology. The population was New Zealand–based excavation practitioners across roles. A sample was used with inclusion criteria of age over 18 and current employment in the NZ excavation industry; participants were recruited via industry associations, contractor organisations, and professional networks. Consistent with HCI guidance that 30 interviews are acceptable for formative studies (Lazar *et al.*, 2017), and stopping when thematic saturation is reached, data collection ceased at 31 once no new codes emerged. Thematic analysis was used to identify recurring patterns, themes, and industry expectations, which informed the subsequent experimental design. To mitigate potential bias, this study followed approved ethics procedures, including voluntary participation and the right to withdraw, used a neutral study description and recruitment materials that did not suggest any right answers or preferred outcomes, ensured no line-management relationships, anonymised all results and blinded analyses to participant identities, no conflicts of interest, and applied predefined inclusion and exclusion criteria.

In the next phase, presented in Chapter 5, a controlled experimental study was conducted with 60 participants who interacted with four different AR visualisation methods. This stage generated both quantitative and qualitative data. Participants were asked to complete questionnaires, including Likert-scale assessments, to evaluate perceived sensory, cognitive, and functional affordances, as well as task load. The inclusion criteria were age over 18 and minimum education at or above high-school level. An a priori Wilcoxon power analysis (G*Power) indicated a minimum n=55 to detect the targeted effect size; we recruited n=60 to allow for attrition. These data were analysed using statistical tests and mixed-effects models to assess differences across visualisation methods. To mitigate potential bias, this study followed approved ethics procedures, including voluntary participation and the right to withdraw, used a neutral study description and recruitment materials that did not suggest any right answers or preferred outcomes, ensured no line-management relationships, anonymised all results and blinded analyses to participant identities, no conflicts of interest, and applied predefined inclusion and exclusion criteria. In parallel, qualitative feedback was gathered through post-session open-ended questions and was analysed using content analysis to capture user preferences and experiential insights (see Appendix 5).

2.7 Summary

This study adopts a pragmatist philosophical stance to investigate how AR can be used to reduce underground utility strikes, recognising that both objectivist and constructivist views are relevant to construction practice. Accordingly, the research integrates deductive and inductive logics in a mixed-methods design. A systematic literature review first clarifies the state of knowledge and gaps; industry engagement through semi-structured interviews then elicits practitioner expectations, adoption barriers, and contextual constraints from an affordance perspective. Insights from these stages inform a controlled experiment that compares four AR visualisation methods and device form factors. The conceptual framework goes from literature review to industry engagement and seeks experimental evaluation, with each phase shaping the next.

Participation was voluntary with informed consent, right to withdraw, anonymised IDs, and secure data storage. Interview data were thematically analysed to derive recurrent patterns and industry expectations, which guided task and interface choices for the experiment. Experimental data combined quantitative measures with qualitative comments.

Chapter 3: Literature Review

The current chapter is based on the following article:

Khorrami Shad, H., Tak Wing Yiu, K., Lovreglio, R., & Feng, Z. (2024). State-of-the-art analysis of the integration of AR with construction technologies to improve construction safety. *Smart and Sustainable Built Environment*, 13(6), 1434-1449. https://doi.org/10.1108/SASBE-07-2022-0151.

3.1 Introduction

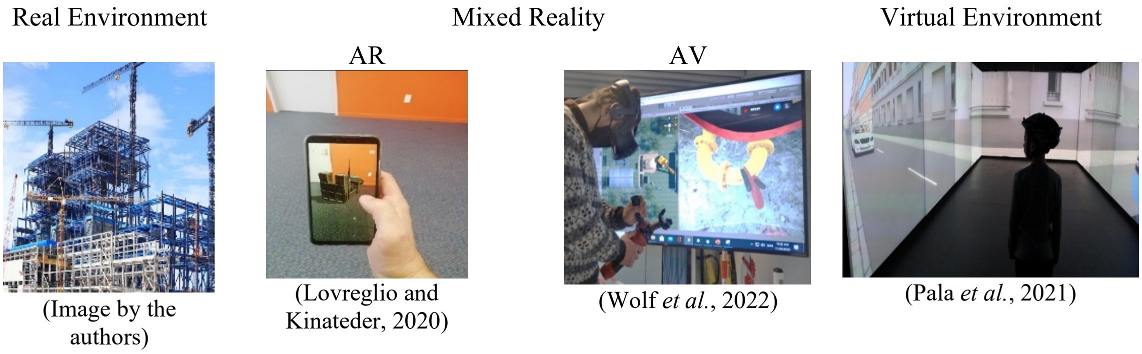
The construction industry is a risky business worldwide (Sherratt *et al.*, 2015). Accidents, injuries, and fatalities commonly occur, and accident rates are about twice those in non-construction sectors (Le *et al.*, 2015). Also, it has been shown that safety on the construction site, on its own, has the non-negligible potential to improve workers' productivity (Hasanzadeh and De La Garza, 2020). Safety plans, such as inspection, training, and monitoring, have improved workers' awareness and behaviours toward the dangerous environment; however, the reported accident rates are still worryingly high (Guo *et al.*, 2017b). Safety management related to a construction project is the most frequently used practice to control risks and reduce unsafe activities (Zhou *et al.*, 2013). However, the high rates of construction site injuries and fatalities indicate that commonly applied safety practices such as PPE, education and safety regulations have not yielded desired results (Harvey *et al.*, 2001; Coglianese *et al.*, 2003). Information visualisation practices have been incorporated into safety management techniques to improve construction safety (Asadzadeh *et al.*, 2020).

Advanced technologies, such as AR, have been considerably implemented to enhance working conditions for workers. AR creates a context where digital data is superimposed on a mainly actual world view (Hou *et al.*, 2014). Recently, AR technology has gained considerable attention from academics, who aim to provide an environment enabling worksite staff to communicate regardless of distance (Lee *et al.*, 2014). AR technology, which allows access to information and visual interaction, has the potential to provide efficacious ways to identify and mitigate hazards (Stanton *et al*., 2013). AR has also been presented as an effective platform for training scenarios in construction (Wang and Dunston, 2007).

The construction industry is experiencing an ever-increasing growth in the integration of technologies throughout its fourth wave of technological advancement, known as Construction 4.0 technologies (El Jazzar *et al.*, 2020). AR is seen as a core technology for this revolution (El Jazzar *et al.*, 2020); the other Construction 4.0 technologies are: (1) Building Information modeling (BIM), by which a 3-dimensional (3D) model of the structure is created (Doan *et al.*, 2020), (2) VR, which allows users experience a completely immersive virtual environment, (3) Robotics that duplicate human actions, (4) AI that duplicates human cognitive ability, (5) Cloud to real-time information sharing, and (6) IoT which provides a persistent and intelligent connection between natural objects and a virtual model (Klinc and Turk, 2019; El Jazzar *et al.*, 2020; Newman *et al.*, 2020; ElMenshawy and Marzouk, 2021).

Several review studies have been carried out to identify existing AR applications for construction health and safety. For example, Li *et al.* (2018) and Moore and Gheisari (2019) presented an in-depth view of the theoretical synthesis of AR and VR applications by reviewing and classifying AR and VR applications in construction safety. Also, Guo *et al.* (2017a) and Gao *et al.* (2019) assessed the visualisation in construction safety and found it an effective technology for training and reducing hazards on construction worksites. However, previous review articles have not elaborated on the integration of AR with the Construction 4.0 technologies. As a result, the main aims of this study are to address the aforementioned limitation and gap by investigating the body of knowledge of AR applications in construction safety and to guide future academic research directions. A systematic literature review may help academics and industry experts uncover critical areas of study by providing them with a better perspective on the state-of-the-art field of study and the related challenges. Furthermore, investigating the connection between technologies contributes to collaborative research opportunities and is a primary way to meet the digital demands of Construction 4.0 advancement (El Jazzar *et al.*, 2020). This study, therefore, undertakes a review of previous studies on use of AR and to explore AR interactions with the Construction 4.0 technologies in construction safety literature.

It is essential to unambiguously clarify the differences between Mixed Reality (MR), AR, VR and Augmented Virtuality (AV) since they have become debated topics in the safety literature in recent years (Feng *et al.*, 2018; Li *et al.*, 2018; Bottani and Vignali, 2019; Lovreglio and Kinateder, 2020). All the systems present virtual objects to participants; however, they differ in how virtuality is linked to reality (Milgram and Kishino, 1994). VR presents artificial content without interaction with the physical world, while MR contains aspects of the natural world and incorporates facets of pure reality and pure virtuality (Carmigniani *et al.*, 2011). As shown in figure 3.1, MR features reality and virtuality, and consists of AR and AV (Feng *et al.*, 2018). With AR, virtual contents are brought into an actual scene, and most visual perception comes from the real world (Carmigniani *et al.*, 2011; Shanbari *et al.*, 2016; Flavián *et al.*, 2019). Conversely, AV, which is not discussed in this study, monitors some real elements in a predominantly virtual world (Ternier *et al.*, 2012).



(Image by the authors)

(Lovreglio and Kinateder, 2020)

(Wolf *et al.*, 2022)

(Pala *et al.*, 2021)

Figure 3.1: Virtuality continuum by Milgram and Kishino (1994)

AR content can be displayed by VST, OST (Lovreglio and Kinateder, 2020), or projective AR devices (Zhang *et al.*, 2020). In a VST device, AR content is captured by a camera on a non-transparent screen, such as a smartphone or tablet (Lovreglio and Kinateder, 2020). In contrast, OST devices display AR objects onto transparent head-mounted devices, e.g., Magic Leap 1, Microsoft HoloLens 2, and Google Glass (Lovreglio and Kinateder, 2020); while projective AR utilises projection equipment to demonstrate virtual objects in the natural environment (Zhang *et al.*, 2020). The correlation between the factual background and AR device outlook position is called "Registration" or "Alignment" (Mizuno *et al.*, 2004). The purpose of alignment is to orient superimposed virtual objects in accordance with reality (Behzadan and Kamat, 2007). Similarly, geometric registration between the live media content and rebuilt virtual model image is called "Tracking" (Bokhari *et al.*, 2020), and is aimed at finding a user's location to augment nearby related virtual models (Jian *et al.*, 2018). To this end, Kim *et al.* (2018) proposed three tracking technologies: vision-based, sensor-based, and hybrid tracking methods. In vision-based tracking methods, nearby visual characters (e.g., markers or unique objects) are used to identify the location. In sensor-based tracking methods, sensors like Global Positioning System (GPS), wireless sensors, Bluetooth, or radio frequency identification present specific location data (Kim *et al.*, 2018). Hybrid tracking methods use visual features and sensors (Kim *et al.*, 2018).

3.2 Review Methodology

The methodology of this study follows the systematic principles presented by Kim *et al.* (2018). The method adopts a five-step process: (1) framing research questions and providing search keywords; (2) identifying databases and conducting an initial search; (3) evaluating the quality of the study; (4) summarising the findings; and (5) interpreting the results.

This study explores AR interactions with Construction 4.0 technologies in construction safety literature. The paper analyses specific purposes to leverage AR technology, then reviews AR integrations with Construction 4.0 technologies in the previous studies of construction safety. Hence, the following research questions are applied:

Research Question 1 (RQ1): What are the specific aims of AR applications in construction safety academic literature?

Research Question 2 (RQ2): What Construction 4.0 technologies have been integrated with AR in construction safety academic literature?

To get the maximum coverage of publications and to address these research questions within academic literature, a comprehensive keyword search string was developed:

("*augmented reality*" OR *"mixed reality"*)

AND

("*construction*")

AND

("*safety*" OR "*health*" OR "*safe*").

The keywords were applied to databases to acquire relevant articles and exclude irrelevant results. A comprehensive exploration was conducted utilising well-established databases—Google Scholar, IEEE Xplore, Web of Science, and Scopus. Also, citations of the most frequent review papers were manually added as a complementary method to cover any missing papers. This review focused on research articles published in peer-reviewed journals and conference proceedings.

Following the keyword search of the specified data sources and journals, 387 potentially relevant articles were extracted during the identification stage. The number of articles found in each database is shown in figure 3.2. Specifically for Google Scholar, 15 pages with ten articles on each page were browsed, but the number of relevant articles significantly dropped after the first ten pages. As a result, the first 100 articles from this database were obtained initially. These 387 papers mentioned keywords in the title, abstract, or keywords. In this step, no other restrictions were imposed.

After removing duplicates, to evaluate the eligibility of the studies, the articles were manually checked by their abstracts, and those not directly associated with construction safety were filtered out. Afterwards, the full text of the remaining articles was checked to determine if AR is in construction safety, and at least one of the research questions of this article was addressed. Consequently, 29 publications (hereafter called eligible papers) were identified after the step-by-step evaluation of studies. The procedure named Preferred Reporting Items for Systematic Literature Reviews and Meta-Analyses (PRISMA) (Moher *et al.*, 2010) was deployed to register this process (see figure 3.2).

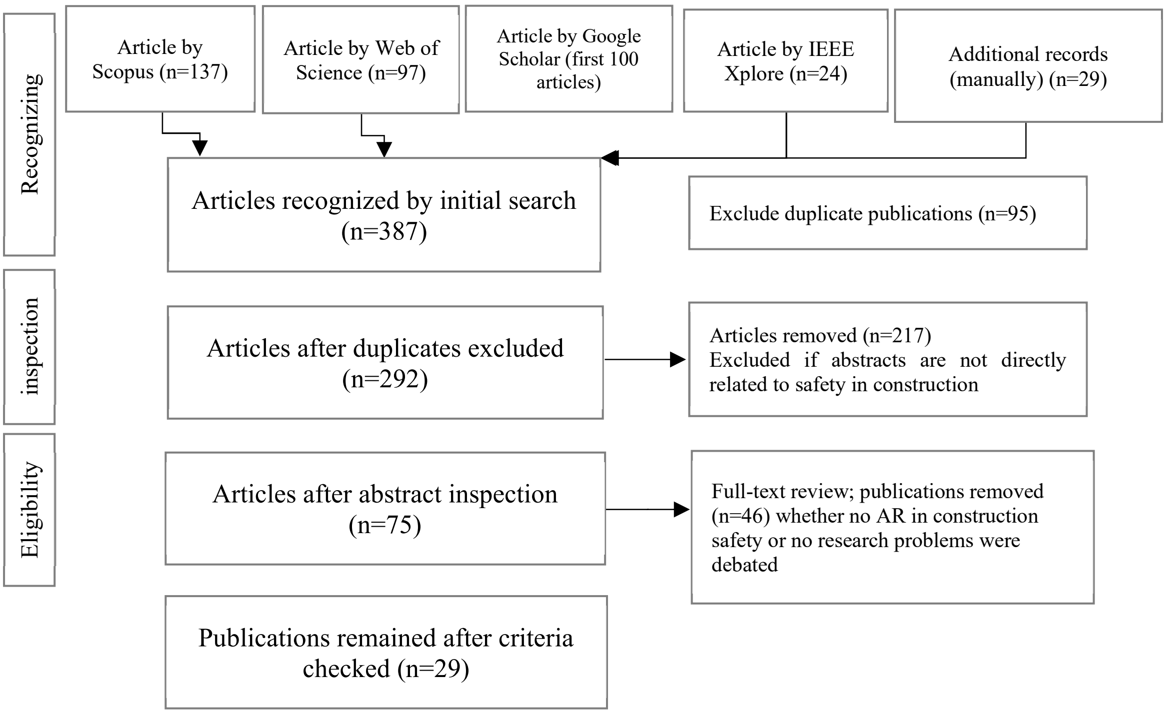


Figure 3.2: The framework of the systematic literature review (Moher *et al.*, 2010)

3.3 Result

In this step, the eligible papers were reviewed, and the evidence was consolidated from the academic literature to answer the two research questions pointed out in section 3.2.

3.3.1 Summarising the Evidence

The eligible papers were systematically classified to segregate the content and facilitate the interpretation of evidence. table 3.1 provides a summary of the evidence retrieved from the eligible papers. Columns 1 and 2 demonstrate the complete safety applications of AR in construction (answer to research question 1). Safety aims of AR in construction safety are explicable in terms of pre-event, during-event, and post-event applications. Pre-event application refers to AR safety practices that prevent or minimise a construction-related disaster in advance. Similarly, during-event and post-event applications are associated with safety AR applications when a disaster is happening and has occurred, respectively. Column 3 gives Construction 4.0 technologies integrated with AR in construction safety (answer to research question 2). The integrated technologies with AR consist of BIM, IoT, AI, Robotics and Cloud. These findings are introduced here and then interpreted in section 3.3.2.

Table 3.1: Summarising evidence for each proposed research question

Safety aims	Safety sub-aims	Integrated technologies with AR
Pre-event application	intelligent operation	BIM
	training	IoT
	safety inspection	AI
	hazard alerting	Robotics
During-event application	pinpointing hazard	Cloud
Post-event application	safety estimation	

3.3.2 Interpreting The Evidence

This section discusses the outcomes of the eligible papers for each research question.

Research question 1: What are the specific aims of AR applications in construction safety academic literature?

As illustrated in column 1 in table 3.1, specific aims of AR applications in construction safety are explicable in terms of pre-event, during-event, and post-event applications. The most common objective of eligible papers was pre-event applications, with 26 out of 29 publications (89.7%), followed by during-event application articles with 2 out of 29 publications (6.9%). Finally, one article stressed a post-event AR safety application (3.4%). Further details of all aims are discussed below. Where reported, the studies spanned North America, Europe, and East Asia and were conducted in laboratory/simulation settings, pilot sites, and active projects, covering building (e.g., housing/office), industrial (e.g., LNG), and infrastructure works (e.g., tunnelling, utilities, highways).

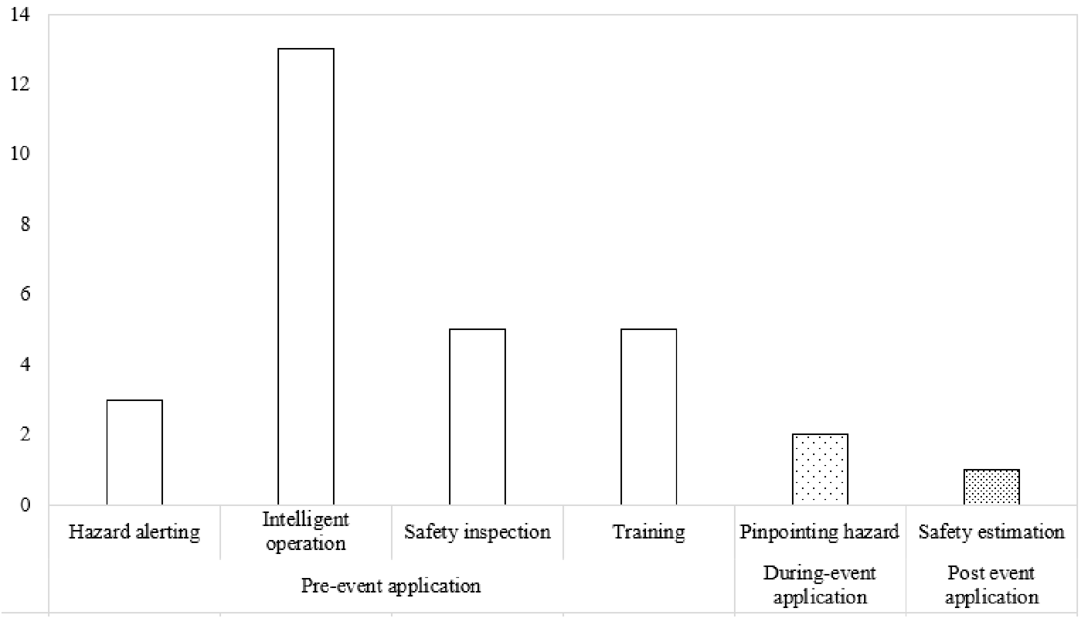


Figure 3.3: Number of publications for each safety sub-aim

3.3.2.1 Pre-event application

As shown in table 3.1 and figure 3.3, the purpose of pre-event applications fell into the following four groups: (1) intelligent operation, (2) training, (3) safety inspection, and (4) hazard alerting. To provide pre-event applications, as shown in table 3.2, the publications most commonly focused on intelligent operation (13 out of 29, 44.8%), followed by training and safety inspection (each 5 out of 29, 17.2%), and finally, hazard alerting application (3 out of 29, 10.3%). Intelligent operation utilising AR for construction workers, designers, engineers, and machinery operators is the most common safety application of AR in construction literature. AR has great potential to improve on-site performance and facilitate safety execution by augmenting virtual construction information onto the physical world in real-time (Park and Kim, 2013; Xiang *et al.*, 2021). In terms of context, intelligent-operation studies appeared across building construction and infrastructure (e.g., crane operations, utilities, tunnelling), with several conducted on active job sites and others in controlled mock-ups. For instance, to overcome low productivity in retrieving information and alleviating the mental workload of construction staff, Wang *et al.* (2014) presented an AR framework, which displayed as-planned data onto actual environments. Therefore, the participants could control inconsistencies between the actual and the scheduled progress (Wang *et al.*, 2014). Similarly, Foroughi Sabzevar *et al.* (2021) dealt with the traditional issue of construction staff-drawing sheets interaction. Specifically, interpreting two-dimensional (2D) drawings with different types of symbols and a referencing may result in distraction and poor data transfer between the designers and construction crews (Foroughi Sabzevar *et al.*, 2021). To overcome this, Foroughi Sabzevar *et al.* (2021) developed and laboratory tested augmented virtual information that could be accessed on mobile phones. Across these exemplars, authors commonly reported improved information access, reduced cognitive effort, or fewer interpretation errors relative to paper-based workflows, although many evaluations were short and lab-based, so external validity remains limited.

To decrease construction information complexities for workers, by utilising projective AR, Xiang *et al.* (2019, 2021) developed and tested a visible, to the naked eye, prototype that superimposed virtual information onto the physical surface. The prototype provides designers and workers with a display of information in the exact location and enhances workers' productivity by identifying pipeline locations before or during installation on construction sites (Xiang *et al.*, 2019, 2021). In contrast to traditional AR applications, Ogunseiju *et al.* (2021) adopted digital twins to improve construction ergonomic risks associated with workers' postures. This prototype contributed to self-control ergonomic risk alleviation by visualising worker body position as a virtual replica, via the head-mounted device, and wearable sensors (Ogunseiju *et al.*, 2021). To be more specific, posture evaluation techniques used in this study consisted of monitoring angles and holding times of body segments. The results of this study show that this prototype provides an opportunity to take self-corrective ergonomic actions (Ogunseiju *et al.*, 2021). These studies were performed in controlled environments and on live sites, and reported positive usability or performance signals (e.g., quicker orientation, posture correction), while noting the need for longer-term field validation.

Through intelligent operation, three studies focused on facilitating machinery operator tasks by instant way-finding for crane operators (Lin *et al.*, 2020), remote control of cranes (Hasan *et al.*, 2021), and simulating equipment operation on construction sites (Kim *et al.*, 2012). In particular, Lin et al. (2020) proposed a vision-based AR prototype to present an instant wayfinding for crane operators during the construction phase to overcome poor navigation skills. This method deployed BIM to avoid obstacles in the lifting environment and provide a safe route for crane operation (Lin *et al.*, 2020). Similarly, Hasan *et al.* (2021) proposed a prototype in which digital twin technology, AR, micro-controllers, and sensors connect a virtual augmented crane with a real crane on the construction site. This connection provided designers and engineers with real-time knowledge and the possibility of remote controlling (Hasan *et al.*, 2021). Similarly, Kim *et al.* (2012) tried to reduce the risk of equipment crashing into structural members by using visual collision analysis, specifically by augmenting equipment in the construction environment and visually monitoring the likelihood of any collision. These crane/equipment studies were situated on building erection sites or realistic site replicas and generally reported safer paths, improved situational awareness, or reduced collision risk under test conditions.

Another four studies in the intelligent operation category facilitated accurate mapping of underground utilities onto AR devices for safe underground construction. Augmenting underground utilities contributed to preconstruction planning, minimising the risk of striking utilities during excavation or drilling (Su *et al.*, 2013). For example, Su *et al.* (2013) evaluated the technical feasibility of geospatial AR visualisation in an ongoing excavation operation. In another example, AR was investigated to reduce the risk of utility strikes during directional drilling (Fenais *et al.*, 2018a; Fenais *et al.*, 2020a). Fenais *et al.* (2018a) and Fenais *et al.* (2020a) developed a prototype utilising Geographic Information Systems (GIS) to collect data, external GPS devices to reduce positional error, Google Earth to store the data, and the AR system to map the data in real-time. These studies showed that AR is an acceptable and safe solution in underground activities (Fenais *et al.*, 2018a; Fenais *et al.*, 2019; Fenais *et al.*, 2020a). These were infrastructure projects in North America and the authors reported acceptable registration when paired with high-quality GIS inputs and improved operator awareness, though accuracy was sensitive to sensor quality and site conditions.

Table 3.2 and figure 3.3 show that safety training via AR was the objective of 5 out of 26 publications within the pre-event application group. For example, to overcome the lack of skilled labourers, Kivrak and Arslan (2019) proposed an animation-based and in-place learning platform for facilitating construction site activities using smart glasses through which workers could follow construction activities and learn while working. A similar study developed training complex procedures and operational tasks for workers by augmenting informative data associated with their duties into AR devices to avoid errors and failures during construction (Hou *et al.*, 2017). Compared to traditional AR training applications, three studies introduced, tested, and evaluated panoramic AR to create a training-based experience of the construction site (Eiris *et al.*, 2018; Pereira *et al.*, 2018; Pereira *et al.*, 2019). To be more specific, panoramic AR focused on training the workers via augmenting 360-degree safety information onto trainees' head-mounted devices to educate about the four leading hazards: falls, being hit, being caught, and electrocution (Eiris *et al.*, 2018; Pereira *et al.*, 2018; Pereira *et al.*, 2019).

As demonstrated in table 3.2 and figure 3.3, safety inspection using AR was the main aim of 5 out of 26 publications within the pre-event application category. Safety inspection is necessary to alleviate or eliminate dangerous construction situations (Zhou *et al.*, 2017; Bokhari *et al.*, 2020). AR has begun to assert itself in facilitating safety inspection; for example, Bokhari *et al.* (2020) and Khairadeen Ali *et al.* (2021) used vision-based AR systems by which safety inspection was performed using 3D scanning and photogrammetry technologies to address risks of traditional in-person inspection such as physical interaction between construction crew and inspector and loss of safety and productivity due to physical observation. In these two studies, 3D computer models were generated from captured photos using point cloud technology; subsequently, possible differences between as-planned and as-built could be augmented via VST AR devices and be transferred from the job site to the construction office and vice versa (Bokhari *et al.*, 2020; Khairadeen Ali *et al.*, 2021). Similarly, Zhou *et al.* (2017) investigated the feasibility of safety inspection with AR on a shield-tunnelling project in China, conducting on-site experiments and a case study. From the field experiment results of these studies, safety discrepancy monitoring of built and planned construction modules was enhanced (Zhou *et al.*, 2017; Bokhari *et al.*, 2020; Khairadeen Ali *et al.*, 2021). Two other studies employed AR to alleviate the risk of inspection in inherently hazardous areas and reduce the cognitive workload of inspectors by assisting safety rebar inspection prior to concrete casting (Hsu and Hsieh, 2019; Abbas *et al.*, 2020). The methodology of these studies focused on monitoring superimposed planned rebar drawings onto built physical objects.

Hazard alerting communication by AR was the objective of 3 out of 26 publications within the pre-event application category (see table 3.2 and figure 3.3). Informing workers automatically about possible dangers on construction sites is essential in the domain of health and safety (Kim *et al.*, 2017). To do so, Kim *et al.* (2017) and Baek and Choi (2020) proposed an AR system that provides workers with a wearable device that, via augmenting hazard data, helps with proactive hazard identification to avoid dangers arising from vehicles and heavy equipment. In the laboratory experiment conducted by Kim *et al.* (2017), the vision-based AR module displayed adequate safety data such as danger location and distance by calculating the distance between workers and vehicles in aboveground projects. In another study, a smart glasses proximity-warning platform, which receives Bluetooth signals attached to moving objects, was developed and tested by Baek and Choi (2020) in underground projects. Similarly, Sabeti *et al.* (2021) improved the proximity-warning system and conducted a field experiment integrating AR and AI. These hazard-alerting studies were set in highway work zones and site simulations. Results generally showed timely warnings and positive user response, though authors emphasised the need for longer field trials to confirm durability and false-alarm performance.

Table 3.2: Safety aims of AR applications

Safety aim	% of publications	Publications
intelligent operation	44.8%	(Kim *et al.*, 2012; Park and Kim, 2013; Su *et al.*, 2013; Wang *et al.*, 2014; Fenais *et al.*, 2018a; Fenais *et al.*, 2019; Xiang *et al.*, 2019; Fenais *et al.*, 2020a; Lin *et al.*, 2020; Foroughi Sabzevar *et al.*, 2021; Hasan *et al.*, 2021; Ogunseiju *et al.*, 2021; Xiang *et al.*, 2021)
training	17.2%	(Hou *et al.*, 2017; Eiris *et al.*, 2018; Pereira *et al.*, 2018; Kivrak and Arslan, 2019; Pereira *et al.*, 2019)
safety inspection	17.2%	(Zhou *et al.*, 2017; Hsu and Hsieh, 2019; Abbas *et al.*, 2020; Bokhari *et al.*, 2020; Khairadeen Ali *et al.*, 2021)
hazard alerting	10.3%	(Kim *et al.*, 2017; Baek and Choi, 2020; Sabeti *et al.*, 2021)

pinpointing hazard	6.9%	(Olorunfemi *et al.*, 2018; Dai *et al.*, 2021)
safety estimation	3.4%	(Kamat and El-Tawil, 2005)

3.3.2.2 During-event application

In contrast to numerous pre-event construction safety publications, during-event safety applications were the sole objective of only 2 out of 29 (6.9%) eligible papers. Effective pinpointing hazards is critical to minimising danger in construction sites (Dai *et al.*, 2021). Dai *et al.* (2021) conducted an AR communication-based experiment via an OST device to determine whether AR enhanced the suitability, accuracy, and ease-of-use of hazard pinpointing on construction sites. The trials and feedback from participants of this study showed that AR provided satisfactory safety and performance metrics compared to conventional methods such as phone calls, walking to people and talking, and video conferencing (Dai *et al.*, 2021). Another AR during-event application was developed and tested by Olorunfemi *et al.* (2018) to enable visual interaction and remote collaboration when pinpointing hazards. This article improved visually risk-based communication on construction sites via smart glasses. The outcome of this study demonstrated effective message delivery and message understanding by using AR in the case of a hazard.

3.3.2.3 Post-event application

Post-event construction safety application was the aim of one article among 29 eligible papers (3.4%). Kamat and El-Tawil (2005) applied AR to real-time damage assessment of under-construction structures after natural or artificial disasters. This prototype allowed construction managers to estimate the safety of the building via the OST AR device and to make on-site decisions on whether to continue the construction operation or leave the hazardous environment if critical structural members failed (Kamat and El-Tawil, 2005). The AR technology used in this study was to superimpose previously-stored building information onto an actual building to evaluate structural integrity by comparing critical discrepancies between a baseline image and the objective view (Kamat and El-Tawil, 2005). The preliminary results of this study showed that the proposed AR-based post-event safety estimation was practical for real-time damage assessment (Kamat and El-Tawil, 2005).

Research question 2: What Construction 4.0 technologies have been integrated with AR in construction safety academic literature?

The eligible papers were analysed to explore the implemented Construction 4.0 technologies alongside AR in safety construction. After reviewing eligible papers, as illustrated in column 3 in table 3.1, five technologies emerged: (1) BIM, (2) IoT, (3) AI, (4) Robotics, and (5) cloud. As shown in table 3.3 and figure 3.4, 17 out of 29 publications (58.6%) articles focused on BIM technology integration followed by robotics, IoT, and AI, each with 2 out of 29 publications (6.9%), and finally, cloud sharing technology was the solution of one study (3.4%). Nine publications (31%) did not incorporate Construction 4.0 technologies with AR. The classifications are not mutually exclusive—several publications integrated AR with multiple technologies. AR has shown great potential for blending with other technologies to improve safety performance on construction worksites. BIM was considered a core technology that collaborated with AR (Zhou *et al.*, 2017). 3D models established on AR devices have been widely accepted in the construction industry (Zhou *et al.*, 2017). For example, Kim *et al.* (2012) deployed BIM as a significant component to create 3D models of equipment that could be augmented via AR devices to monitor the possibility of collisions between structural members and virtual 3D models of equipment. In a similar article, since dealing with 2D drawings resulted in increasing the cognitive workload of the construction crew, Wang *et al.* (2014) applied BIM technology to create a detailed 3D model of a whole structure, which was registered via an AR device, that could be superimposed onto the physical construction worksite.

Table 3.3: Construction 4.0 technologies incorporated with AR

Technologies	% of publications	Publications
BIM	58.6%	(Kamat and El-Tawil, 2005; Kim *et al.*, 2012; Park and Kim, 2013; Wang *et al.*, 2014; Hou *et al.*, 2017; Zhou *et al.*, 2017; Fenais *et al.*, 2018a; Hsu and Hsieh, 2019; Xiang *et al.*, 2019; Abbas *et al.*, 2020; Bokhari *et al.*, 2020; Fenais *et al.*, 2020a; Lin *et al.*, 2020; Foroughi Sabzevar *et al.*, 2021; Hasan *et al.*, 2021; Khairadeen Ali *et al.*, 2021; Xiang *et al.*, 2021)
IoT	6.9%	(Hasan *et al.*, 2021; Ogunseiju *et al.*, 2021)
AI	6.9%	(Ogunseiju *et al.*, 2021; Sabeti *et al.*, 2021)
Robotics	6.9%	(Xiang *et al.*, 2019, 2021)
Cloud	3.4%	(Fenais *et al.*, 2019)

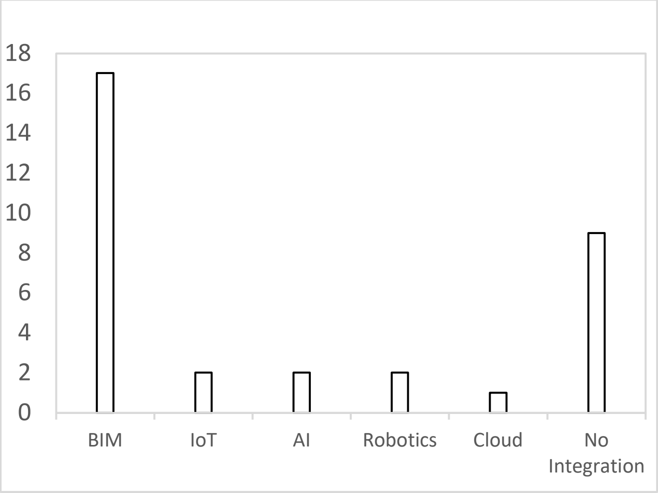


Figure 3.4: Number of publications for AR integration

In two other studies, IoT technology was adopted to develop a cyber model in which physical objects and virtual models were linked (Hasan *et al.*, 2021; Ogunseiju *et al.*, 2021). To this end, IoT contributed to transferring real-time data between actual objects and cyber models (Hasan *et al.*, 2021; Ogunseiju *et al.*, 2021). For instance, Hasan *et al.* (2021) integrated IoT and AR to propose a cyber-physical platform where construction equipment could be monitored and controlled remotely. Similarly, Ogunseiju *et al.* (2021) developed a bi-directional communication system by combining IoT and AR and enabled workers to monitor their body postures and avoid ergonomic injuries.

Two other studies implemented AI alongside AR to create a system in which the cognitive function of humans could be duplicated and augmented onto wearable AR devices (Ogunseiju *et al.*, 2021; Sabeti *et al.*, 2021). Sabeti *et al.* (2021) presented a platform using AI technology for real-time moving vehicle detection to enhance workers' safety and minimise the possibility of fatal accidents in the construction environment by informing workers about hazards in their vicinity via their AR device. The preliminary results of this study show that the integration of AR and AI can allow construction staff to react to identified hazards (Sabeti *et al.*, 2021).

Integration of robotics and AR was the other interaction studied by two publications. In contrast to AI, robotics duplicates the actions of a human, so Xiang *et al.* (2019, 2021) used robotics technology to design a prototype to overcome AR-related concerns such as weight and restricted field of view while wearing a head-mounted AR device. These studies demonstrated that AR, mounted on a robot, provided promising safety outcomes in construction worksites (Xiang *et al.*, 2019, 2021).

Consolidation of cloud and AR was the primary integrating means of one article among the eligible papers. To improve the accessibility of information, Fenais *et al.* (2019) designed a cloud-based technology through which real-time augmented virtual objects are stored and shared with construction managers.

3.4 Discussion

AR integration with Construction 4.0 technologies has evidence to support its potential for construction safety. Therefore, this section discusses AR incorporation with Construction 4.0 technologies from several vital aspects that enhance safety at construction sites. According to the literature, AR applications have three technical aspects: display, tracking, and HCI (Zhang *et al.*, 2020). In current excavation practice, underground utility information is obtained and validated through standards-based processes that combine electromagnetic locating, GPR, and potholing (Muthalif *et al.*, 2022b), with outputs classified by quality level for design and construction risk management. AR does not detect utilities; rather, it communicates and contextualizes verified utility data from paper drawings. Accordingly, AR should be viewed as complementary to current practice of excavation.

It is perceived that technology integration has the potential to enhance these three features and has led to improved safety on construction sites. Details of these aspects are discussed below.

3.4.1 Display

The prime technical aspect of the AR system is the display technology employed to visualise virtual objects so that users consider these objects as part of the natural environment (Zhang *et al.*, 2020). VST vs. OST usage among the eligible papers is about the same; 55% used VST devices, and 48% used OST as the display technology. The classifications are not mutually exclusive; several publications used VST and OST devices. Compared to the VST device, the OST device provides users with a greater sense of reality (Rolland and Fuchs, 2000); however, there are problems such as delayed display and inappropriate matching (Rolland and Fuchs, 2000). IoT technology has been integrated with AR to overcome delayed presentation and enhance the sense of reality (Hasan *et al.*, 2021; Ogunseiju *et al.*, 2021). IoT contributes to transferring real-time data between actual objects and cyber models (Hasan *et al.*, 2021; Ogunseiju *et al.*, 2021).

A study by Dai *et al.* (2021) demonstrated that a limited field of view was the most unfavourable response by participants when wearing AR glasses. Therefore, Xiang *et al.* (2019, 2021) stressed this issue and proposed a projective AR device that integrates AR and Robotics.

These studies demonstrated that AR, mounted on a robot, provides promising safety outcomes on construction worksites.

Compared to OST and VST, projective AR has no profound connection between the device and the user. As a result, it can be extended to multiple participants and allows cooperation between users (Zhang *et al.*, 2020). In addition, projective AR can increase safety performance and alleviate cognitive workload (Baumeister *et al.*, 2017). Robotics can play a critical role in display technology and needs further investigation in the field of construction safety.

3.4.2 Tracking

The sensor-based method is a common tracking solution for outdoor AR applications (Su *et al.*, 2013; Fenais *et al.*, 2018a; Bokhari *et al.*, 2020; Fenais *et al.*, 2020a); however, there was a shift in the position of the data from three to four meters because of sensor accuracy issues (Quezada-Gaibor *et al.*, 2021). Tracking near tall buildings affects accuracy since these structures can block sensor signals (Fenais *et al.*, 2019; Quezada-Gaibor *et al.*, 2021). Similarly, the vision-based tracking method fails when the marker is blocked or insufficient light (Zhang *et al.*, 2020). As a result, Xiang *et al.* (2021) used a hybrid tracking method in which sensor data is used alongside a vision-based method; however, it took about five seconds to track the user’s position (Xiang *et al.*, 2021). Ogunseiju *et al.* (2021) and Hasan *et al.* (2021) integrated AR with IoT to ensure continuous and accurate tracking between the AR device location and virtual object. The proposed sensing system showed promise for tracking corresponding virtual objects (Hasan *et al.*, 2021; Ogunseiju *et al.*, 2021).

3.4.3 HCI

HCI aims to provide operators efficient and user-friendly performance (Ziegler, 1996). However, the study results conducted by Olorunfemi *et al.* (2018) showed that AR training for workers lacking adequate knowledge of the technology could affect users' performance and contribute to bias towards AR technology. As a result of this unwillingness, users' perceptions, responses, and judgments may differ from person to person (Olorunfemi *et al.*, 2018). To improve users' perception and enhance their awareness, Sabeti *et al.* (2021) integrated AR with AI and proposed a user-centred system in which the end-user received safety notifications directly from the AI component. The outcome of this study demonstrated that users felt an effective interaction with the incorporation of AI and AR (Sabeti *et al.*, 2021).

The survey questionnaire used by Dai *et al.* (2021) showed that the non-negligible weight of wearable AR devices prevented users from wearing and walking comfortably. As a result, AR integration with Robotics has the potential to assist humans in blending virtual objects into the real environment while avoiding a substantial physical workload (Xiang *et al.*, 2019, 2021).

Hasan *et al.* (2021) presented the integration of AR and IoT, which enabled construction crews to monitor and remotely operate heavy equipment. The main result of this study supports the proposition that IoT and AR integration provide promising outcomes in HCI (Hasan *et al.*, 2021). Similarly, Ogunseiju *et al.* (2021) showed that this integration could promote human-machine interaction by providing actionable data in a format understandable by humans. Moreover, Fenais *et al.* (2019) established an interactive cloud-based AR application that construction staff could instantaneously share, add to and edit data through the cloud system.

3.5 Conclusion

The construction industry involves many potentially dangerous hazards to workers, engineers, and supervisors. AR technology provides researchers and safety engineers with a powerful visualisation feature. This study reviews existing publications on AR applications in the construction safety field. Consequently, we introduced a comprehensive classification of AR applications in construction safety and provided insights into the effectiveness and potential of AR integration with Construction 4.0 technologies. However, the review found no theoretical framework guiding AR adoption in the excavation industry. The absence of AR-specific protocols risks clashes with existing site processes and raises health and safety concerns, such as limited field of view and potential distraction.

As discussed in section 3.3, the purposes of AR applications in construction safety were divided into pre-event, during-event, and post-event applications. Pre-event applications were further divided into intelligent operation, training, safety inspection, and hazard alerting. Furthermore, the objectives of during-event and post-event applications of AR were identified as pinpointing risk and safety estimation, respectively (see section 3.3.2). Likewise, five Construction 4.0 technologies have been integrated with AR—BIM, IoT, AI, robotics, and cloud (see section 3.3.2). However, the evidence supporting AR integration's potential is still somewhat limited. Based on the results from the systematic literature review, apart from BIM, which is seen as the core technology of AR, other Construction 4.0 technologies integrated with AR to cater to various pre-event safety demands focused only on intelligent operation and hazard alerting. Therefore, other identified application domains, such as training, safety inspection, pinpointing risks, and safety estimation, have not been investigated through AR integration with Construction 4.0 technologies. Specifically, the post-event application of AR is limited to one article. Thus, there is a lack of evidence that would allow for a conclusive assessment of the potential and effectiveness of AR integrations.

Further, AR incorporation in terms of vital technical aspects was discussed, and three technical aspects of the display, tracking, and HCI were elaborated. The key contribution of this research is that although few studies integrated AR, this incorporation showed promising safety results in construction sites and helped advance AR technology. Additionally, this paper opens up a window for future academic research and shows that more study is necessary to produce sufficient evidence of the value and benefits of integrating AR with Construction 4.0 technology.

3.6 Summary

This chapter presented a systematic review of existing literature on the use of AR in construction safety, with a particular focus on its potential application in underground utility management. The findings revealed that while AR is widely utilised for safety training and hazard visualisation in the pre-event phase, there is a significant gap in its application for utility strike prevention during excavation. The summary of eligible papers including study contexts and key outcomes is provided in the table 3.4. The review also identified a lack of empirical validation in existing AR studies and highlighted the need for research that addresses user needs, practical constraints, and interface effectiveness in high-risk construction scenarios.

The insights gained from this chapter established a research gap and provided the foundation for the next stage of the study. Chapter 4 builds on this foundation by engaging with industry professionals to explore real-world perceptions, expectations, and barriers related to AR adoption in excavation.

Table 3.4: Summary of HCI characteristics of eligible papers

AR device	**Experiment location**	**Safety aims**	**Safety sub-aims**	**key outcome**	**Reference**
OST	lab	Pre-event	training	Hazard recognition	(Eiris et al., 2018; Pereira et al., 2018, 2019)
VST	field	Pre-event	safety inspection	As-planned vs as-built discrepancies highlighted	(Bokhari et al., 2020)
VST	field	Post-event	safety estimation	Faster situational visualisation for damage eval	(Kamat & El-Tawil, 2005)
Projective AR	lab	Pre-event	intelligent operation	Hands-free, multi-user legibility for co-robots	(Park and Kim, 2013 Xiang et al., 2019)

VST	lab	Pre-event	intelligent operation	Feasibility for operator	(Kim et al., 2012)
VST	Field	Pre-event	safety inspection	Segment displacement inspection enhanced	(Zhou et al., 2017)
VST	Field	Pre-event	intelligent operation	Framework for safety management	(Wang et al., 2014; Su et al., 2013)
OST	Lab	During-event	pinpointing hazard	Proactive alerts to moving hazards	(Olorunfemi et al., 2018; Dai et al., 2021)
VST	Field	Pre-event	safety inspection	Rebar spacing checks faster than manual	(Hsu & Hsieh, 2019)
VST	lab	Pre-event	intelligent operation	easier tower-crane path navigation	(Lin et al., 2020)
OST vs VST	lab	Pre-event	safety inspection	Segment displacement inspection enhanced	(Abbas et al., 2020; Khairadeen Ali et al., 2021)
VST	lab	Pre-event	intelligent operation	Lower cognitive load reading floor plans	(Foroughi Sabzevar et al., 2021)
VST	Field	Pre-event	hazard alerting	Proximity to hazard alarming	(Kim et al., 2017; Baek and Choi, 2020; Sabeti et al., 2021)
VST	Lab	Pre-event	training	HCI learning framework for complex tasks	(Hou et al., 2017; Kivrak and Arslan, 2019)
OST	Lab	Pre-event	intelligent operation	supports posture self-correction	(Ogunseiju et al., 2021)
VST	Field	Pre-event	intelligent operation	communication	Hasan et al., 2021
VST	Field	Pre-event	intelligent operation	fewer assembly errors	Xiang et al., 2021

VST	Field	Pre-event	intelligent operation	External GPS markedly improves AR accuracy	(Fenais et al., 2020a)
VST	Field	Pre-event	intelligent operation	Increase Awareness	(Fenais et al., 2018a; Fenais et al., 2019)

Chapter 4: AR Solutions for Locating and Protecting Underground Utilities

The current chapter is based on the following article:

Khorrami Shad, H., Feng, Z., Paes, D., Yiu, T. W., & Lovreglio, R. (2025). Augmented Reality Applications for the Excavation Industry: Locating and Protecting Underground Utilities. *Journal of Pipeline Systems Engineering and Practice*, 16(1), 04024072. https://doi.org/10.1061/JPSEA2.PSENG-1652

4.1 Introduction

Underground utilities represent an essential feature of infrastructure services that support the critical functions of the societal framework (Fenais *et al.*, 2018b; Abebe and Tesfamariam, 2020). These networks accommodate the core necessities of modern life, including sewage systems, telecommunication channels, and distribution pipelines for electricity, water, and gas (Wu *et al.*, 2021). Nevertheless, the societal and economic consequences of inadvertent excavation damage to these utilities are substantial (Wu *et al.*, 2021). The main hazard to the integrity of underground utilities arises from inadvertent damage during excavation (Talmaki and Kamat, 2014). Recent incidents underline the continuing risk. As per NTSB (2024) in Maryland, a natural-gas explosion destroyed a home, killing the homeowner and a utility contractor. In Missouri, a residence exploded after a fibre-installation crew struck a gas line during excavation in August 2024 (Crowley, 2024). Beyond individual cases, the Common Ground Alliance DIRT (2022) dataset recorded 213,792 unique damage events in 2022 across the U.S. and Canada, evidence that utility strikes remain widespread.

Identifying utilities' location during excavation is critical in construction projects, as any existing underground utilities could be disrupted or damaged (Muthalif *et al.*, 2022b). Although this process is crucial, it still largely relies on traditional paper-based drawings in current excavation practices (Fenais *et al.*, 2018b). Nowadays, various tools are available for locating underground utilities, such as Ground Penetrating Radar (GPR) and electromagnetic locators. However, accurately locating underground utilities using specialised devices poses several challenges (Grote *et al.*, 2005). Each of these devices has inherent limitations, and their effectiveness can be compromised by various factors such as site geology, utility characteristics, accessibility, density of utilities, and operator experience (Uslu *et al.*, 2016). For example, GPR works by sending microwave pulses into the ground and analysing the reflected signals; however, real-time data of underground utilities is not directly visualised on the ground surface (Grote et al., 2005; Uslu et al., 2016; Al-Bayati and Panzer, 2020; Pereira et al., 2020; Solla et al., 2021). Furthermore, the utility locating process can sometimes be time-intensive and costly when multiple utilities need to be identified and marked on the surface (Solla *et al.*, 2021).

Services like the One-Call system in the United States, Dial Before You Dig (DBYD) in Australia, and BeforeUDig in New Zealand aim to connect individuals requiring information about underground utilities with the respective asset owners to facilitate safe excavation (Fenais *et al.*, 2020b; Maree *et al.*, 2021; Muthalif *et al.*, 2022b). However, several challenges do exist. First, not all asset owners participate in these services, leaving gaps in the available data when a specific owner is not a member. Another obstacle arises after utility providers mark locations using spray paint, stakes, or flags. These markers are often the first to be removed during excavation, requiring operators to rely on memory or re-initiate the one-call process, causing inevitable project delays (Su *et al.*, 2013; Talmaki and Kamat, 2014; Fenais *et al.*, 2020b; Muthalif *et al.*, 2022b).

Despite numerous challenges in the construction industry, innovative technologies like AR are gaining traction as valuable tools to visualise the utilities (Hou *et al.*, 2014; Khorrami Shad *et al.*, 2022). AR's usefulness is supported by existing literature, which confirms its efficacy in various construction-related applications. These include enhancing safety protocols (Behzadan *et al.*, 2015; Hou *et al.*, 2017; Chu *et al.*, 2018), streamlining information sharing and progress monitoring (Lee and Akin, 2011; Zhou *et al.*, 2017), assisting with equipment operations (Koch *et al.*, 2014; Tavares *et al.*, 2019), ensuring construction quality through inspections (Kim *et al.*, 2014; Kim *et al.*, 2015; Kim *et al.*, 2016; Sidani *et al.*, 2021; Tarek and Marzouk, 2022), managing facilities (Wang *et al.*, 2016), and facilitating operational training (Yoon *et al.*, 2018; Yang *et al.*, 2021).

AR technology overlays virtual attributes onto real-world objects, offering an interactive and immersive experience that can enhance communication among construction workers, irrespective of their geographical locations (Moore and Gheisari, 2019; Kanangkaew *et al.*, 2023). An illustrative example is a vision-based hazard avoidance system developed by Kim *et al.* (2017), which uses AR to proactively warn workers about possible workplace dangers. The technology is increasingly being employed to automate the visualisation of various construction tasks, and it is academically acknowledged as an effective tool for visualisation across diverse applications. However, the adoption of AR to avoid damage to underground utilities has been limited studied (Khorrami Shad *et al.*, 2022). This gap highlights an urgent need to understand the reasons for this slow adoption, especially since some construction teams have displayed noticeable hesitancy in adopting such cutting-edge technologies (Makkonen *et al.*, 2016). This suggests that, despite AR's proven benefits, there remains a level of caution or even reluctance to fully integrate it into all sides of the construction industry.

In this work, we aim to investigate how excavation professionals perceive AR in preventing damage to underground utilities. Our primary goal is to discover the excavation industry's needs, expectations, and perceived challenges toward adopting AR technology. To achieve this goal, we interviewed 31 professionals in the excavation sector. We asked them to test and compare the OST and VST AR technologies in the context of excavation tasks with similar augmented data. Through our semi-structured interview, we assessed the limitations and risks of the current excavation practice. Also, we investigated the participants' preferences on the type of AR solutions they would adopt in excavation tasks, as well as the challenges and barriers to adopting AR solutions.

4.2 Research Background

4.2.1 Underground Utility Damage Prevention

Various techniques are used worldwide to avoid damage to underground utilities while excavating (Hao *et al.*, 2012; Li *et al.*, 2016; Cai *et al.*, 2018). This section provides the theoretical background for the present study through an overview of current underground utility damage prevention practices.

According to the existing body of literature, the underground utility location techniques can be classified as a) Visual Techniques, sub-divided into visual inspection (hand digging, hydro excavation, and potholing) and Closed Circuit Television (CCTV), b) Electromagnetic and Radio Frequency Techniques including low-frequency electromagnetic field survey, GPR and Passive Magnetic Fields (PMFs), c) Acoustic and Vibration Techniques, d) Radio Frequency Identification (RFID), e) Pipe and Cable Locator (C.A.T and Genny scan), f) Elastic Wave Method, g) Infrared Thermography, h) Broadband Electromagnetic (Koo and Ariaratnam, 2006; DiBenedetto *et al.*, 2010; Saha *et al.*, 2010; Hao *et al.*, 2012; Li *et al.*, 2016; Sagnard *et al.*, 2016; Cai *et al.*, 2018).

Hao *et al.* (2012) conducted a comprehensive overview of underground utility location techniques, evaluating their main advantages and disadvantages across varied application fields. It is noted that what may be an advantage in one technique can often be a disadvantage in another, mainly due to the differing practical scenarios for which the techniques were developed, such as pipe materials, utility types, soil conditions, and ground surface. While having a range of these techniques allows flexibility in choice, there are circumstances where a single technique may not yield satisfactory inspection outcomes, necessitating the incorporation of additional methods for more comprehensive results (Farrag and Guerrero Merino, 2022). For example, Cai *et al.* (2018) proposed a methodology to enhance the accuracy of underground utility mapping by combining techniques such as GPR, utility records, and specifications. Incorporating utility specifications could moderate location estimation errors and support the reliability of the results. Employing non-sensing data, such as as-built drawings and site observation, can provide necessary data related to the utility location (Cai *et al.*, 2018).

4.2.2 Augmented Reality

AR technology has been demonstrated as a promising visualisation tool in many fields (Sangiorgio *et al.*, 2021; Malek and Moreu, 2022; Settimi *et al.*, 2022; Wu *et al.*, 2022; Panya *et al.*, 2023). This section provides the theoretical background and rationale for the present study through an overview of recent developments in AR in construction. In AR, displays come in two main categories: OST and VST. OST devices, like Microsoft HoloLens, overlay computer-generated holograms onto the real world through smart glasses. On the other hand, VST devices, such as smartphones and tablets, combine a live camera feed with computer-generated holograms (Paes *et al.*, 2024).

The existing body of literature illustrates the capacities of AR technology in utility visualisation as a means to bolster safety and productivity (Su *et al.*, 2013; Uslu *et al.*, 2016; Fenais *et al.*, 2018a; Fenais *et al.*, 2019; Fenais *et al.*, 2020a). An investigation by Su *et al.* (2013), for example, examined the technical viability of implementing AR visualisation approaches in the midst of ongoing excavation procedures. Additionally, three studies by Fenais *et al.*(2018a; 2019; 2020a) examined the prospective use of AR to alleviate the hazards linked with inadvertent utility damages during directional drilling tasks. In parallel, these researchers also devised a prototype that utilised an AR platform to delineate the configuration of underground utilities, thereby leveraging Geographic Information Systems (GIS) for effective data gathering and archiving.

Moreover, AR has shown promising results in utilities inspection and maintenance. For example, Li *et al.* (2022) and Baek *et al.* (2019) introduced an AR-based method to inspect the structural integrity and safety of utilities by comparing the augmented objects with the existing ones. Kwiatek *et al.* (2019) presented an AR application to assist pipe fitters in assembly tasks. Similarly, Um *et al.* (2023) introduced a VST application to recognise and visualise the utilities' deformations. Also, Liu and Seipel (2018) studied the usability of AR technology in utility positioning and highlighted the capability of AR in positioning behind-the-wall utilities.

The literature suggests that AR technology may provide diverse interactions (e.g., voice commands, gesture recognition, hand interaction, eye gaze interaction), lower workload, and more efficiency than traditional methods. For example, Chen *et al.* (2021), Hou and Wang (2013), and Funk *et al.* (2015) compared AR devices and traditional methods of assembly in construction and found that the hands-free feature of OST devices brings about an interactive experience. Also, AR, compared to traditional methods, presents a lower mental workload, focusing on secondary tasks or distractions (da Silva, 2014). Zhang *et al.* (2021) showed a significant reduction in participants' workload when working with AR-assisted applications. Similarly, using OST led to shorter assembly time and lower error counts than VST and traditional techniques (Hoover *et al.*, 2020). A comparison of AR devices in the construction phase conducted by Kolaei *et al.* (2022) indicates notable similarities between OST and VST across various parameters. Despite these similarities, the usage rates for these two platforms differ significantly. AR glasses offer advantages such as resistance to environmental factors and user convenience.

On the other hand, VST excels in terms of accessibility and affordability. In this evaluation, the factors of affordability and accessibility appear to be more heavily weighted, explaining the significant disparity in the usage rates of VST in academic literature. In a similar study, Wu *et al.* (2023) studied AR impacts on human factors and found that the OST device presents better results in the NASA task load than paper-based traditional drawings. Collectively, these research efforts prove the potential of AR as a feasible and secure means for data visualisation in all construction fields.

A review of academic literature shows that a few studies explored the use of AR technology to visualise underground utilities in excavation tasks. These explorations have primarily been centred around the accuracy of smartphones in managing data (Khorrami Shad *et al.*, 2022). Nevertheless, the derived insights highlight a significant limitation: the deficiency in the precision of integrated GPS systems within current smartphones diminishes their applicability in this field (Fenais *et al.*, 2018b; Fenais *et al.*, 2020a). Furthermore, these studies lack focus on the anticipated outcomes of AR implementations from an industry perspective.

This research intends to fill the research gap and expand the knowledge of collecting and examining the industry's requirements and expectations concerning adopting AR technology as a preventative measure against inadvertent utility damages during excavation activities. This work is a new investigation to assess the needs, expectations, and challenges associated with AR adoption in the excavation sector. Further, it provides insights into how professionals perceive both OST and VST, perceived barriers and willingness to use AR in the future.

4.3 Materials and Methods

The research methods used in this work are influenced by prior studies, as detailed in section 4.3.3. These foundational studies centred on creating and interacting with AR-based prototypes. Emphasis is placed on existing studies involved in designing their prototypes, executing user-focused exposure, and actively collecting participant feedback.

This study's approach involves designing and presenting participants with an AR-integrated excavation system. The prototype's primary objective is to familiarise participants with AR capabilities and generate their feedback, needs, and expectations concerning the AR system. Following the system's development, semi-structured interviews were conducted with 31 excavation industry professionals—hereafter called participants. Participants were introduced to two distinct AR-based prototypes during each session: the VST and the OST. Both were presented consecutively within the same interview timeframe. As explained in section 4.3.2, these prototypes were engineered to augment an underground pipeline within the interview setting, showing its real-time distance from the AR device. Interactive features were also incorporated, including a button-press mechanism allowing users to put on and turn off specific details of the underground pipeline, like its diameter and relative distance to the AR device's camera. The comprehensive framework of the method is depicted in figure 4.1 below.

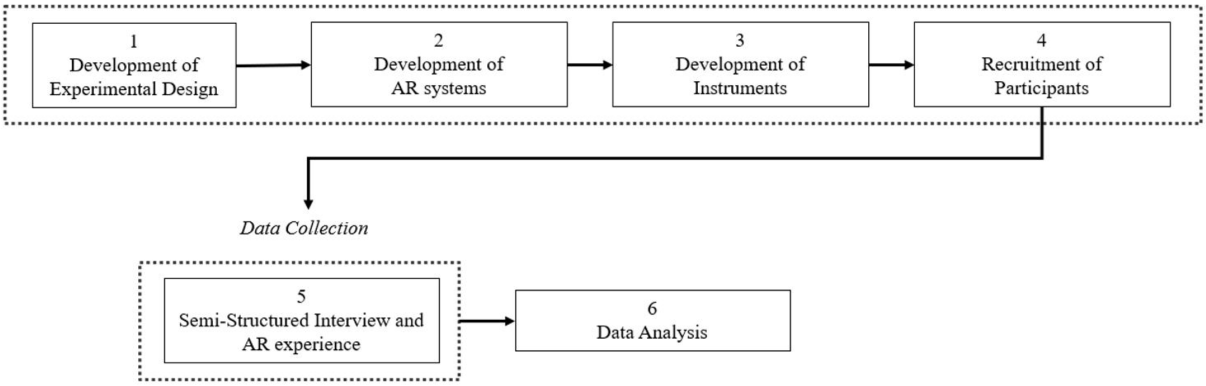


Figure 4.1: Research method framework

4.3.1 Semi-Structured Interview Design

The research strategy employed in this study integrated the triangulation method, incorporating both quantitative and qualitative data analysis techniques. Data was gathered using a diverse set of survey questions. Each interview session commenced with the participant's background, followed by inquiries related to earthwork. This section aims to determine a) common underground utility damage prevention practices in New Zealand, b) excavation limitations, and c) associated risks. Subsequently, participants engaged with two distinct prototypes: a VST version on an Android tablet and an OST version via Microsoft HoloLens 2. While both conveyed identical data, their interaction mechanisms varied due to the nature of each device, as elaborated upon in section 4.3.2. Once participants gained a degree of familiarity with the AR interface, the line of questioning shifted to exploratory topics, focusing on a) feedback to the prototypes, b) user preferences, c) expectations regarding an AR system, and d) reasons, based on their perspective, for the yet unfulfilled adoption of AR technology. A schematic representation of the semi-structured interview approach is presented in figure 4.2 below.

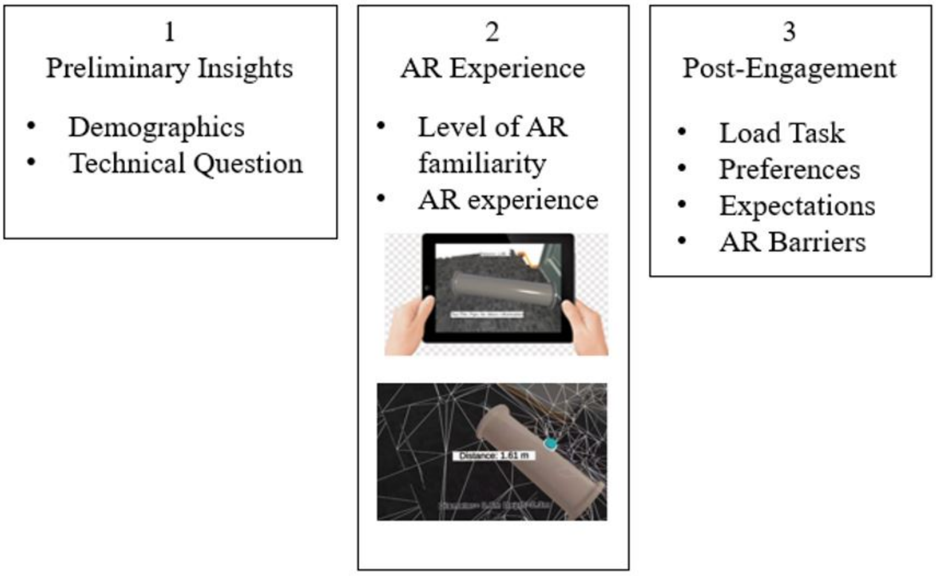


Figure 4.2: Semi-structured interview approach

4.3.2 AR System Analysis

The study utilised two prototypes created using a HoloLens 2 head-mounted AR display and a Samsung Galaxy Tab S5e tablet. These devices were selected to represent the two dominant AR display at the time: HoloLens 2 as the most widely adopted OST platform with a mature MRTK SDK (Dai *et al.,* 2021), and a tablet as the standard VST form factor used on sites and readily available AR (Kolaei *et al.,* 202). Alternative industry exemplars (e.g., Trimble XR10 for OST hard hat integration; Trimble SiteVision for VST) were noted but were outside scope due to cost and availability. Unity 3D game engine (version 2021.3.20f1) was used for the development process of the two prototypes. A user-friendly interface was crafted based on the Mixed Reality Toolkit (MRTK) design recommendations (Microsoft, 2022).

As illustrated in figure 4.3, the AR applications offered real-time distance tracking from the virtual object, a pipe, to the respective AR device. For the HoloLens 2 setup, a button-press mechanism was embedded in the virtual pipeline. However, since participants used both hands to hold the tablet device, this interaction was not feasible on that device. Therefore, for the tablet interaction, the virtual object was touch responsive as a form of user interaction. Both these features facilitated the display of essential information, such as the diameter and depth of the pipeline. All the presented data was visualised through a text UI screen, crafted following the Mixed Reality Toolkit (MRTK) design guidelines.

(a) (b)

Figure 4.3: Screenshots of the AR environment: (a) AR view through the HoloLens II system; (b) AR view through the tablet system

Prior to the start of the AR experience, the interviewer introduced participants to both prototype systems, explaining the functionalities, such as how to activate the button, the significance of the displayed distance metrics, and clarifying the interpretations of diameter and depth indications.

Before immersing participants into the AR environment, anchoring (the process of attaching a virtual object to a specific point in the real world (Schmalstieg and Hollerer, 2016) is crucial to ensure precise placement of the virtual augmentation, specifically, the virtual pipeline. For the purpose of this study, the virtual pipeline was set at a distance of 1.6 metres beneath the AR devices at the start of the session. This initial placement ensures participants are provided ample space to interact with the virtual pipeline and facilitates actions such as button pressing and observing distance variations as they manoeuvre closer or farther from it.

4.3.3 Data Collection Instruments

The research employed two sets of questions presented to participants at separate interview stages: preliminary insights set prior to the AR experience and a post-engagement set following their interaction with the AR prototypes. The objective is to capture participants' backgrounds, collect insights from their excavation experiences, and understand their perceptions of AR technology. This methodology drew inspiration from earlier works that developed and utilised similar instruments (Billinghurst and Kato, 2002; Billinghurst *et al.*, 2015; Creswell and Creswell, 2017; Fenais *et al.*, 2019; Makransky and Petersen, 2019; Yip *et al.*, 2019)

The clusters of items included in this work aim at data collection regarding 1) Demographics, 2) Technical questions, 3) AR familiarity, 4) Task load, 5) Preferences, 6) AR demands and expectations, and 7) AR barriers. As shown in figure 4.2, the first three clusters were introduced in the preliminary insights stage. Next, participants familiarised themselves with both OST and VST AR prototypes, which are detailed in section 4.3.2. Subsequent questions corresponding to the remaining clusters were asked in the post-engagement interview stage. The clusters of items are described in more detail as follows.

1) The *Demographics* section comprises five items used to collect participants' characteristics and excavation experience. These characteristics include gender, education level, age, number of years in the excavation industry, and current professional role. This data collection aims to ensure that the sample includes a comprehensive range of independent variables.

2) The *Technical questions* section comprises five items. Initially, it delves into common excavation practices that prevent underground utility damage during excavations. Participants then rank a pre-determined set of excavation work

limitations, as established by (De Reu *et al.*, 2014; Fenais *et al.*, 2018b; Al-Bayati, 2021). Following this, they suggest solutions to alleviate the most severe limitations. The subsequent questions prompt participants to rank pre-determined sets of risks associated with excavation work, as studied by (Crapper *et al.*, 2014; Spink, 2020; Uzairuddin, 2021). Solutions to mitigate the most severe risks are then sought. Participants can introduce additional limitations and risks they deem relevant, ensuring the inclusion of all aspects from the industry's perspective.

3) The *AR familiarity* section comprises one item used to gauge participants' daily interaction levels with AR technology. For clarity, participants are provided with examples of AR, such as car reverse cameras, Instagram face filters, and Pokémon Go. Subsequently, they are asked about the frequency of their AR utilisation in day-to-day life. The participants indicate their AR familiarity using four options: "never," "rarely," "occasionally," and "regularly."

4) The *Task load* section comprises four items from the NASA Task Load Index (TLX), a well-validated method in the field that gauges participants' perceived task loads during AR interactions. Its implementation in AR assessment is supported by previous studies, such as De Crescenzio *et al.* (2010). The task load items explore the physical and mental effort associated with the HoloLens and tablet usage. Feedback will be captured on a 7-point Likert scale, ranging from -3 ("strongly disagree") to +3 ("strongly agree").

5) The *Preferences* section comprises three items to delve into participants' viewpoints on the superiority of AR tools (HoloLens and tablet) over conventional paper-based drawings for underground utility locations. These items draw inspiration from prior research (Lam *et al.*, 2021; Pozharliev *et al.*, 2022).

Feedback will be collected using a 5-point Likert scale, stretching from -2 ("Strongly Disagree") to +2 ("Strongly Agree"). Additionally, participants are prompted to select between the HoloLens and the tablet as their preferred tool for everyday excavation tasks, subsequently exposing their rationale in an open-ended query.

6) The *AR demands and expectations* section comprises two items used to collect participants' needs from an AR-based prototype. This segment focuses on participants' expectations from an AR prototype. Open-ended questions are composed to provoke their requirements from such a prototype and their anticipated information display.

7) The *AR barriers* section comprises 1 item used to collect participants' opinions regarding why AR has not been adopted yet. In an open-ended format, they are encouraged to list three impediments they believe have obstructed AR's integration into the industry.

A qualitative analysis method supported in similar literature (Zhang and Pan, 2021) has been used for all open-ended questions. Interview recordings were initiated with the express consent of the participants. Subsequent to the recording, these interviews were thoroughly transcribed, and NVivo software was employed to facilitate a comprehensive analysis of the data. The analytical process adopted the content analysis approach, systematically progressing from data extraction to recognising patterns and identifying key themes.

4.3.3.1 Participants and Semi-Structured Interview Session

The nonprobabilistic sample comprises 31 participants and complies with the following inclusion criteria: over 18 years of age and working in the New Zealand excavation industry, regardless of the role. As per (Lazar *et al.*, 2017), 30 respondents would be an acceptable number of participants in HCI research and stopping when thematic saturation is reached, data collection ceased at 31 once no new codes emerged. Participants were recruited from a range of educational backgrounds and roles in the excavation industry. This reflects the composition of excavation crews and decision-makers and was intended to assess usability and workload across a representative workforce, not only engineers. Including varied educational attainment also enabled observation of how digital familiarity and technical literacy may influence AR perceptions and task performance.

Data collection took place in semi-structured interview sessions, which all occurred in the participants' offices. All sessions were recorded to avoid missing any responses. Each session took approximately 30 minutes and 15 hours of data collection over eight weeks. The interview obtained Massey University's human ethics approval for application number 4000026685.

4.4 Results

The triangulation method for data analysis had several objectives: a) to identify common practices among New Zealand excavation professionals for avoiding underground utilities during excavation and to list the ranked risks and limitations associated with them, b) to determine any significant differences in task load, specifically the mental and physical demands, between the tablet and HoloLens, c) to verify if participants' demographics and AR familiarity are influential factors in their preferences, d) to classify expectations for an AR system and the type of information participants want displayed, and e) to identify barriers preventing the adoption of AR in the New Zealand excavation industry.

4.4.1 Participant Demographics and Background

The gender distribution of participants, 24 out of 31 (77%) male and 7 out of 31 (23%) female, aligns with a report by the New Zealand Ministry of Business, Innovation and Employment (Alice Cleland, 2022). This report indicated that between 2012 and 2022, the female percentage in the construction sector fluctuated between 11% and 15%. The participants' ages ranged from

24 to 61 years (*M* = 35.5, *SD* = 11.41). The participants had a diverse range of educational backgrounds: 7 out of 31 (22.6%) did not have a university degree, 9 (29%) had a diploma, 7 (22.6%) had an undergraduate degree, and 8 (25.8%) held postgraduate qualifications. The participants in the study held a variety of roles within their organisations and had a diverse range of experience levels in the excavation industry. There were five forepersons and five site engineers, each constituting 16.1% of the participants. Project engineers were represented by 3 participants (9.7%), field operation managers by 2 participants (6.5%), project managers by 6 participants (19.4%), and senior project managers by 5 participants (16.1%). The roles of plant manager, business development manager, and commercial manager were represented by 3 (9.7%), 1 (3.2%), and 1 (3.2%) participant(s), respectively. The years of experience among participants widely ranged from 2.5 to 40 years in the excavation industry.

4.4.2 Excavation Practices, Risks and Limitations

This section delves into the strategies participants have been adopting to prevent damage to underground utilities during excavation, along with the accompanying risks and limitations. table 4.1 provides a detailed breakdown of the damage prevention practices. A unanimous consensus was observed, with every participant emphasising the indispensable role of maps and plans in identifying the location of underground utilities prior to the initiation of excavation activities. Hydro excavation was another unanimously endorsed technique. This method employs the power of high-pressure water to displace soil and detritus in the vicinity of underground utilities (Rijal, 2021). Such a technique is pivotal in eliminating direct physical contact with the utilities, drastically mitigating the likelihood of inadvertent damage.

An overwhelming majority, with 30 out of 31 participants, highlighted the practice of hand-digging, especially in proximity to underground utilities. This approach is favoured for its precision and reduced risk of causing unintentional damage. Similarly, 30 participants acknowledged the efficacy of non-destructive testing tools, with GPR being a preferred choice to detect and pinpoint the position of underground utilities. Only 12 out of the 31 participants reported reliance on Cable Avoidance Tools (CAT) and Genny Scans (which utilise a signal generator, often nicknamed a genny, to emit a traceable signal for the CAT to detect (Maksoud, 2022). These tools are instrumental in preventing unintended damage to underground utilities, especially live cables, during excavation (Sun *et al.*, 2014).

Table 4.1: Current measures to prevent damage to underground utilities during excavation

Measures	Number of participants
The use of maps and plans to identify the location of underground utilities before excavation works commence (before you dig)	31 (100%)
Hydro excavation or suction using high-pressure water or air to excavate soil and debris around underground utilities while avoiding physical contact that may cause damage.	31 (100%)
Hand digging techniques, which allow for more precise excavation in areas where underground utilities are present	30 (97%)
The use of non-destructive testing methods, such as GPR, to locate underground utilities	30 (97%)
C.A.T. and Genny scan	12 (39%)

Following the exploration of preventive measures, participants were prompted to rank a set of pre-determined limitations encountered during excavation activities. An option was provided, allowing the addition of any unidentified limitations. The consolidated rankings are presented in figure 4.4. An outstanding observation from the rankings was the united agreement regarding the foremost challenge: the lack of information about existing buried utilities. Another limitation that ranked high on the list was the lack of vertical accuracy, primarily attributed to alterations in elevation that the original as-built drawings failed to capture or represent accurately.

Furthermore, participants shared insights on supplementary limitations not on the list. Among these, poor communication emerged as a concern, highlighting the inherent challenges when multiple stakeholders are involved in excavation projects. The limited workspace was another limitation identified by a participant.

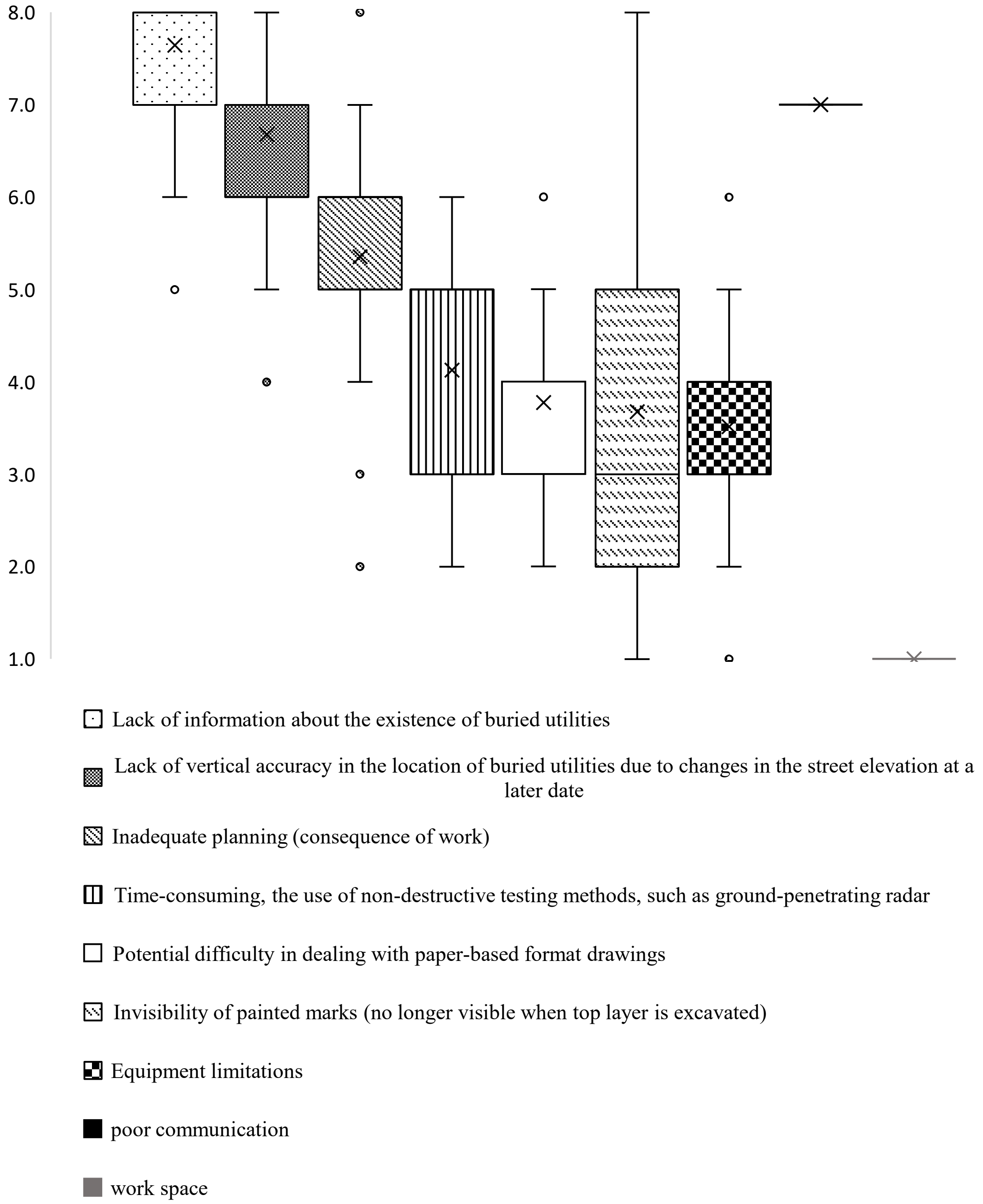


Figure 4.4: Limitations in excavation works

Upon inquiring about potential mitigation strategies for the limitations mentioned above, a majority of participants, 28 out of 31, advocated for the combined use of GPR, hydro excavation, and potholing. Then, the study probed into the risks intrinsic to excavation work. Even though participants were encouraged to introduce and rank any unlisted risks based on their expertise and experience, the initial list remained unchanged, with no additions. This emphasises the comprehensiveness of the risk assessment initially presented to the participants. Figure 4.5 delineates the consolidated rankings of these risks. Two primary concerns were brought to the fore. First, the potential damage to underground utilities during excavation was a significant concern. And the risk of injuries or fatalities to construction professionals and bystanders was emphasised. Another concern was the structural risk of cave-ins or collapses, particularly in unstable geologies. A recurring theme was observed when deliberating on mitigation strategies for these risks. A significant majority, 18 out of 31 participants, advocated the interactive use of GPR, hydro excavation, and potholing.

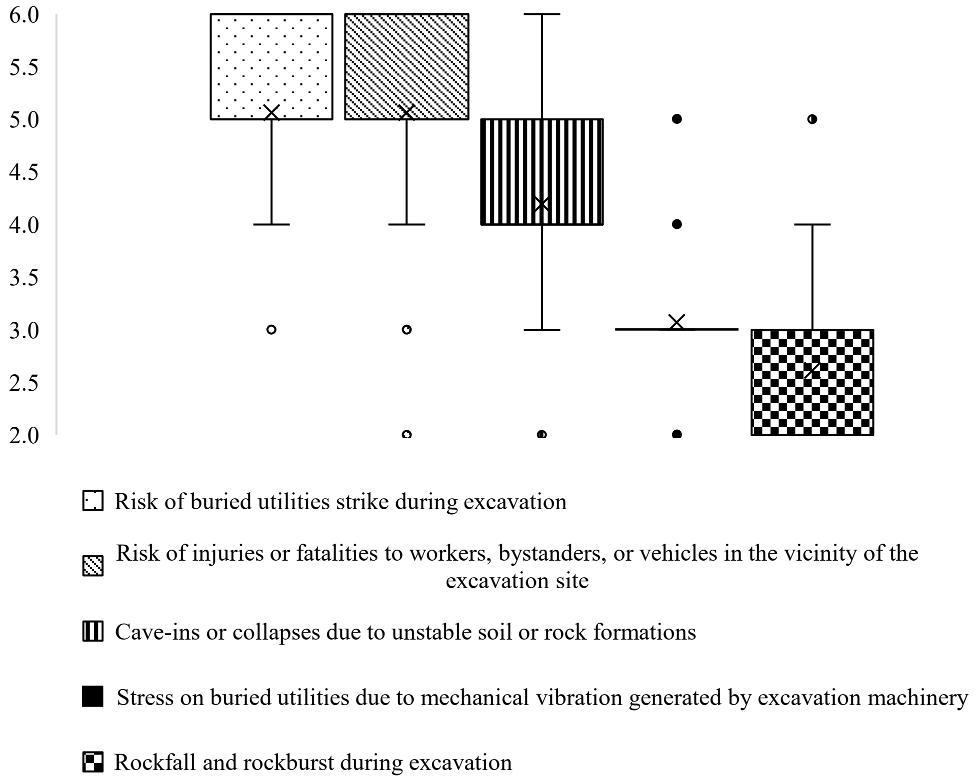


Figure 4.5: Risks in excavation works

4.4.3 AR System Testing

This section delves into the participants' familiarity with AR and assesses the perceived task loads associated with two AR prototypes – the tablet and the HoloLens. The familiarity with

AR technology was assessed before engaging participants in the AR experience. Interestingly, a third of the participants (10 out of 31) admitted to rarely using AR in their daily lives. Concurrently, an equal number (10 out of 31) revealed that they regularly utilise AR technology in their everyday activities. The remaining 11 participants opted for occasional use.

The task load analysis aimed to measure and compare the mental and physical demands participants experienced when navigating the AR systems. So, participants were familiarised with both AR prototypes.

Figure 4.6 visually represents the collected task load scores, presented through box plots. These scores ranged from one to seven, representing a spectrum from low to high perceived task loads. It was crucial to ensure that the collected data met assumptions of normality for statistical analysis. However, the Kolmogorov-Smirnov test results, with p-values below 0.05, confirmed non-normal distributions of the task load scores. As a result, the Mann-Whitney U test, a non-parametric statistical analysis, was employed to determine whether significant differences existed between the demands of the two AR prototypes. Table 4.2 offers a comprehensive summary of these results. The findings revealed no significant differences (p-values > 0.05) between the tablet and the HoloLens concerning both physical and mental demands. However, the distribution of the load task table of scores (figure 4.7) indicates a slightly increased perceived demand for the HoloLens compared to the tablet. This suggests that while the differences may not be statistically significant, there may still be practical implications in the field that could affect user preference.

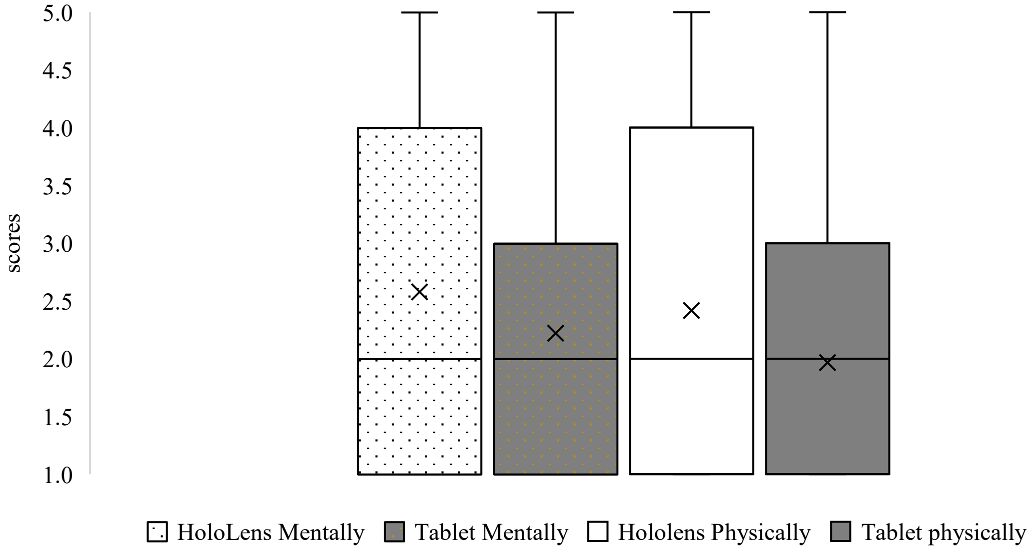


Figure 4.6: Task load scores for the HoloLens and tablet

Table 4.2: Comparison between the load task scores of HoloLens and Tablet

Tablet vs HoloLens	Mentally Demanding	Physically Demanding
Mann-Whitney U	422	385.5
Z	-0.858	-1.397
p-value	0.391	0.162

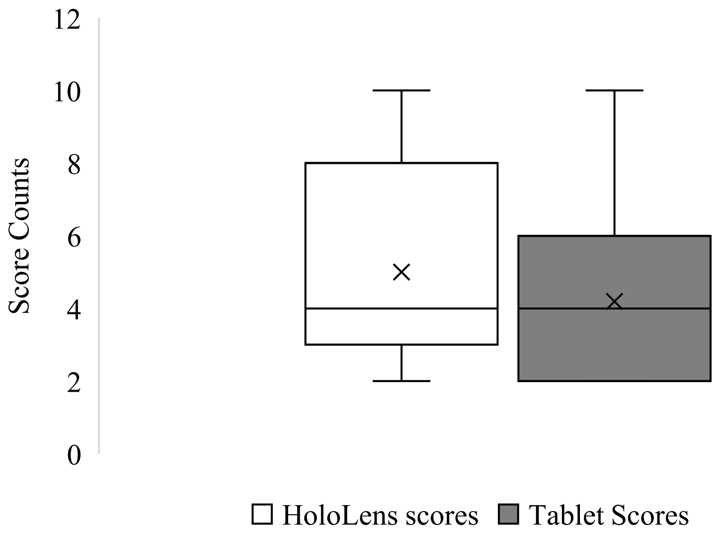


Figure 4.7: Task load table of scores for HoloLens and Tablet

4.4.4 AR Preference

The desirability of AR—through both tablet and HoloLens—compared to conventional paper-based drawings is quantitatively analysed in this section. Moreover, a deeper qualitative analysis was undertaken to determine if participants were inclined significantly toward either the tablet or the HoloLens when considering AR as the medium of choice.

The participants were asked to rate their preference for AR technologies, both tablet and HoloLens, against traditional paper-based drawings. Ratings were based on an ordinal scale ranging from one to seven, with one indicating a strong preference for paper-based drawings and seven signifying a definitive inclination towards AR. The consolidated results of these ratings are visually summarised in figure 4.8. The data shows a clear trend: most participants leaned towards the AR experience compared to traditional methods. As demonstrated in table 4.3, although there was an evident interest in both AR devices, the preference statistics did not significantly sway towards either the tablet or the HoloLens compared to traditional paper-based drawings.

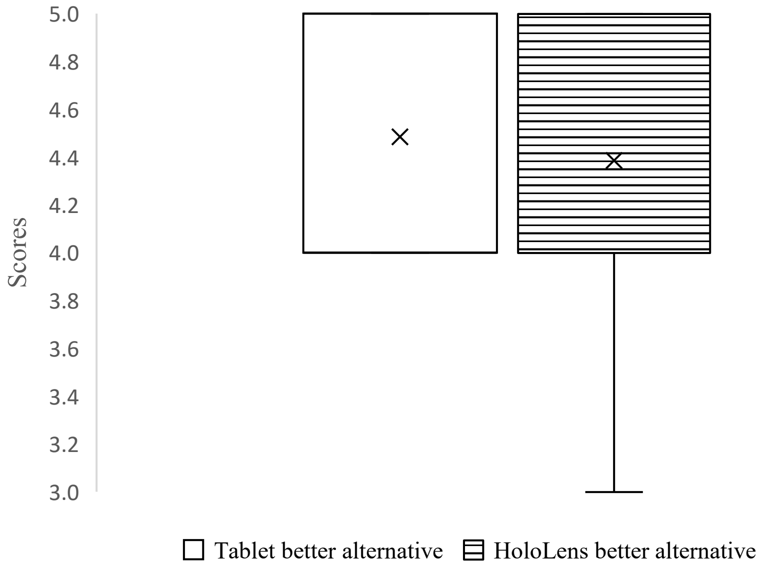


Figure 4.8: HoloLens and tablet preference against paper-based drawings

Table 4.3: Comparison between the HoloLens and tablet against paper-based drawings

Mann-Whitney U	441.5
Z	-0.631
p-value	0.528

When the participants faced a choice between the tablet and HoloLens for everyday excavation activities, an apparent inclination towards the tablet was observed. As demonstrated in the Sankey diagram (figure 4.9), out of 31 participants, 22 showed a preference for the tablet, citing 36 reasons for this choice. Note that a higher frequency of a reason results in a thicker Sankey diagram representation. Interestingly, this preference did not centre on the participant's demographics, education, or experience in the excavation industry. Statistical tests indicated no significant correlation between Gender and device preference (p-value: 0.976), age and device preference (p-value: 0.654), educational level and device preference (p-value: 0.986), current professional role and device preference (p-value: 0.415), years of experience and device preference (p-value: 0.694).

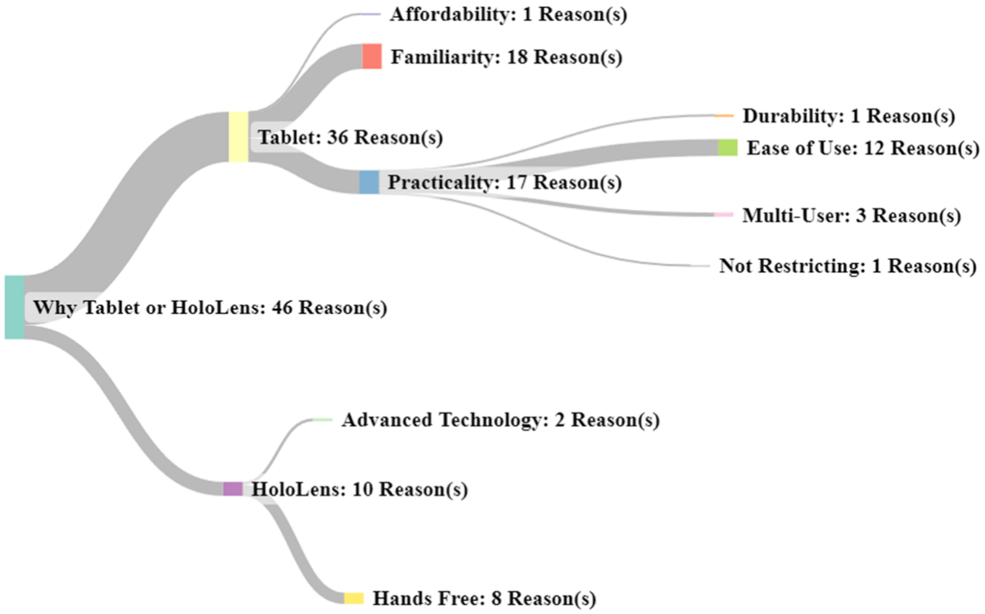


Figure 4.9: AR device preference

A deeper dive into the participants' reasoning demonstrates why the tablet gained more favour. The reasons are grouped into affordability, familiarity, and practicality:

- Affordability: "*In a job where we need multiple devices across the site, cost matters. Tablets are simply more cost-effective.*" A participant said.
- Familiarity: "*I've used tablets before in other contexts. I know how they work, and that makes it easier for me to trust them here.*" A participant said.
- Practicality:
    - Durability: "*Tablets are robust; they can handle the rugged environment of an excavation site.*" A participant mentioned.
    - Ease of Use: "*With a tablet, what you see is what you get. There's no steep learning curve.*" A participant mentioned.

- Multi-User: "*Multiple team members can use and view a tablet. It's more collaborative.*" A participant mentioned.
- Not Restricting Field of View: "*While excavating, I want a clear view of the site. Tablets don't obstruct my view like other devices*." A participant mentioned.

On the other hand, the participants preferred HoloLens because of two features: a) Hands-Free and b) Advanced Technology.

- Hands-Free: "*Not having to hold a device is freeing. With the HoloLens, my hands can do the work while my eyes get the data.*" A participant stated.
- Advanced Technology: "*The HoloLens feels like the future. The way it overlays information on the real world can be game-changing*." A participant said.

4.4.5 AR System Expectations and Required Information

This section delves into participants' expectations for an AR system and the information they felt essential to view on the AR devices. The qualitative data analyses use participants' ideas toward AR system expectations. As illustrated in figure 4.10, the participants focused on the following features: a) Affordability, b) Durability, c) Usability, and d) Performance. The performance falls into 1) Accuracy and 2) Response Speed—how quickly the virtual object adjusts on the AR device to match the user's position.

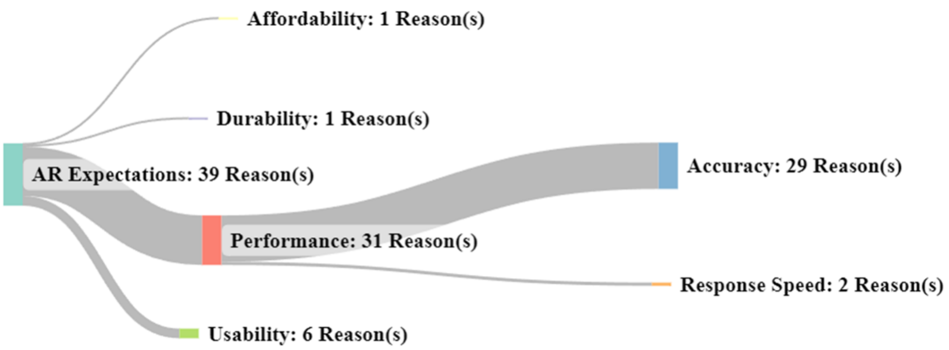


Figure 4.10: Industry expectations from AR technology

For system accuracy, a participant mentioned, "*When you're dealing with underground utilities, even a minor error can have major consequences. The system must be precise*." The other participant said, "*We need real-time data. Any lag in response can slow down operations significantly*." As a statement to support response speed.

The required information to be shown on an AR device is demonstrated in figure 4.11. Participants emphasised the need for the following: A) Coordination details, which fall into clashes and sequence of work, were mentioned as essential for excavation works. A participant noted, "*Having a visual representation of potential clashes and the work sequence can streamline our operations* ". Additionally, B) underground utility specifications showing the utility owner, depth, size, type, and operational status were highlighted as required information. A participant noted, "*The more we know about a utility - its size, type, operational status - the better our excavation strategy*".

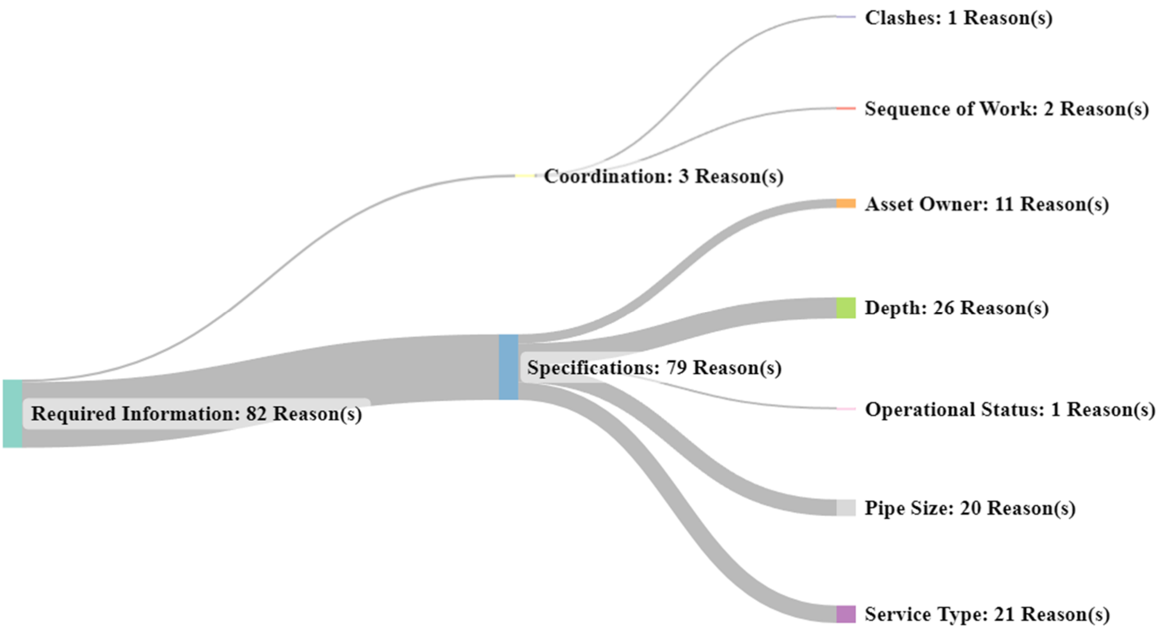


Figure 4.11: Required information to be shown on an AR device

4.4.6 Barriers Towards AR Adoption

This section delves into the barriers that have deterred the New Zealand excavation industry from fully embracing AR technology. We aim to unpack the reasons underlying the industry's hesitance or delay in integrating this advanced tool into their operations. According to figure 4.12, the qualitative analysis pinpoints three significant barriers: a) Accessibility (28 participants), b) Outdated As-Built Drawings (11 participants), and c) Scepticism (10 participants). Delving deeper into the accessibility factor, the main concerns expressed by the participants were 1) Affordability, with device cost being a hurdle for 27 participants, and training cost concern for 19. Only 1 participant voiced concerns about 2) Availability of AR devices. When examining scepticism, 7 participants revealed a Resistance to Change, while 5 questioned the Trustworthiness of AR systems.

Note that the numbers are not mutually exclusive; participants could mention as many reasons as they saw fit.

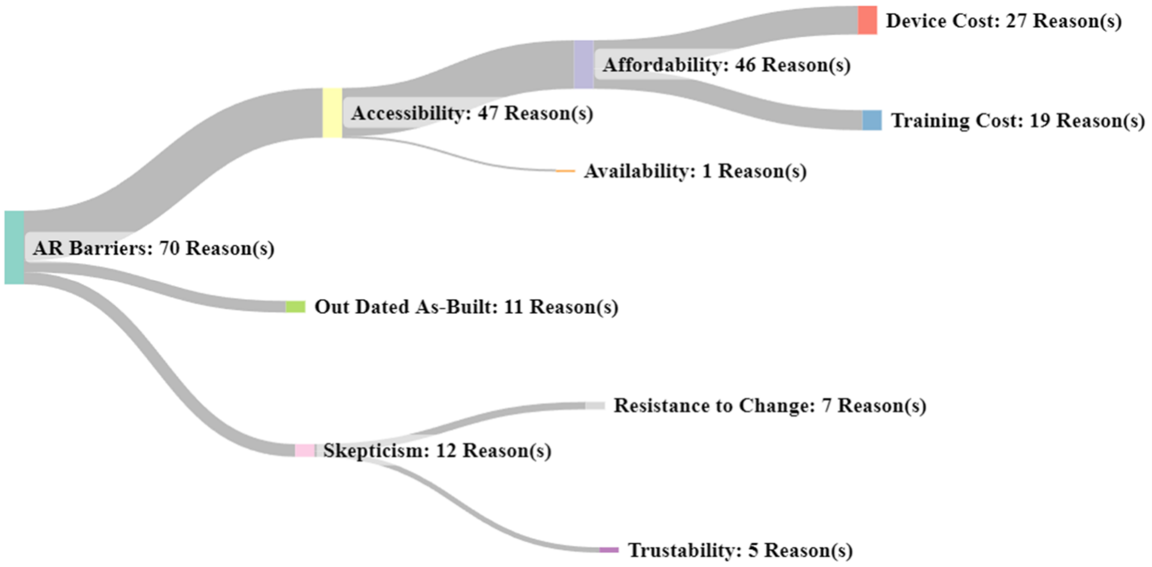


Figure 4.12: AR barriers

The summary of the qualitative analysis demonstrated in figure 4.13 will help future researchers with an overview of what expectations, preferences, and barriers are associated with AR technology.

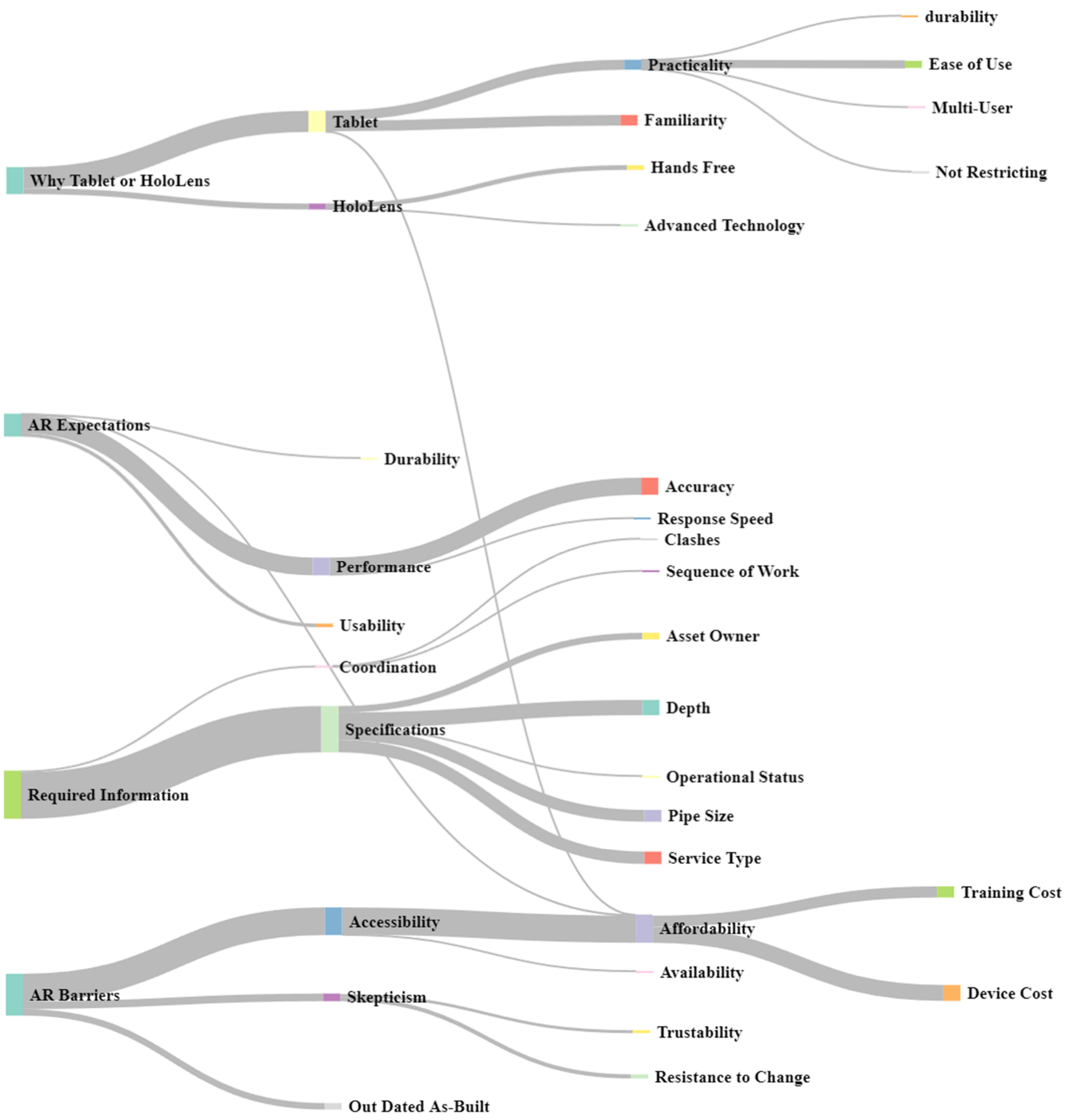


Figure 4.13: Summary of qualitative analysis

4.5 Discussion

This study investigates the potential use of AR in preventing strikes to underground utilities in the excavation sector. The multifaceted nature of excavation operations necessitates a more integrated and encompassing approach, and AR can be a promising technology to overcome these challenges. One practical implication is that adopting AR can help excavation teams reduce utility strike risk by turning disparate sources (e.g., GPR scans, pothole findings, as-built records) into a single, on-site visual overlay that speeds coordination, clarifies depth, location, and supports faster decisions. In this work, we investigate the existing needs of professionals, how they perceive different types of AR hardware, and their willingness and perceived barriers to using them in the future.

When focusing on the current measures to prevent strike to underground utilities during excavation (see section 4.4.2), our findings in table 4.1 align with prior research that the integrated use of GPR, hydro excavation, and potholing techniques are mentioned as common methods to overcome limitations and risks associated with excavation works (Qin *et al.*, 2016; Fenais *et al.*, 2018a; Feng *et al.*, 2019; Wang *et al.*, 2023). In our study, we also observed diverse levels of AR familiarity reported by participants (see section 4.4.3). In fact, one-third of participants rarely used AR in their daily lives, another third used it occasionally, and the remaining third used it regularly. This disparity in AR familiarity highlights a distribution of exposure to AR tools and applications among the participant population.

Our findings show that participants preferred the AR solutions over traditional methods in excavation work, as shown in figure 4.8. The marked tilt in participants' favourability towards AR technology underscores its transformative potential within the excavation industry. This finding suggests that AR has the potential to revolutionise current excavation practices. This aligns with existing literature that found AR a better alternative to traditional paper-based methods (Kwiatek *et al.*, 2019). According to section 4.4.3, the tablet gained lower scores in the field of mentally demanding tasks compared to the HoloLens. This finding also aligns with existing literature on the AR technology (Funk *et al.*, 2016). Approximately 71% of participants have chosen the tablet as their preferred AR device. It does not undermine the efficacy of HoloLens, but it highlights that both devices possess unique merits, and their applicability is contingent upon the specific requirements of the projects.

While comparing the HoloLens over tablet solutions, we identified a key characteristic of HoloLens over tablet in the context of excavation work: hands-free operation (figure 4.9). This characteristic affords greater convenience for users, as it eliminates the need to constantly hold and manipulate a device, while previous studies show that tablets are perceived as more accessible and affordable (Kolaei *et al.*, 2022). 73% of researchers in this field of study used the tablet for their preferred prototypes (Kolaei *et al.*, 2022). Similarly, choosing tablets because of familiarity and not restricting the field of view (see figure 4.9) is in line with existing studies (Stoltz *et al.*, 2017; Abbas *et al.*, 2020; Qin *et al.*, 2021; Xiang *et al.*, 2021). Interestingly, Qin *et al*. (2021) found that restricting the field of view by HoloLens is not always a disadvantage, and it may increase participants' efficiency by decreasing distractions. In our study, 9 participants preferred HoloLens because of its hands-free and advanced technology features. Similarly, prior research reiterates these findings (Fazel and Izadi, 2018; Makhataeva and Varol, 2020; Chen *et al*., 2021; Moghaddam *et al*., 2021; Wen *et al*., 2021) (Hoover *et al*., 2020). For example, Hoover *et al*. (2020) found that the participants with HoloLens need a shorter time to complete a procedural task, resulting in lower error counts. Also, Chen *et al.* (2021) put forth the idea that the hands-free feature of HoloLens enables developers to incorporate more interactions and brings about an intact experience in procedural assignment. Moreover, AR system expectations and required information detailed in section 4.4.5 align with prior research that accuracy is one of the most important expectations from AR technology (Behzadan *et al.*, 2008; Stylianidis *et al.*, 2020; Kyaw *et al.*, 2023). As an example, Kyaw *et al.* (2023) used multiple AR codes as markers to increase the accuracy and reduce the tolerance in augmentation. Also, the accuracy of the data feeding the AR system is crucial (Nguyen *et al.*, 2020). The accuracy of the data depends on the source and recency of the information. Recent underground locating methods like GPR and potholing can provide more accurate data, potentially leading to higher confidence in the AR system for users (Fenais *et al.*, 2018b; Tan *et al.*, 2022). While 2D GPR-based drawings offer a valuable starting point, integrating this data into the AR system and ensuring a user-friendly experience with minimal effort compared to the 2D format are critical for successful AR adoption (Kusumo and Poh, 2022). In section 4.4.5, AR response speed, affordability, and durability are other significant AR technology expectations. Similarly, the findings align with the previous literature (Park and Kim, 2013; Stoltz *et al.*, 2017; Fazel and Izadi, 2018; Abbas *et al.*, 2020; Chu *et al.*, 2020; Stylianidis *et al.*, 2020; Wen *et al.*, 2021; Kolaei *et al.*, 2022; Um *et al.*, 2023). For example, based on findings by Stoltz et al. (2017), the main concern for HoloLens is its affordability. Also, Um *et al.* (2023) showed that two limitations of the tablet device are its durability and performance. Similarly, Fazel and Izadi (2018) and Kolaei *et al.* (2022) concluded that tablets are more affordable and accessible. It is important to acknowledge that participant comments, for example Participant 5's remark, "*We need real-time data...*," in section 4.4.5, may reflect a lack of familiarity with AR technology. While the AR system displays data recently collected (not truly real-time), user misconceptions can lead to unrealistic expectations. This potential gap between user expectations and the current capabilities of AR technology could hinder user adoption.

The findings regarding the preference between HoloLens and tablet solutions (figure 4.9) diverge from existing literature in highlighting the potential of tablets as multi-user devices. Yeh *et al.* (2012) and Ahn *et al.* (2019) found that tablets are a single-user solution and introduced projective AR as a multi-user solution. Moreover, Liu and Seipel (2018) found that tablets and smartphones restrict the field of view. This finding contradicts our finding in section 4.4.4, which states that some participants have preferred tablets because they do not restrict the field of view. One possible explanation can be a difference in the size of the virtual object—participants in Liu and Seipel's (2018) study inspected a large object from a short distance.

This study shows why AR has not yet been adopted in the excavation industry in section 4.4.6. The AR barriers reported in this study fell into three categories: accessibility, outdated as-built drawings, and scepticism. These findings are in line with existing literature (Park and Kim, 2013; Wang *et al.*, 2014). For example, Harikrishnan *et al.* (2021) categorised AR barriers into technological and non-technological factors. Technological factors fall into AR device accessibility and durability. Non-technological factors refer to resistance to change and fear of relying on technology rather than experienced professionals. Moreover, Park and Kim (2013) and Wang *et al.* (2014) found that AR public scepticism is one major challenge to its wide adoption.

It should be noted that this study's findings are limited to the specific hardware and software combination used. We used Unity as the primary software for developing an AR system for the Tablet and HoloLens as discussed in section 4.3.2. This choice aligns with existing literature that identifies Unity as a leading platform for creating AR content (Koumpouros, 2024). To enable cross-platform functionality, we incorporated AR Foundation and MRTK, which are widely recognised as common platforms that work well with Unity (Pierdicca *et al.*, 2024). Based on the literature, various AR Software Development Kits (SDKs) such as Metaio, Vuforia, Wikitude, D'Fusion, ARToolKit, and ARmedia have been compared in terms of several technical aspects. These aspects include license type (open source, free, commercial), supported platforms (iOS, Android, Windows, etc.), marker generation capabilities, tracking technologies supported, and overlaying/rendering capabilities. Each of these SDKs offers unique features and functionalities that cater to different needs and requirements of AR applications (Amin and Govilkar, 2015). However, despite these comparisons, there has been a notable gap in evaluating these SDKs based on user experience. Understanding how different SDKs influence user interaction, satisfaction, and overall usability is crucial for the effective adoption and implementation of AR technology. Therefore, future studies should consider incorporating user experience metrics to provide a more holistic evaluation of AR SDKs.

As technology constantly evolves, user experience should be the focal point of such studies rather than just the systems or equipment used. Therefore, digital technology validation studies must take into account user experiences. Also, the research results may be limited to the AR system design, so results could change, for example, by altering user interactions. In the future, the prototype AR application can be expanded to include procedural tasks, augmentations, and interactions, covering a broader range of outcomes of AR adoption in the excavation industry in various contexts. The prototypes developed for this study were intentionally simple with limited interactions to avoid overwhelming participants and effectively demonstrate the core concepts of AR.

Future studies should consider developing more comprehensive prototypes encompassing a broader range of functionalities and interactions. Also, the current study primarily focused on evaluating the single-user experience of the AR prototypes. While this study provided insights into individual user preferences and interactions, it overlooked the multi-user collaboration's potential benefits and challenges in AR-assisted excavation tasks. Future research should delve into the multi-user aspects of AR, exploring how collaborative interactions can enhance task efficiency, safety, and communication among excavation teams.

Participants interacted with each device and visualisation in a single session; therefore, the reported usability and workload reflect first-exposure performance. With repeated use, strategies and perceived effort may change, particularly among participants with less familiarity with AR. Future studies should include longitudinal designs to assess how usability and workload evolve over time. Another potential limitation of the study is that it focuses on mental and physical task loads as indicators for evaluating AR prototypes. The authors suggest evaluating a broader range of metrics, such as response speed and action error rate, to obtain a more comprehensive understanding of user experience and preference in the context of AR-assisted excavation tasks in future studies.

Several other potential avenues are worth further investigation in future studies. First, the common excavation methods (e.g., use of GPR and hydro excavation) mentioned by the participants may highlight the possibility of offering a comprehensive solution by combining AR technology with current practices to avoid utility strikes. Second, the AR expectations may vary based on the type of AR device, user interactions, and the size of underground utilities. Third, the safety concerns about wearing head-mounted AR devices during excavation operations remained absent. Fourth, the complexity of tasks may also impact the required AR information to be shown or the preferred AR device. Thus, future research may also delve into HCI aspects such as visual perception, interactions, user interface, and human factors to enhance the transformative potential of AR adoption in excavation practices. Fifth, future research should also explore streamlining AR data development. To be more specific, converting accurate field data into a usable 3D AR solution can be time-consuming and expensive. While revised 2D drawings might suffice for some excavation tasks, minimising the trade-off between 3D accuracy and development efficiency is crucial for broader AR adoption.

4.6 Conclusion

The adoption of AR in the excavation industry has been repeatedly reported despite the lack of industry perspective to support such a statement. This study addressed this gap by exploring end users' expectations from AR-based prototypes, a crucial step in promoting AR adoption in this field. Through open-ended questions, we investigated barriers to adoption, industry needs, and the necessary information to be displayed.

Our results indicate a general preference for AR over traditional methods among participants, with affordability emerging as a key determinant for adoption. A quantitative analysis of participants' task load using the NASA Task Load Index provided valuable insights into the mental and physical demands of using AR in excavation tasks. The analysis showed a statistically significant reduction in perceived workload for specific tasks, such as utility location, but also highlighted areas where AR implementation needs refinement to truly outperform traditional methods.

Our qualitative analysis of AR device preferences revealed a strong inclination towards tablets over HoloLens. This preference was primarily driven by familiarity and ease of use, suggesting that the learning curve associated with newer technologies might be a significant barrier to adoption. However, a subset of participants recognised the potential long-term benefits of hands-free devices, indicating a possible shift in preferences as the technology matures and users become more accustomed to it.

The study uncovered challenges hindering AR adoption in the excavation industry. Participants emphasised the importance of accuracy for underground utility detection. The identified lack of accurate vertical information about utilities emerged as a significant technical challenge, highlighting a critical area for improvement in AR systems designed for this industry.

Furthermore, our analysis revealed that the high risk of unintentional damage during excavation remains a major concern, even with AR assistance. This finding suggests that while AR has the potential to improve safety and efficiency, it must be implemented in conjunction with robust safety protocols and training programs to effectively mitigate risks.

This study is the first in the published academic literature to develop two prototypes, OST and VST, for the excavation industry and compare users' mental and physical workload through a user-centred assessment. By combining quantitative task load analysis with qualitative preference and adoption barrier assessments, we provide a comprehensive view of AR's current standing and future potential in the excavation industry.

Our findings enhance the understanding of AR technology's suitability from the industry's standpoint, offering nuanced insights into the interplay between technological capabilities, user preferences, and practical constraints. This analysis provides directions for developing and implementing more effective AR systems, addressing both the technical and human factors aspects crucial for facilitating full AR adoption within the excavation industry.

Future research should focus on addressing the identified challenges, particularly improving depth accuracy for utility detection and developing intuitive user interfaces that minimise cognitive load. Additionally, as noted in our discussion, AR expectations may vary based on the type of AR device, user interactions, and the size of underground utilities. This opens up avenues for future research to explore how these factors influence user experience and AR adoption in the excavation industry.

In conclusion, while AR shows promise for improving safety and efficiency in excavation work, its full adoption faces several barriers. By addressing these challenges and continuing to refine AR systems based on user needs and preferences, the technology has the potential to significantly transform the excavation industry, enhancing both safety and productivity.

4.7 Summary

This chapter presents the results of an investigation involving 31 excavation professionals, aimed at understanding industry perspectives on the adoption of AR technology for underground utility strike prevention. The interviews provided insights into current practices, user expectations, and barriers to AR implementation in the field. Key findings included the preference for VST devices due to their usability and familiarity, the need for clear visualisation of pipe specifications, and concerns around affordability, training, and environmental limitations.

These findings validated the relevance of AR in excavation contexts and directly informed the experimental design of the next research phase. Specifically, the user-identified needs shaped the selection of AR display devices and visualisation methods tested in Chapter 5. The transition from qualitative insights to controlled experimentation ensures that the study remains user-centred and responsive to industry challenges.

Chapter 5: Comparing AR Solutions for Underground Utilities

The current chapter is based on the following article:

Khorrami Shad, H., Lovreglio, R., Paes, D., Feng, Z., & Yiu, T. W. K. A Comparative Study of AR Solutions for Visualising Underground Utilities. *Tunnelling and Underground Space Technology* (Under Review).

5.1 Introduction

Underground utilities are a vital part of the infrastructure that supports the essential functions of modern life (Fenais *et al.*, 2018b; Abebe and Tesfamariam, 2020; Su *et al.*, 2023b). These networks include sewage systems, telecommunication channels, and pipelines for electricity, potable water, and gas (Su *et al.*, 2023b). However, their integrity is often threatened by inadvertent excavation damage, resulting in significant societal and economic consequences (Talmaki and Kamat, 2014; Zhou *et al.*, 2018). Recent incidents underline the continuing risk. As per NTSB (2024) in Maryland, a natural-gas explosion destroyed a home, killing the homeowner and a utility contractor. In Missouri, a residence exploded after a fibre-installation crew struck a gas line during excavation in August 2024 (Crowley, 2024). Beyond individual cases, the Common Ground Alliance DIRT (2022) dataset recorded 213,792 unique damage events in 2022 across the U.S. and Canada, evidence that utility strikes remain widespread.

Accurate visualisation and identification of underground utilities remain persistent challenges in construction and infrastructure management. The growing complexity of urban underground infrastructure exacerbates the risk of utility strikes during excavation works, posing significant safety hazards, economic losses, and disruptions to essential services. Globally, thousands of utility strike incidents are reported annually, leading to substantial repair costs, project delays, and potential injuries to workers, bystanders, or vehicle occupants in the vicinity. Secondary hazards can include cave-ins or collapses from unstable soils, and rockfall or rock bursts during excavation (Khorrami Shad *et al.*, 2025).

Traditional methods for avoiding utility strikes during excavation include manual digging, mechanical excavation, ground-penetrating radar (GPR), electromagnetic detection tools, utility marking services, and two-dimensional utility maps. While GPR and electromagnetic tools offer improved detection capabilities, their effectiveness is often limited by factors such as soil composition, signal interference, and the operator's expertise (Uslu *et al.*, 2016; Muthalif *et al.*, 2022b). For instance, GPR signals can be significantly weakened or entirely absorbed in highly conductive soils like wet clay or saltwater-saturated soils, severely limiting the technology's effectiveness (Anchuela *et al.*, 2009; Su *et al.*, 2023a). Utility marking services and manual digging rely heavily on outdated or incomplete records, leading to inaccuracies and increased risks of utility strikes. Additionally, two-dimensional maps fail to accurately represent the depth and complexity of underground utility layouts, often resulting in misinterpretations (Khorrami Shad *et al.*, 2025).

AR technology has emerged as a solution for improving underground infrastructure's visualisation and spatial understanding. By overlaying digital information in the real world, AR can provide construction professionals with an intuitive way to see underground utilities before and during excavation. This capability has the potential to reduce utility damage significantly (Muthalif *et al.*, 2022b), improve worker safety (Albahbah *et al.*, 2021), and enhance operational efficiency (Khorrami Shad *et al.*, 2022).

(VST and OST are two common types of AR systems. VST works by showing a live camera feed on a screen with digital information overlaid, allowing users to see real-world and virtual elements together on the same display. In contrast, OST uses transparent displays, such as smart glasses, to project virtual content directly into the user's field of view, blending it with the real world (Khorrami Shad *et al.*, 2022; Lovreglio *et al.*, 2024; Paes *et al.*, 2024; Paes *et al.*, 2025). Based on the literature, construction professionals tend to prefer OST because they are more familiar with it, making it easier to use in their work environments (Khorrami Shad *et al.*, 2025).

While various methods have been proposed for visualising underground utilities in AR, there is limited empirical evidence comparing their effectiveness and identifying their advantages and limitations. Also, previous research has primarily focused on technical implementations of individual visualisation methods. For example, Stylianidis *et al.* (2020) described developing and evaluating a mobile AR and GIS solution to support utility management professionals by enabling accuracy. Ortega *et al.* (2019) developed an AR application for visualising underground utilities, integrating variable transparency blending, terrain ditches, and excavation tools. Eren and Balcisoy (2018) also assessed the X-Ray visualisation method for vertical depth judgments in AR based on users' perceptual performance accuracy. However, these studies have not systematically compared different visualisation methods using a comprehensive approach that considers user perception and task load.

The present study addresses this research gap by conducting a systematic comparison of four VST visualisation methods for underground utilities. The visualisation methods compared in this work were identified from the existing literature (see Section 2), including X-Ray visualisation, Shadow visualisation, Cross-Sectional visualisation, and a novel visualisation method that combines the previous three solutions. These four methods were tested using the Theory of Affordances and Task Load. This allowed a comparative evaluation of the visualisation methods across multiple dimensions of user experience and effectiveness (Gibson, 1977; Harris *et al.*, 2020). According to Gibson (1977) theory of affordances, an object is perceived based on what it offers or enables an individual to do in the context of their goals. In other words, an affordance refers to the potential actions an object provides, depending on the user's intentions. To systematically analyze the affordances provided by a system, it is helpful to categorize them into four distinct types: sensory affordance, which relates to the user’s ability to sense or see, cognitive affordance, which supports understanding, physical affordance, which involves physical manipulation, and functional affordance, which contributes directly to achieving the user’s goals.

The comparison was carried out with a within-subject experiment that included 60 participants. The collected data were analysed using qualitative and quantitative methods to identify key factors that contribute to successful AR implementation in underground utility visualisation. Additionally, the analysis evaluated whether and how user characteristics could impact the effectiveness of the tested visualisation methods. As such, this analysis allowed the development of recommendations for improving AR visualisation methods based on empirical evidence.

5.2 Research Background

5.2.1 Underground Utility Strike Prevention Techniques

Traditional approaches to preventing underground utility strikes have relied heavily on manual techniques and conventional technologies. One of the most fundamental methods is the "Call Before You Dig" system, which requires contractors to request utility location information prior to excavation (Muthalif *et al.*, 2022b). This system, while essential, often provides only approximate locations and depends on the accuracy of historical records (Fenais *et al.*, 2018a; Khorrami Shad *et al.*, 2025).

GPR and electromagnetic locating devices represent more advanced detection methods, offering non-invasive ways to identify underground utilities (Muthalif *et al.*, 2022b). These technologies have improved accuracy in utility detection but still present limitations in terms of data visualisation and real-time interpretation (Leucci *et al.*, 2002). Traditional marking methods, such as spray paint and flags, remain common practice but are temporary and subject to environmental degradation (Fenais *et al.*, 2018a; Khorrami Shad *et al.*, 2025).

Recent technological advances have introduced more sophisticated damage prevention techniques, including integrating BIM with GIS. These digital tools enhance planning and coordination but often lack the intuitive, on-site visualisation capabilities needed for real-time decision-making during excavation activities.

Current techniques for preventing utility strikes during excavation face several limitations, including a heavy reliance on historical records, which are often incomplete or inaccurate, leading to misinterpretations of utility locations (Khorrami Shad *et al.*, 2025). Also, a significant challenge lies in the difficulty of visualising depth and spatial relationships, which are critical for accurate excavation planning (Schall *et al.*, 2009). Furthermore, real-time data interpretation is also problematic, as existing tools struggle to provide intuitive and actionable insights during dynamic excavation activities (Piroozfar *et al.*, 2021).

5.2.2 AR for Underground Utility

AR has emerged as a transformative technology for underground utility visualisation, offering unique capabilities that address many limitations of traditional methods (Khorrami Shad *et al.*, 2025). AR systems can provide real-time, three-dimensional visualisation of underground infrastructure, enabling workers to see utilities in their actual spatial context before and during excavation work (Fenais *et al.*, 2018b).

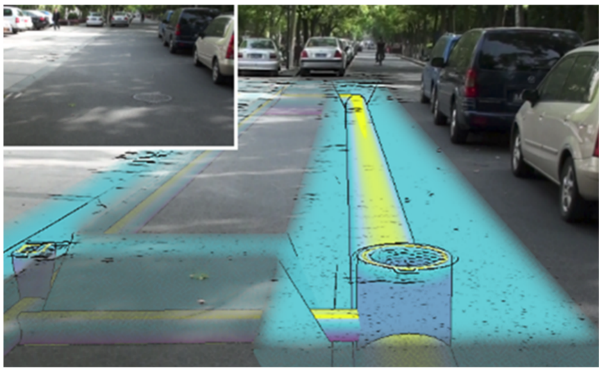
Early applications of AR in utility visualisation focused primarily on simple overlay techniques, displaying 2D utility maps in the user's field of view (Dunston, 2008). However, rapid advancement in AR technology has enabled more sophisticated visualisation methods. Modern AR systems can now integrate multiple data sources, including BIM models, GIS data, and real-time sensor information, to create comprehensive visualisation solutions (Stylianidis *et al.*, 2020).

The AR visualisation methods for underground utilities encompass a range of techniques, each offering unique ways to represent subsurface features. X-Ray visualisation creates a transparent view through the ground surface, allowing users to see utilities as if the surface were semi-transparent (Schall *et al.*, 2013) (figure 5.1a). Shadow visualisation displays the utilities in their location while simultaneously projecting their shadows onto the ground surface (figure 5.1 b). While this technique enhances the visual connection between utilities and their surface position, it may lack precision in depth representation (Muthalif *et al.*, 2022b). Cross-sectional visualisation, shown in vertical cutting planes (figure 5.1c), offers a view of utility placements by slicing through the subsurface. This approach is particularly useful for understanding depth relationships and overlapping utilities, making it a valuable tool for complex excavation planning (Muthalif *et al.*, 2022b). In turn, Topo visualisation presents utilities at the surface level (Figure 5.1d). It focuses on horizontal positioning without addressing depth, making it a more simplistic method for quick utility location tasks (Stylianidis *et al.*, 2020). Finally, Image Rendering visualisation overlays virtual utility models onto the real-world view by masking the ground surface (figure 5.1e). This technique creates an experience by blending the digital and physical worlds (Chen *et al.*, 2010).

(a) X-Ray (Schall *et al.*, 2013)

(b) Shadow (Schall *et al.*, 2013)

(c) Cross-Sectional (Doolani *et al.*, 2020)　(d) Topo (Stylianidis *et al.*, 2020)



(e) Image Rendering (Chen *et al.*, 2010)

Figure 5.1: Different AR visualisation methods for underground utilities

The effectiveness of different AR visualisation methods in practical applications remains inadequately understood. While technical capabilities continue to advance, there is limited empirical evidence comparing how different visualisation approaches impact user performance and task load. For example, Schall *et al.* (2013) have evaluated specific AR methods that integrate geospatial data into AR for on-site visualisation and management of underground infrastructure, demonstrating improvements in workflow efficiency and error reduction compared to traditional methods. Similarly, Eren and Balcisoy (2018) studied user depth perception with the X-ray visualisation technique, highlighting the need for tailored solutions. These studies underscore the importance of systematically comparing AR techniques to identify the most effective solutions for underground utility visualisation.

The present study addresses this knowledge gap by conducting a systematic evaluation of the three most cited AR visualisation methods (X-Ray, Cross-Sectional, Shadow) in the literature, as well as introducing a new method which combines the key features of X-Ray, Cross-Sectional and Shadow. This study then examines their effectiveness through the lens of the theory of affordances and task load analysis. This approach provides a comprehensive solution for understanding the technical capabilities of the visualisation methods and their practical implications for user experience and performance in field applications.

5.3 Materials and Methods

The research method used in this research builds on approaches outlined in sections 5.2 and 5.3.3, which focus on developing and testing AR-based prototypes. It draws from existing studies on designing AR prototypes, exposing users to these systems in real-world scenarios, and actively gathering participant feedback to evaluate their effectiveness.

The research method comprises the development and testing of four different AR-based underground utility visualisation methods, namely, Shadow, Cross-Sectional, X-Ray – the three most cited AR visualisation methods for underground utilities (Schall *et al.*, 2013; Doolani *et al.*, 2020; Stylianidis *et al.*, 2020; Muthalif *et al.*, 2022b) – along with Combination, a newly introduced method. Following their development, the testing involved a controlled within-subject experiment utilising pre- and post-experiment survey questionnaires with 60 participants. All participants were exposed to those visualisation methods in a random order. The experiment compared the four different AR visualisation methods based on task loads and affordances. The method used in this work is provided in figure 5.2.

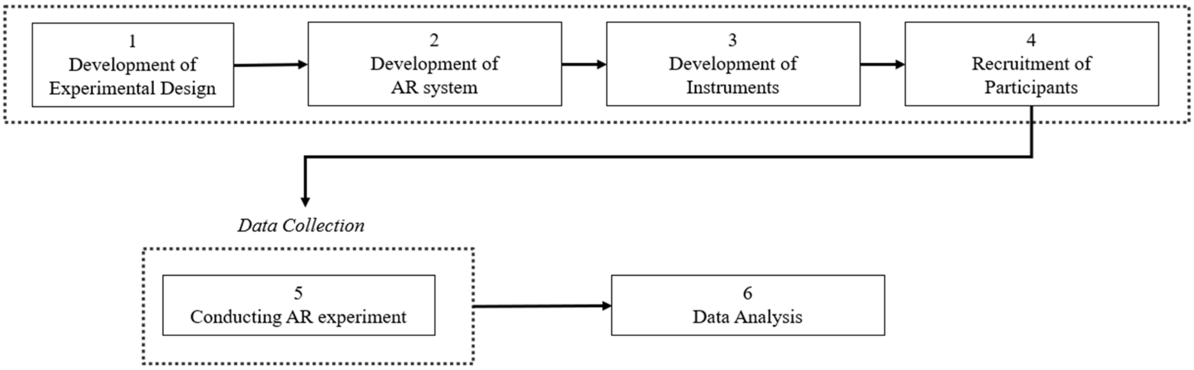


Figure 5.2: Research method framework

5.3.1 Experimental Design

This study adopts a within-group experimental design, also referred to as a “within-subject” design, where participants are exposed to all experimental conditions. Data collection makes use of various survey questionnaires. Data analysis consists of comparing the participants’ responses under different conditions. The number and values of the independent variable (AR visualisation) create four different experimental conditions, namely, X-Ray, Shadow, Cross-Sectional and Combination (Lazar *et al.*, 2017). Combination is the newly introduced method by the authors that combines key features of X-Ray, which reveals hidden pipes within visible objects, Shadow, which projects a shadow of pipes onto the surface, and Cross-Sectional, which creates a virtual plane intersecting the virtual pipes (Muthalif *et al.*, 2022b). The dependent variables for this experiment were a) affordances, b) task load, c) experiment order, and d) reported orders of pipelines associated with the different AR visualisation types. Demographics and AR familiarity were identified as confounding variables and tested for statistical independence of each other (Paes *et al.*, 2021), allowing for the selection of one factor from any correlated pair or group to serve as an independent variable in the model. This study represents the first attempt to use affordances and task load to compare different AR visualisation solutions for underground utilities.

Each visualisation method consists of four underground utilities (pipelines) with the same diameter (0.5m), with four different colours and depths below the ground surface. This ensures that users are exposed to the same visual information in four trials, eliminating the effects due to differences in the information represented and isolating the effects due to the visualisation method for accurate comparison. Randomised trial order (see appendix 2) was adopted in order to remove the learning effect that may be caused by gaining experience with the AR interface and functions over the experiment (Lazar *et al.*, 2017).

The selected experimental space, measuring approximately 30 meters long and 20 meters wide, was chosen to ensure all participants experienced the same conditions during the experiment. The AR application involved a guided mission with three sequential steps prompted by a researcher. In the first step, a pre-test survey was conducted to collect data on participants' demographics and AR familiarity. In the second step, participants identified AR objects and verbally reported the order of pipelines from top to bottom based on their vertical positions using their colour, with a researcher recording their responses. Participants were encouraged to explore the visualisation methods freely, such as by walking around or manipulating the AR device, to facilitate task completion. After each visualisation experience, participants answered 12 paper-based questions by marking responses on provided sheets. These two activities were repeated for each of the four pre-selected visualisation methods in step two. Finally, in the third step, participants verbally answered two open-ended questions, and their responses were audio-recorded by the researcher. The overall experimental design structure is illustrated in figure 5.3.

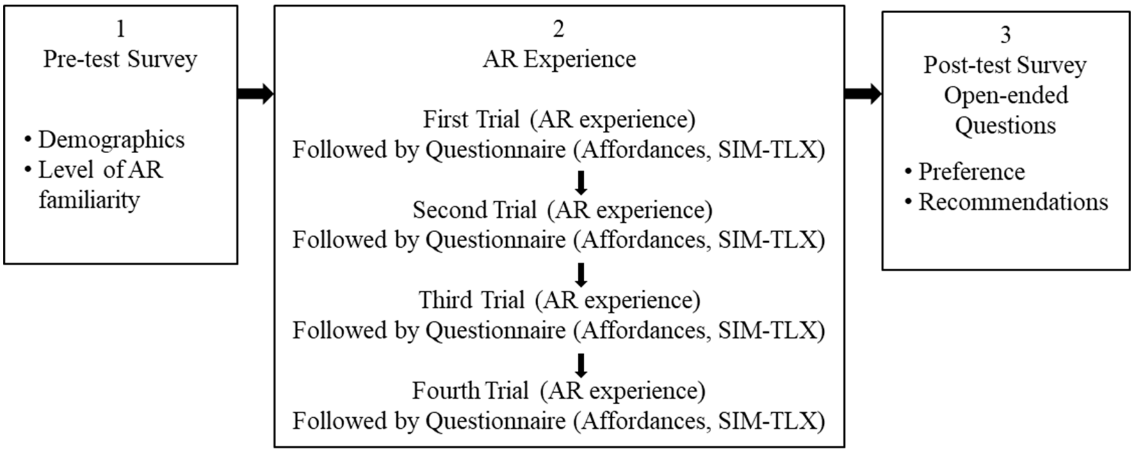


Figure 5.3: Experimental design structure

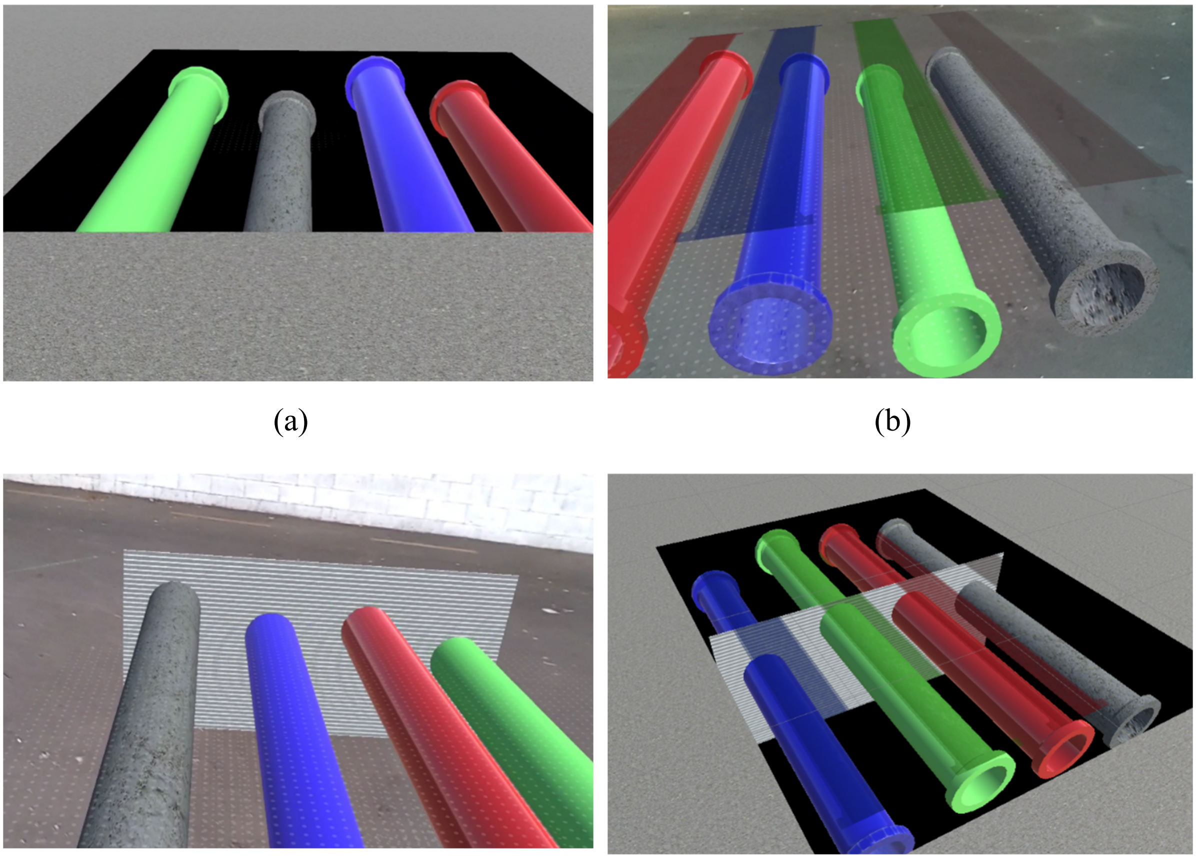
5.3.2 AR System Design

The AR prototype system was developed for a VST AR device (Samsung Galaxy Tab S5e tablet), using Unity (2022.3.23f1) on a Windows PC. Development was done on a local computer with an Intel Xeon W-2235 3.8GHz CPU, 64GB DDR4 RAM, NVIDIA RTX A4000 GPU, and Windows 10. The user interface (UI) was designed according to MRTK (Mixed Reality Toolkit) design guidelines. The AR system was implemented in a covered car park to ensure consistent lighting conditions throughout the day, providing uniform visibility for all participants regardless of their session time.

AR anchor manager was used to create anchor points in the study environment (covered car park), and a researcher initiated the AR visualisation with the tablet and passed it to participants for each visualisation method. This ensured all participants experienced the same utility distances to the ground surface. figure 5.4 shows a set of screenshots of the AR visualisations. Before the experiment, calibration was carried out to place the augmentations (virtual pipelines) in position. In this study, the virtual pipelines were placed at four positions based on their colours as indicated in table 5.1. It should be noted that the prototype allows for customisation through the calibration procedure. The location of the virtual pipelines can be easily modified to fit any floor layout and experience requirements (duration, difficulty, etc.).

Table 5.1: Orientation of pipelines in the experiment

Visualisation	Depth in meters (pipeline centre to ground surface)	Pipeline colour
X-Ray	-0.5, -0.7, -0.4, -0.6	Green, Grey, Blue, Red
Shadow	-0.4, -0.5, -0.7, -0.6	Red, Blue, Green, Grey
Cross-Sectional	-0.4, -0.6, -0.5, -0.7	Grey, Blue, Red, Green
Combination	-0.7, -0.4, -0.5, -0.6	Blue, Green, Red, Grey


(a) (b)

(c) (d)

Figure 5.4: Screenshots of AR visualisations: (a) X-Ray; (b) Shadow; (c) Cross-Sectional; (d) Combination

5.3.3 Data Collection Instruments

The data collection instruments consist of three questionnaires applied at different stages of the experiment: pre-test survey, AR experience, and post-test survey. Each questionnaire includes a different combination of clusters of items aiming at measuring the characteristics of the participants as well as several constructs describing participants' attitudes and perceptions of the AR-based underground utilities' visualisations. These questionnaires were based on previous studies that have developed and used similar instruments (Ronchi and Nilsson, 2013; Ronchi *et al.*, 2016; Olander *et al.*, 2017; Harris *et al.*, 2020; Bernardini *et al.*, 2023).

Most constructs are based on the Theory of Affordances (Gibson, 1977) and the Simulation Task Load Index (SIM-TLX) (Harris *et al.*, 2020). The theory describes how an object is perceived in relation to what it offers or affords the individual. This theory has been adopted in several previous VR-based studies to evaluate different emergency wayfinding systems and fire evacuation signage (Ronchi *et al.*, 2016; Olander *et al.*, 2017; Bernardini *et al.*, 2023).

In turn, the SIM-TLX is a multidimensional task load measurement tool in line with the NASA task load index (NASA-TLX) and the surgery task load index (SURG-TLX). The SIM-TLX is based on participants' ratings on the level of demand required to complete a task on a 21-point Likert scale (Harris *et al.*, 2020). It has been applied in several previous studies to measure participants' task load and user performance in tasks such as surgical training, industrial safety, and evacuation simulations. It has also been used to compare traditional and immersive methods, showcasing the benefits of VR for realistic training and controlled skill acquisition (Radhakrishnan *et al.*, 2021; Skulmowski and Xu, 2022; Bird *et al.*, 2023; Rebol *et al.*, 2023; Skulmowski, 2023).

The clusters of items included in this work collect information regarding: 1) Demographics, 2) AR Familiarity, 3) Affordances, 4) Task Load, 5) Method Preference, and 6) Method Improvement Recommendations. The pre-test questionnaire encompasses clusters 1 and 2. The questionnaire, right after each visualisation, encompasses clusters 3 and 4. The final stage questionnaire (after experiencing the four different visualisation methods) encompasses clusters 5 and 6. The clusters of items are described in more detail as follows.

1) The *Demographics* section comprises five items used to collect participants' characteristics, including gender, educational level, age, background (construction or non-construction), and occupation. These data serve to ensure that the sample includes a comprehensive range of potential confounding variables and is representative of the target population.

2) The *AR Familiarity* section refers to a single confounding variable aimed at assessing participants' daily interaction with AR technology. This variable has been found to be a significant predictor of user engagement and interaction with AR-based systems (Khorrami Shad *et al.*, 2025). To ensure clarity, figures showing examples of AR applications, such as car reverse cameras, Instagram face filters, and the Pokémon Go game, are provided. Participants are then asked to report the frequency with which they use AR in everyday life by selecting one of four options: "never," "rarely," "occasionally," or "regularly".

3) The *Affordances* section comprises seven items designed to assess participants' perceptions of affordances, defined as the possibilities for action that the system offers based on its design and the user's capabilities (Gibson, 1977). The measure was based on questions specifically developed to compare the efficiency of four visualisation methods in terms of three types of affordances: cognitive, sensory, and functional affordances. Data regarding physical affordances were not collected in this section, as they are addressed in the task load section. The seven items, along with their associated affordances, are presented in table 5.2. Responses were collected

using a 7-point Likert scale (1 = "strongly disagree" to 7 = "strongly agree"). Responses were averaged separately for each type of affordance, with three cognitive affordance questions and two functional affordance questions being calculated individually to form their respective final scores.

Table 5.2: Items to assess participants' perceptions of affordances

Items	Affordance
Ease of understanding that virtual objects represent utilities	Cognitive affordance
Ease of noticing the utilities	Sensory affordance
Ease of understanding that the utilities are underground	Cognitive affordance
Ease of understanding the vertical position of utilities	Cognitive affordance
Ease of understanding the horizontal position of utilities	Cognitive affordance
Belief that the system will facilitate identifying utility positions in excavation tasks	Functional affordance
Belief that the system will reduce the risk of utility damage during excavation tasks	Functional affordance

4) The *Task Load* section comprises five items used to evaluate participants' task load. This measure assesses perceived mental demand, physical demand, frustration, task complexity, and visual perception strain associated with completing the experimental tasks, providing insights into the demands of the system on users (Harris *et al.*, 2020). Several items from the original SIM-TLX were excluded to better suit the nature of the experiment. The temporal demand question was removed as the task was not time restricted. The situational stress question was excluded because the frustration question already encompasses stress-related factors. Additionally, distraction and presence questions were omitted as they are specific to VR prototypes, which were

not used in this study. Finally, the task control question was removed because the experiment did not involve control or navigation tasks. The questionnaire is presented in table 5.3. Participants rated their experiences on a 21-point Likert scale (1 = "very low" to 21 = "very high") with marks placed along the scale to best represent their experience, and answers were added together to form the final score for each participant.

Table 5.3: Items to assess participants' task load

Items	Task load
Measuring how mentally fatiguing the task was	Mental demand
Assessing the physical strain experienced during the task	Physical demand
Evaluating feelings of insecurity, discouragement, irritation, stress, or annoyance	Frustration
Capturing the perceived complexity of the task	Task complexity
Measuring discomfort or irritation caused by visual elements of the task	Visual perception strain

5) The *System Preference* section comprises one item to capture participants' subjective opinions on the most effective system among the four visualisation methods. The open-ended question format was preferred as it does not suggest to participants any reasonable answer as a multiple-choice questionnaire might do (Chittaro and Sioni, 2015). Participants were asked the following open-ended question: "Which system do you think is the best, and why?". The responses were analysed using a thematic analysis method inspired by previous studies (Chen *et al.*, 2021; Khorrami Shad *et al.*, 2025) to identify recurring themes and factors influencing participants' choices,

helping to understand which features were most valued and how the systems could be improved to better meet user needs.

6) The *System Improvement Recommendations* section comprises one item used to collect participants’ insights on enhancing the system. Participants were asked the following open-ended question: "What do you recommend for improving our system?" The responses were analysed using a thematic analysis method inspired by previous studies (Chen *et al.*, 2021; Khorrami Shad *et al.*, 2025) to identify recurring recommendations to refine the system's usability, functionality, and overall effectiveness.

5.3.4 Participants and Experiment Session

The sample comprises 60 participants, who were offered a \$10 voucher to compensate their time for participation. The sample complies with the following qualification and inclusion criteria: over 18 years of age and a minimum educational level equal to or over high school. To determine the required sample size, Wilcoxon *a priori* power analysis was conducted using G*Power software. The analysis indicated that a minimum sample size of 55 participants would be needed, considering a medium effect size ($|\rho| = 0.5$), a significance level of 0.0083 with Bonferroni correction for six pairwise comparisons (0.05/6) (Dunn, 1961), and a statistical power of 0.8. These figures are consistent with those presented in the seminal work by Primer (1992). To mitigate potential bias, this study followed approved ethics procedures, including voluntary participation and the right to withdraw, used a neutral study description and recruitment materials that did not suggest any right answers or preferred outcomes, ensured no line-management relationships, anonymised all results and blinded analyses to participant identities, no conflicts of interest, and applied predefined inclusion and exclusion criteria. In parallel, qualitative feedback was gathered through post-session open-ended questions and was analysed using content analysis to capture user preferences and experiential insights.

A low-risk notification (4000026685) was obtained from the Ethics approval, and participants' consent was obtained prior to the commencement of the study. Data collection took place in the experiment sessions. Each session took approximately 20 minutes. figure 5.5 shows a participant during the experiment session.

Figure 5.5: Participant undergoing the experiment

5.3.5 Data analysis

The study employed multiple statistical approaches to analyse the collected data. To examine differences between visualisation methods, statistical tests were conducted for sensory affordance, functional affordance, cognitive affordance, and task load. Given the multiple comparisons performed, a Bonferroni correction was applied to control for family-wise error rates. This conservative approach adjusts the significance threshold to reduce the likelihood of Type I errors. Specifically, with six comparisons (n=6) and a desired family-wise significance level of $\alpha = 0.05$, the adjusted significance threshold is calculated as $\alpha_c = 0.0083$ (Dunn, 1961). To account for potential confounding variables and their effects on the dependent variables, correlation analysis was first performed to test for independence between individual factors (age, gender, and AR familiarity), as in Paes *et al.* (2021). Variables showing Pearson correlations below 0.5 were considered independent and included in subsequent analyses.

Linear Mixed-Effect Models (LME) were then employed to analyse the continuous dependent variables (sensory affordance, cognitive affordance, functional affordance, and task load scores). A Generalised Linear Mixed-Effect Model (GLME) was used for the binary outcome of the reported correct order of utilities. These models were chosen for their ability to handle both fixed effects (visualisation methods, age, gender, AR familiarity) and random effects (participant-specific variations) while being suitable for the within-subject experimental design. The goodness-of-fit for the mixed-effect models was assessed using conditional pseudo-R^2 values (Nakagawa and Schielzeth, 2013). Chi-square tests of independence were also conducted to analyse the relationship between visualisation methods and error rates in the reported order of utilities.

For the qualitative data collected through open-ended questions about system preference and improvement recommendations, responses were analysed using thematic analysis to identify recurring themes and patterns.

5.4 Results

The inferential data analysis aimed to a) determine significant differences in affordances and task load across visualisation methods, b) examine how participants' demographics and AR familiarity influenced these scores, c) identify the most preferred AR visualisation and reasons for this preference, and d) compile suggestions for AR system improvements.

5.4.1 Participant Demographics and Background

Table 5.4 provides a breakdown of sample characteristics. The study included a balanced gender distribution with 31 male and 29 female participants. The majority of participants (51) held postgraduate degrees, while 6 had undergraduate degrees, 2 had diplomas, and 1 had no university degree. Most participants (48) came from construction-related backgrounds. In terms of occupation, the largest group consisted of PhD students (31), followed by quantity surveyors (9) and site engineers (6), with various other occupations represented in smaller numbers. Regarding AR experience, 23 participants reported rarely using AR in their daily life, 20 used it occasionally, 10 had never used it, and 7 used it regularly. The age distribution of participants ranged from 19 to 47 years (M = 32.27, SD = 5.77).

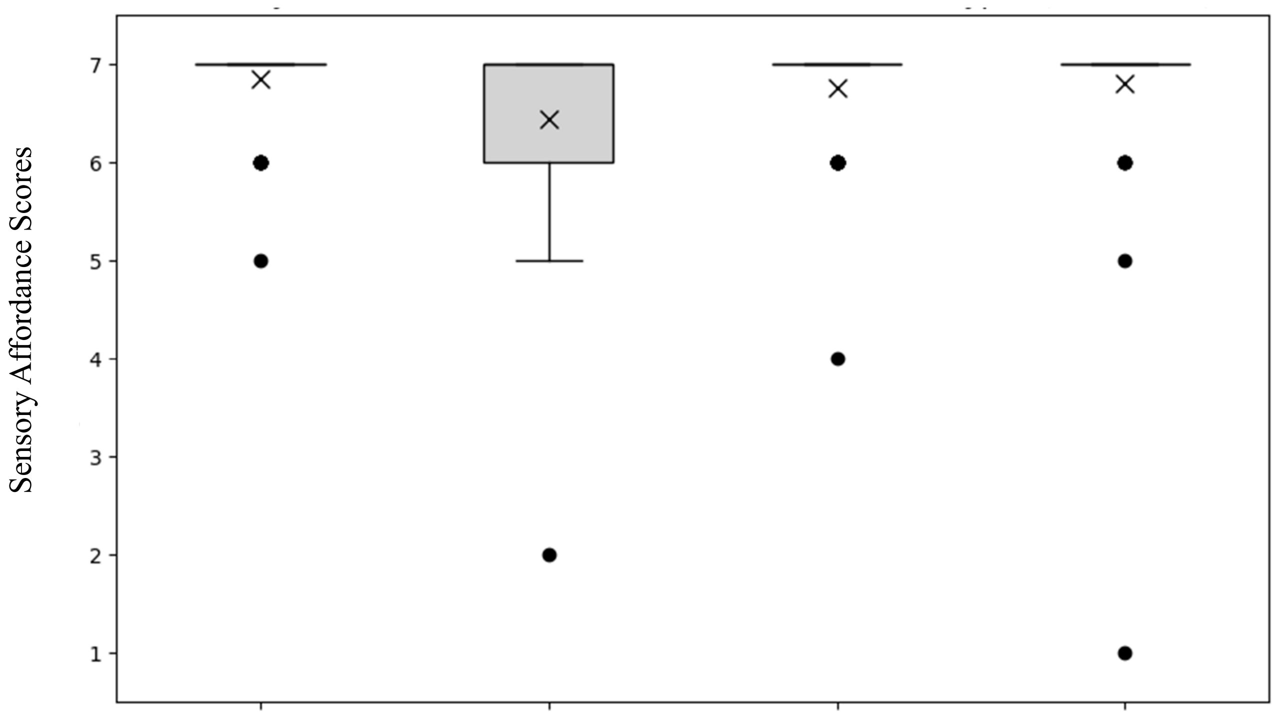
Table 5.4: Sample demographics

Parameter	Subcategory	#	%
Gender	Male	31	52%
	Female	29	48%
Education	Postgraduate	51	85%
	Undergraduate	6	10%
	Diploma	2	3%
	No university degree	1	2%
Background	Construction-related	48	80%
	Non-construction	12	20%
Occupation	PhD students	31	52%
	Quantity Surveyors	9	15%
	Site engineers	6	10%
	Other	14	23%
Use of AR in daily life	Rarely	23	38%
	Occasionally	20	33%
	Never	10	17%
	Regularly	7	12%
Age	Mean	32.27 years	-
	Standard Deviation	5.77 years	-
	Min	19 years	-
	Max	47 years	-

5.4.2 Analysis of Sensory Affordance

This section analyses the sensory affordance scores obtained from participants across four different visualisation methods: X-Ray, Shadow, Cross-Sectional, and Combination. The results are illustrated in figure 5.6 using boxplots. In these boxplots, the ‘x’ markers represent the mean values, while the dots indicate individual data points. Normality tests were carried out using the Kolmogorov-Smirnova test. The result of tests (p-values < 0.05) indicates that scores are not from normal distributions. Therefore, multiple Mann–Whitney U tests were used in this section to check for statistically significant differences between the visualisation methods. Given the multiple comparisons performed, a Bonferroni correction ($\alpha_c = 0.0083$) was again applied.

The data indicate a statistically significant superior sensory affordance for both the X-Ray and the Combination over the Shadow (see table 5.5). However, no significant differences were found when comparing X-Ray with Cross-Sectional, X-Ray with Combination, Shadow with Cross-Sectional, or Cross-Sectional with Combination.



X-Ray	Shadow	Cross-Sectional	Combination
M= 6.85	M= 6.43	M= 6.75	M= 6.80
SD=0.40	SD=0.93	SD=0.54	SD=0.84

Overall: M= 6.71 SD=0.72

Figure 5.6: Participants' sensory affordance scores across four visualisation methods

Table 5.5: Comparison of sensory affordance scores between different visualisation methods

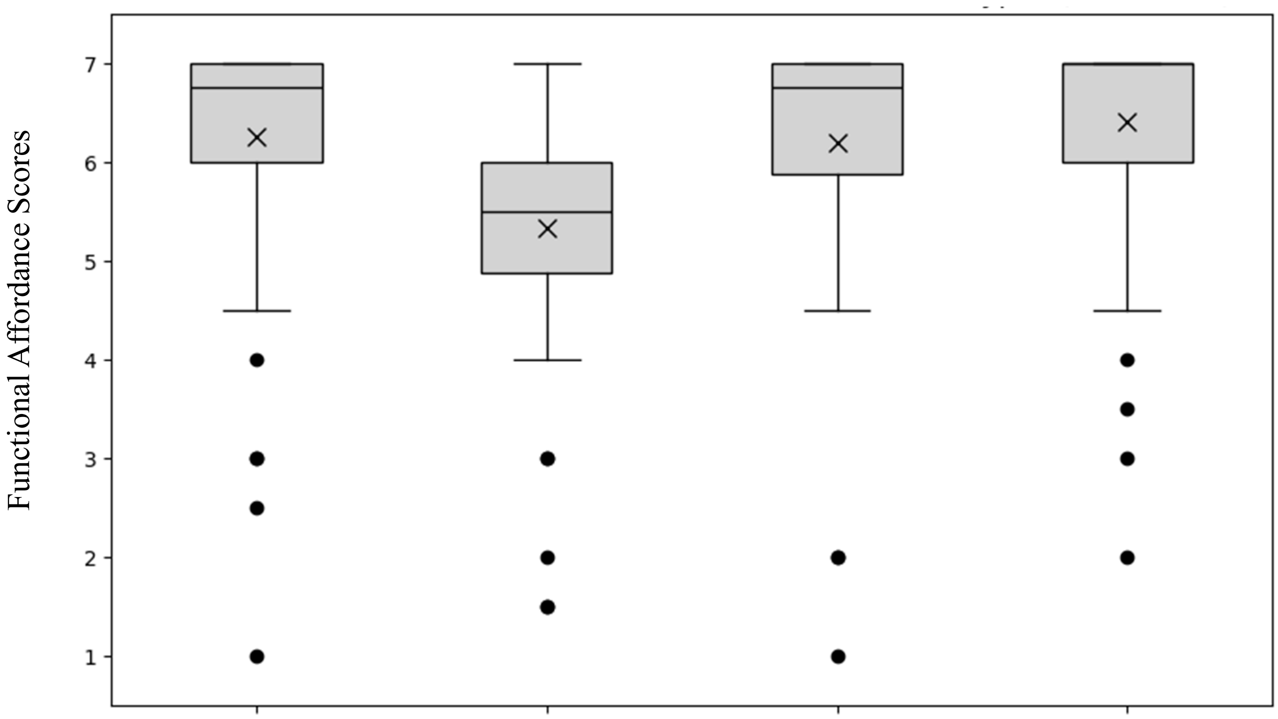
($\alpha_c = 0.008$)

	X-Ray vs Shadow	X-Ray VS Cross	X-Ray vs Combination	Shadow vs Cross	Shadow vs Combination	Cross-Sectional vs Combination
Mann-Whitney U	1354.5	1652	1745.5	1486	1319	1600
Z	-3.089	-1.178	-0.514	-2.068	-3.416	-1.657
P-value	**0.002**	0.239	0.607	0.039	**<0.001**	0.98
Cohen's d	0.85	0.15	0.08	0.65	1.1	0.05

5.4.3 Analysis of Functional Affordance

This section analyses the functional affordance scores obtained from participants across the four visualisation methods: X-Ray, Shadow, Cross-Sectional, and Combination. The results of the average functional affordance scores are illustrated in figure 5.7 using boxplots. In these boxplots, the ‘x’ markers represent the mean values, and the dots indicate individual data points. Normality tests were carried out using the Kolmogorov-Smirnova test. The result of tests (p-values < 0.05) indicates that scores are not from normal distributions. Therefore, multiple Mann–Whitney U tests were used in this section to check for statistically significant differences between the visualisation methods. Given the multiple comparisons performed, a Bonferroni correction ($\alpha_c = 0.0083$) was again applied.

The data indicate a statistically significant superior functional affordance for the X-Ray over the Shadow, along with Cross-Sectional and Combination over the Shadow (see table 5.6). However, no significant differences were found between the X-Ray and Cross-Sectional, X-Ray and Combination, or between the Cross-Sectional and Combination.



X-Ray	Shadow	Cross-Sectional	Combination
M= 6.26	M= 5.33	M= 6.19	M= 6.41
SD=1.24	SD=1.32	SD=1.27	SD=1.11

Overall: M= 6.05 SD=1.30

Figure 5.7: Participants' functional affordance scores across four visualisation methods

Table 5.6: Comparison of functional affordance scores between different visualisation methods

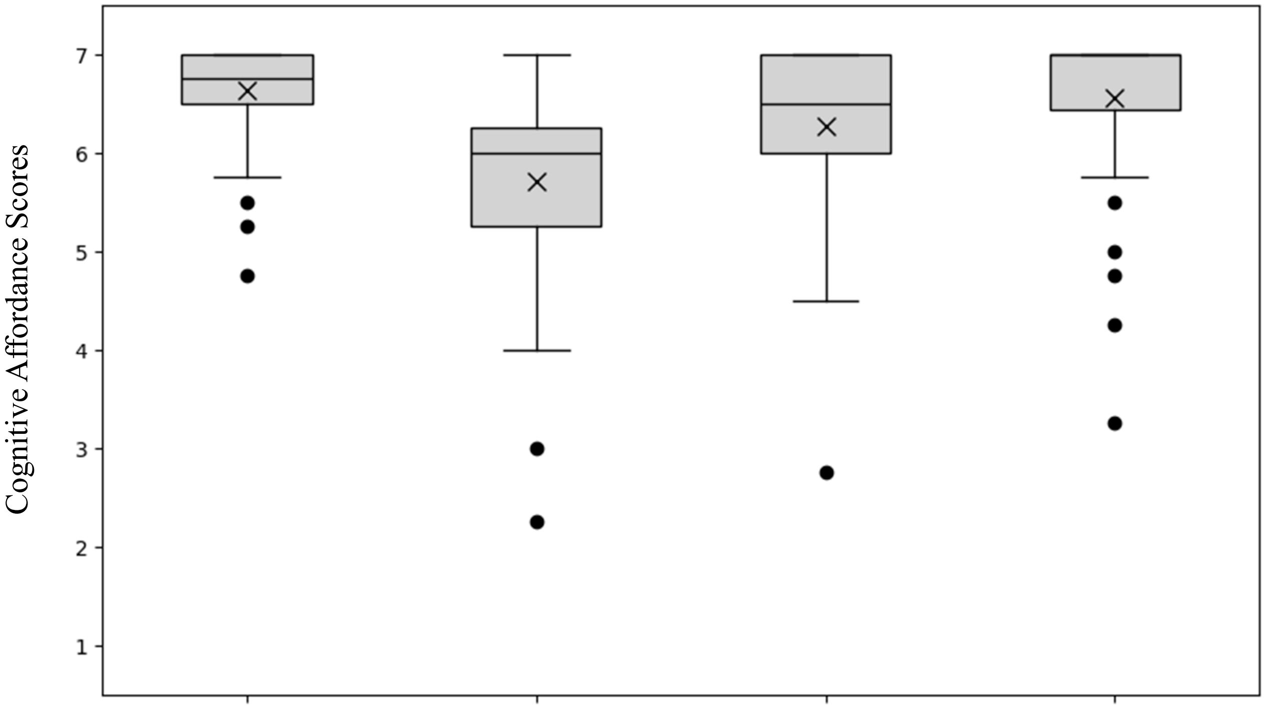
($\alpha_c = 0.008$)

	X-Ray vs Shadow	X-Ray VS Cross-Sectional	X-Ray vs Combination	Shadow vs Cross-Sectional	Shadow vs Combination	Cross-Sectional vs Combination
Mann-Whitney U	915	1733	1570	982	835	1533.5
Z	-4.762	-0.375	-1.352	-4.402	-5.287	-1.565
P-value	**<0.001**	0.708	0.176	**<0.001**	**<0.001**	0.118
Cohen's d	0.72	0.05	-0.12	-0.66	-0.88	-0.18

5.4.4 Analysis of Cognitive Affordance

This section analyses the cognitive affordance scores obtained from participants for the four different visualisation methods: X-Ray, Shadow, Cross-Sectional, and Combination. The results of the average cognitive affordance scores are presented in figure 5.8 using boxplots. In these boxplots, the ‘x’ markers indicate the mean values, while the dots represent individual data points. Normality tests were carried out using the Kolmogorov-Smirnova test. The result of tests (p-values < 0.05) indicates that scores are not from normal distributions. Therefore, multiple Mann–Whitney U tests were used in this section to check for statistically significant differences between the visualisation methods. Given the multiple comparisons performed, a Bonferroni correction ($\alpha_c = 0.0083$) was again applied.

The data indicate a statistically significant superior cognitive affordance for the X-Ray over the Shadow, as well as a significant superiority for both the Cross-Sectional and Combination over the Shadow (see table 5.7). However, no significant differences were observed between X-Ray and Cross-Sectional, X-Ray and Combination or Cross-Sectional and Combination.



X-Ray	Shadow	Cross-Sectional	Combination
M= 6.63	M= 5.70	M= 6.28	M= 6.56
SD=0.48	SD=0.85	SD=0.82	SD=0.73

Overall: M= 6.29 SD=0.81

Figure 5.8: Participants' cognitive affordance scores across four visualisation methods

Table 5.7: Comparison of cognitive affordance scores between different visualisation methods ($\alpha_c = 0.008$)

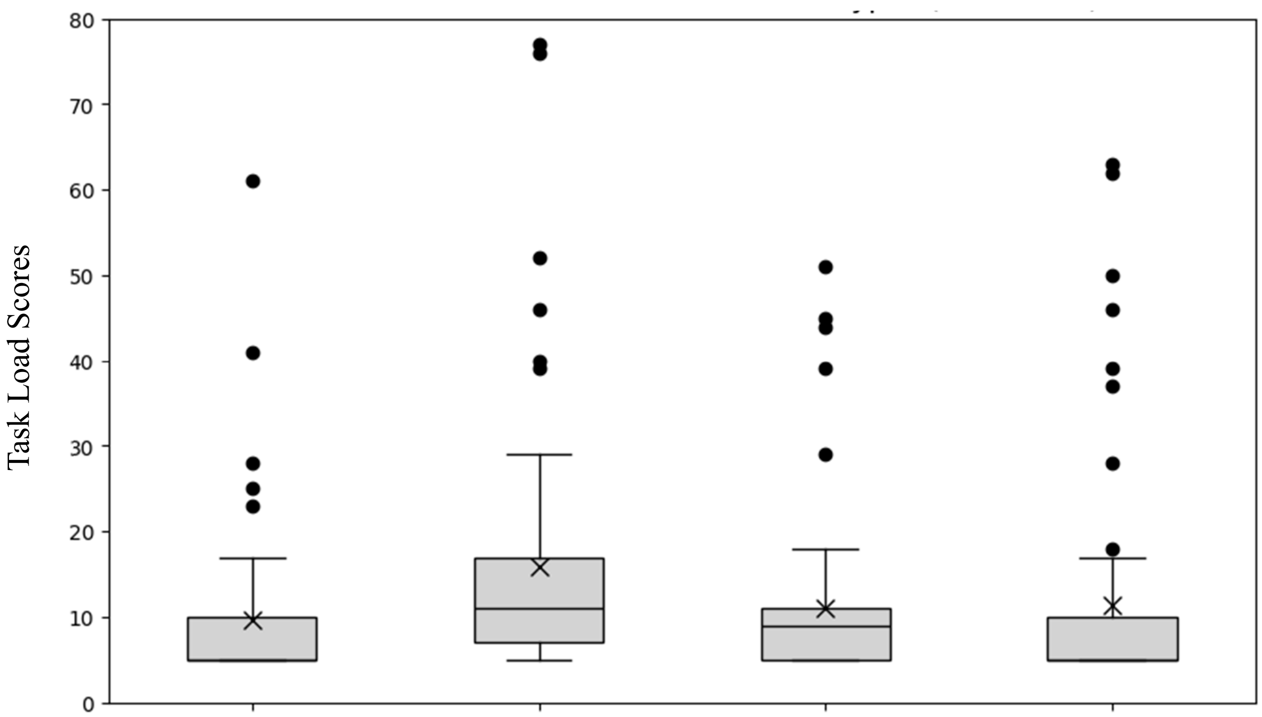
	X-Ray vs Shadow	X-Ray VS Cross-Sectional	X-Ray vs Combination	Shadow vs Cross-Sectional	Shadow vs Combination	Cross-Sectional vs Combination
Mann-Whitney U	472.5	1359	1705	981	554	1331.5
Z	-7.039	-2.381	-0.527	-4.33	-6.629	-2.560
P-value	**<0.001**	0.17	0.598	**<0.001**	**<0.001**	0.010
Cohen's d	1.34	0.52	0.11	-0.69	-1.08	-0.36

5.4.5 Analysis of Task Load

This section analyses the task load scores obtained from participants for the four visualisation methods: X-Ray, Shadow, Cross-Sectional, and Combination. The results of the task load scores are illustrated in figure 5.9 using boxplots, where the ‘x’ marks represent the mean values, and the dots indicate individual data points.

Since the task load scores are measured on an ordinal scale (SIM-TLX) ranging from 0 to 105 (5 items x 21 points each), Mann-Whitney U tests were used to examine whether statistically significant differences existed between the visualisation methods. Given the multiple comparisons performed, a Bonferroni correction ($\alpha_c = 0.0083$) was again applied.

The data indicate a statistically significant difference in task load scores between X-Ray and Shadow, as well as between Shadow and Combination, with p-values less than 0.0083 (see table 5.8). This suggests that participants experienced a higher perceived task load with the Shadow compared to the mentioned methods. Additionally, a significant difference was observed between Cross-Sectional and Combination, with Cross-Sectional showing lower task load scores, indicating a lower perceived task load. However, no significant differences were found between X-Ray and Cross-Sectional or between X-Ray and Combination, as the p-values in these comparisons exceeded the adjusted significance threshold of 0.0083. These findings suggest that the Shadow generally resulted in a higher perceived task load.



X-Ray	Shadow	Cross-Sectional	Combination
M= 9.60	M= 15.97	M= 11.08	M= 11.33
SD=9.62	SD=15.24	SD=10.04	SD=13.91

Overall: M= 12.00 SD=12.59

Figure 5.9: Participants' task load scores across four visualisation methods

Table 5.8: Comparison of task load scores between different visualisation methods

($\alpha_c = 0.008$)

	X-Ray vs Shadow	X-Ray VS Cross-Sectional	X-Ray vs Combination	Shadow vs Cross-Sectional	Shadow vs Combination	Cross-Sectional vs Combination
Mann-Whitney U	1055	1404	1655	1315.5	1034	1319
Z	-4.007	-2.154	-0.850	-2.568	-4.186	-2.672
P-value	**<0.001**	0.031	0.395	0.01	**<0.001**	**0.0076**
Cohen's d	-0.50	-0.15	-0.14	0.38	0.32	-0.02

5.4.6 Mixed Effect Models

To include confounding variables (individual factors) in the model, they must be independent of each other (Paes *et al.*, 2021). Therefore, the first step in this analysis was to determine which ones are significantly correlated with each other. This allowed for selecting a single factor from any pair or group of correlated factors to be included in the model as an independent variable. Naturally, the effects of correlated factors cannot be interpreted separately. The individual factors examined were age, gender, and AR familiarity (educational level, background, and occupation were only used to ensure a representative sample). The analysis revealed no significant correlation among these three factors – Pearson Correlation below 0.5 (see table 5.9).

Table 5.9: Correlation of individual factors

Individual Factors		Gender	Age	AR Familiarity
Gender	Pearson Correlation	1	-0.094	0.022
	Sig. (2-tailed)	-	0.145	0.731
	N	240	240	240
Age	Pearson Correlation	-0.094	1	0.06
	Sig. (2-tailed)	0.145	-	0.355
	N	240	240	240
AR Familiarity	Pearson Correlation	0.022	0.06	1
	Sig. (2-tailed)	0.731	0.355	-
	N	240	240	240

A variance-components covariance structure was adopted in the LME analysis, with participant ID specified as a random effect to account for repeated measurements from the same individuals (West *et al.*, 2022). This random effect structure was necessary as each participant experienced all four visualisation methods, creating within-subject correlations in the data. The model analysed the fixed effects of age, AR Familiarity, visualisation methods, and gender on multiple dependent variables: sensory affordance, cognitive affordance, functional affordance, and task load. The variance-components structure assumes that measurements between different participants are independent, while measurements within the same participant may be correlated (Littell *et al.*, 2000). This approach is particularly suitable for this study's repeated-measures design as it accounts for individual differences in participants' baseline responses while examining the effects of experimental manipulations.

The results of the LME and GLME analyses are summarised in table 5.10, comparing different visualisation types to the Combination as the reference. Each independent variable's effect on sensory affordance, cognitive affordance, functional affordance, and task load was assessed. The estimates, standard errors, and p-values are reported for each predictor across the models, with a significance level of $\alpha = 0.05$. Pseudo-R Square conditional is used to determine the goodness-of-fit of the mixed-effect models (Nakagawa and Schielzeth, 2013).

In the LME results for sensory affordance, the Shadow was statistically significant compared to the Combination ($p < 0.05$), indicating that Shadow reduced sensory affordance scores, which is in line with section 5.4.2. Age was also significant in the sensory affordance model, with older participants reporting lower sensory affordance ($p = 0.01$). Additionally, experiment order showed a significant effect: the second attempt was significantly different from the first ($p < 0.05$), though the third and fourth attempts showed no significant difference compared to the first attempt. AR familiarity and gender did not demonstrate statistically significant effects on sensory affordance ($p > 0.05$), indicating that these factors did not impact sensory affordance scores.

Age was again a significant factor in cognitive affordance, with older participants reporting lower cognitive affordance ($p = 0.01$). Both the Shadow and Cross-Sectional showed lower scores compared to the Combination, though only the Shadow reached statistical significance. Visualisation order did not have a significant impact on cognitive affordance.

In the functional affordance model, age was not a significant factor, suggesting that participant age did not impact functional affordance scores. However, the Shadow again had the lowest scores compared to the Combination, reaching statistical significance ($p < 0.05$).

For the task load measure, age was statistically significant, with older participants reporting higher task load scores, reflecting increased cognitive demand ($p < 0.001$). AR familiarity also showed significance, where participants who were more familiar with AR reported lower task load, suggesting that prior experience with AR technology may reduce perceived task difficulty. Consistent with other affordances, the Shadow was associated with significantly higher task load scores, indicating a more demanding experience compared to the Combination. The GLME model was used for the reported correct order of utilities because it has a binary result (not a continuous result). The analysis showed that Shadow had a statistically significant effect ($p = 0.05$), with a coefficient that suggests an impact on performance compared to other visualisation methods.

Table 5.10: Results of mixed-effect models (α = 0.05)

Independent Variables	LME												GLME		
	SA			CA			FA			TLX			Error Analysis*		
	Estimate	Std. Error	P-Value	Estimate	Std. Error	P-Value	Estimate	Std. Error	P-Value	Estimate	Std. Error	P-Value	Coefficient	Std. Error	P-Value
Age	**-0.02**	**0.01**	**0.01**	**-0.03**	**0.01**	**<0.001**	-0.01	0.01	0.49	**0.55**	**0.13**	**<0.001**	0.08	0.05	0.14
Gender	0.11	0.09	0.23	0.07	0.10	0.51	-0.02	0.18	0.90	-2.09	1.65	0.21	-1.35	0.77	0.08
AR Familiarity	0.08	0.05	0.13	0.03	0.06	0.62	0.17	0.10	0.08	**-2.16**	**0.86**	**0.01**	0.15	0.39	0.69
X-ray	0.07	0.13	0.61	0.08	0.13	0.54	-0.14	0.20	0.49	-1.99	1.72	0.25	0.71	1.56	0.65
Shadow	**-0.36**	**0.13**	**<0.001**	**-0.85**	**0.13**	**<0.001**	**-1.07**	**0.20**	**<0.001**	**4.54**	**1.72**	**0.01**	**2.68**	**1.36**	**0.05**
Cross-Sectional	-0.04	0.13	0.77	**-0.27**	**0.13**	**0.03**	-0.21	0.20	0.30	-0.41	1.72	0.81	1.55	1.43	0.28
Trial order no. 2	**0.30**	**0.13**	**0.02**	0.16	0.13	0.20	0.02	0.20	0.90	-2.17	1.72	0.21	-1.21	0.96	0.21
Trial order no. 3	0.16	0.13	0.21	0.09	0.13	0.50	0.15	0.20	0.47	-2.43	1.72	0.16	-1.48	1.08	0.17
Trial order no. 4	0.21	0.13	0.10	0.18	0.13	0.15	0.05	0.20	0.79	-2.48	1.72	0.15	-0.48	0.83	0.57
	Pseudo-R Square: 0.124			Pseudo-R Square: 0.292			Pseudo-R Square: 0.321			Pseudo-R Square: 0.48			Pseudo-R Square: Not applicable (McCullagh, 2019)		

*Error result is binary: 0 incorrect, 1 correct

5.4.7 Analysis of Errors

This section analyses the participants' reported pipeline orders according to their vertical positions across different visualisation methods: X-Ray, Combination, Cross-Sectional, and Shadow. The analysis is based on the number of true and false reports as shown in the contingency table 5.11 and evaluated using the Chi-Square test of independence. The contingency table illustrates that the Shadow recorded the highest incorrect count (10), followed by Cross-Sectional (4), X-Ray (2), and Combination (1).

To determine whether the differences in reported orders among the visualisation methods were statistically significant, a chi-squared test was conducted. The results indicate a significant relationship between the visualisation methods and the reported order outcomes (Pearson Chi-Square value = 12.345, df = 3, p = 0.006). This suggests that the distribution of true and false reports is not independent of the visualisation method used.

Table 5.11: Contingency table showing the number of true and false reported orders for each visualisation method

Visualisation	Incorrect	Correct
X-Ray	2	58
Combination	1	59
Cross-Sectional	4	56
Shadow	10	50

5.4.8 Qualitative Analysis

The analysis of participant responses revealed varied preferences for which system was considered the best, along with suggestions for system improvement. Participants responded to two open-ended questions: 1) "Which system do you think is the best and why?" and 2) "What do you recommend improving our system?"

As per table 5.12, among the responses, 21 participants (35%) identified the X-Ray system as the best choice, citing its advantages in a) ease of locating utility, b) providing a realistic view of underground utilities, and c) maintaining a non-distracting background. As one participant described, “The X-Ray system gives a realistic view of underground utilities without being visually overwhelming.”

The Combination also received substantial support, with 21 participants (35%) favouring it due to a) its ability to show more detail and b) its effectiveness in helping users locate underground utilities. One participant commented, “The Combination system shows more detail, making it ideal for tasks that require a comprehensive view.”

Meanwhile, the Cross-Sectional was preferred by 18 participants (30%), who valued its ability to offer a “clear view of the vertical position of utilities.” One participant noted, “With the Cross-Sectional, I can instantly understand how the utilities are layered.”

No participants selected the Shadow as their preferred option.

Table 5.12: Results of qualitative analysis

Preferred System	Number of Participants (%)	Reasons for Preference
X-Ray	21 (35%)	Ease of locating utilities
		Realistic view of underground utilities
		Non-distracting background
Combination	21 (35%)	Ability to show more detail
		Effective for locating underground utilities
Cross-Sectional	18 (30%)	Clear view of the vertical position of utilities
Shadow	0	-

A significant number of participants suggested adding features to enhance spatial orientation and clarity, as detailed below:

- Adding arrows to coordinate axes: 32 participants recommended the addition of arrows on the X, Y, and Z axes to facilitate navigation and improve understanding of spatial relationships within the system.

- Incorporating scaled gridlines: 19 participants emphasised the importance of adding scaled gridlines to help differentiate the positions of utilities relative to one another and the ground surface. As one participant noted, this addition would “make it easier to pinpoint exact utility locations relative to each other,” thereby enhancing spatial accuracy.

- Displaying utility diameter: 5 participants suggested displaying the utility diameter to provide essential details for specific tasks that require precision.

- Blurring or hiding non-essential elements: 4 participants suggested an option to select a primary utility while blurring or hiding surrounding utilities and environmental features. This enhancement would enable users to concentrate on the main structures of interest, reducing visual distractions and improving focus.

5.5 Discussions

This study provides a comparative analysis of AR visualisation methods for underground utilities, evaluating participants' affordances and task load. The findings highlight the significant differences among the four AR visualisation methods evaluated: X-Ray, Shadow, Cross-Sectional, and Combination, with several key insights emerging from both quantitative and qualitative analyses. The results align with prior research that identified a superior performance in X-Ray as well as integrating multiple visualisation methods to improve spatial understanding (Behzadan *et al.*, 2015; Kim *et al.*, 2017; Chu *et al.*, 2020)

The X-Ray and Combination emerged as the most effective visualisation methods across multiple measures. These approaches demonstrated superior performance in all three affordance categories. In terms of sensory affordance (see section 5.4.2), both methods achieved significantly higher scores (X-Ray: M=6.85, SD=0.40; Combination: M=6.80, SD=0.84) compared to the Shadow (M=6.43, SD=0.93). Similarly, for functional affordance (see section 5.4.3), they showed better performance (X-Ray: M=6.26, SD=1.24; Combination: M=6.41, SD=1.11) versus Shadow (M=5.33, SD=1.32). The pattern continued in cognitive affordance (see section 5.4.4), where both methods demonstrated stronger results (X-Ray: M=6.63, SD=0.48; Combination: M=6.56, SD=0.73) compared to Shadow (M=5.70, SD=0.85). This quantitative superiority is reinforced by the qualitative findings, where 70% of participants selected either X-Ray or Combination as their preferred visualisation method (35% each as per table 5.12). The error analysis (see table 5.11) further supports this preference, with X-Ray and Combination showing the lowest rates of incorrect utilities order reporting (2 and 1 errors, respectively, compared to 10 errors for Shadow). The X-Ray system was preferred for its ease of locating utilities, realistic representation of underground utilities, and a non-distracting background, making it particularly suitable for quick assessments (see table 5.12). This is consistent with Behzadan *et al.* (2015), who found that X-Ray-based AR visualisations reduce cognitive load and enhance clarity during excavation planning. The Combination system was preferred for its ability to provide more detailed information and its effectiveness in locating underground utilities, suggesting its ability in more complex tasks requiring comprehensive spatial analysis (see table 5.12). The findings are consistent with previous studies that highlighted the enhanced effectiveness of combining multiple visualisation methods to enhance spatial comprehension (Kim *et al.*, 2017; Chu *et al.*, 2020).

The Cross-Sectional performed statistically significant in terms of functional affordance and cognitive affordance over the Shadow. Regarding the task load, X-Ray and Cross-Sectional performed superior (lower average task load demand and lower standard deviation) and statistically significant over the Shadow and Combination methods (see section 5.4.5).

In contrast, the Shadow consistently demonstrated inferior performance across all measures. It received the lowest affordance scores across all three categories, demonstrated the highest task load scores (M=15.97, SD=15.24), showed the most frequent errors in utilities order identification with 10 incorrect reports (see table 5.11), and received zero participant preference in qualitative analysis (see table 5.12). These findings align with previous research by Muthalif *et al.* (2022b), confirming the method's limitations in depth perception and cognitive demand.

The mixed-effects model analysis revealed several significant demographic and experiential factors. Age emerged as a crucial variable, showing significant influence on sensory affordance, cognitive affordance and task load (see table 5.10). Older participants generally reported higher demands and lower affordances. This finding contrasts with Singh *et al.* (2018), possibly due to differences in task complexity and repetition patterns. Gender was not statistically significant across all models, indicating no meaningful differences between genders in affordance perceptions or task load. This is in line with previous studies, which found no statistically significant gender differences in AR applications' perceived demands (Hanafi *et al.*, 2023; Rapti *et al.*, 2023; Paes *et al.*, 2024; Khorrami Shad *et al.*, 2025). Table 5.10 suggests that while age and visualisation type (particularly Shadow) impact affordance and task load, familiarity with AR technology can mitigate task load demands in the task load analysis. This aligns with the findings of Khorrami Shad *et al.* (2025), which emphasised the importance of prior AR experience in enhancing AR usability. In the mixed effect model, sensory affordance order 2 rather 1 is statistically significant, given the fact that it is only one question asked of participants, it is likely to be because of randomness rather than meaningful data. The sample was drawn from New Zealand and should be treated as a boundary condition for interpreting the findings. Certain preferences such as reliance on VST tablets or the perceived task load may reflect local regulatory settings, training practices, and the state of utility record systems. Technology readiness and practice may differ across regions. Therefore, validation in settings beyond New Zealand is recommended.

Participant feedback in section 5.4.7 yielded recommendations for AR system enhancement. A significant number of participants emphasised the importance of spatial orientation improvements, with 32 participants suggesting the implementation of coordinate axes with directional arrows, 19 recommending the integration of scaled gridlines, and 5 suggesting the addition of utility diameter information. Visual clarity enhancements were also recommended, including selective focus capabilities for primary utilities and options to reduce visual clutter from non-essential elements. These recommendations align with Tavares *et al.* (2019) regarding the importance of spatial aids in complex AR applications.

Excavation is a team activity (Liu *et al*., 2022). While this study tested AR in single-user mode, shared AR could cut miscommunication and speed coordination (Piumsomboon *et al.,* 2019). Future work should prototype collaborative AR on live excavation and measure team outcomes. Moreover, AR devices should also be examined in future research, considering their potential health and safety concerns due to the limited field of view, motion sickness or potential distraction highlighted by Kaufeld *et al.* (2022).

5.6 Conclusions

This study represents a step forward in understanding the effectiveness of AR visualisation methods for managing underground utilities. By conducting a comparative analysis of sensory, cognitive, and functional affordances, along with task load implications, the research highlights the strengths and limitations of different visualisation methods, including X-Ray, Combination, Cross-Sectional, and Shadow.

The results demonstrate that the Combination and X-Ray perform comparably well, providing users with enhanced spatial understanding. These findings align with prior research emphasising the benefits of integrating multiple visualisation methods to improve user comprehension. However, the consistent underperformance of the Shadow highlights its limitations in providing clear spatial cues and relatively high demands in task load.

This study represents the first formal attempt in the published academic literature to compare different underground visualisation methods using the task load analysis and the theory of affordances. As such, it contributes to the body of knowledge by advancing our understanding of the suitability and effectiveness of these visualisation methods from a user-centred perspective. It also provides valuable directions for designing and implementing more efficient AR systems tailored to the specific needs of underground utility management. Ultimately, this user-focused research could lead to the development of increasingly effective tools that enhance users' spatial understanding and task performance in complex environments.

Nonetheless, several limitations in this study should be acknowledged. The controlled testing environment may not fully reflect real-world conditions, and the study was limited by single-location testing in a covered car park. The participant pool was predominantly from construction-related backgrounds (80%) with a limited age range (M=32.27, SD=5.77 years) and primarily postgraduate level education (85%). Future research should address these limitations by conducting field studies in actual excavation environments, including more diverse professional backgrounds, testing under various environmental conditions, incorporating time pressure and physical constraints, and examining long-term learning effects and user adaptation. This study focuses on AR visualisation using the same VST device. As such, only sensory, cognitive, and functional affordances are relevant to the analysis, while physical affordance is not taken into consideration. It is recommended that future studies compare OST and VST devices to explore how physical affordance influences user interaction and task performance. Additionally, anchoring was not considered the primary focus of this study, as emphasis was placed on the visualisation aspect of AR. The comparison of different anchoring systems is recommended for future studies to evaluate their impact on participants' performance. VST displays were selected in this study due to their common usage on construction sites, as noted by Xu *et al.* (2024). However, OST displays should also be examined in future research, considering their potential health and safety concerns due to the limited field of view or motion sickness highlighted by Kaufeld *et al.* (2022). Lastly, the depth and size of pipes may affect perceived affordance and task load scores; therefore, it is advised that a variety of layouts with differing depths and sizes be investigated in future studies to gain a more comprehensive understanding of these factors.

In summary, this research lays a foundation for designing more effective and user-centred AR systems for underground utility management. By addressing the challenges identified and building on the strengths of the tested visualisation methods, future AR solutions can achieve greater accuracy, enhanced affordance, and reduced task load efficiency across a wide range of applications.

5.7 Summary

This chapter details the results of a controlled experiment comparing four AR visualisation methods delivered via VST devices. The evaluation focused on their effectiveness in enhancing spatial understanding and reducing task load in underground utility management tasks.

The results showed that the Combination and X-Ray methods were most effective, providing higher sensory, cognitive, and functional affordances and resulting in lower task load scores. In contrast, the Shadow method consistently underperformed across both quantitative and qualitative measures. The study also confirmed that participants with prior AR experience experienced lower task load, and that older participants tended to report greater difficulty, highlighting the importance of user training and age-inclusive design.

Chapter 6: Discussion and Conclusions

This research aimed to investigate how AR can be effectively adopted to prevent underground utility strikes during excavation activities. Through a combination of literature review, industry engagement, and experimental testing, the study generated an understanding of the current limitations, industry needs, and user experiences associated with AR in this domain.

The initial literature review established the groundwork by analysing existing research on AR applications in construction safety. It revealed a strong focus on pre-event applications (89.7%), underscoring AR's value in proactive safety management. However, it also exposed a significant gap: the limited application of AR in visualising underground utilities, despite the high risks involved in excavation work. This recognition shaped the study's direction and provided a foundation for the next research phase.

Motivated by the literature gap, the second phase of the research engaged 31 excavation professionals to understand real-world practices and perceptions around AR adoption. This qualitative phase served not just as a standalone inquiry but as a critical bridge that informed the design of the experimental study phase. For example, industry professionals consistently reported frustrations with current methods, such as inaccurate as-built drawings, invisible markings post-excavation, and paper-based drawings. The findings align with prior research that the integrated use of GPR, hydro excavation, and potholing techniques are mentioned as common methods to overcome limitations and risks associated with excavation works (Qin *et al.*, 2016; Fenais *et al.*, 2018a; Feng *et al.*, 2019; Wang *et al.*, 2023). The marked tilt in participants' favourability towards AR technology underscores its transformative potential within the excavation industry. This finding suggests that AR has the potential to revolutionise current excavation practices. This aligns with existing literature that found AR a better alternative to traditional paper-based methods (Kwiatek *et al.*, 2019). As per the findings in this phase (section 4.4.3), tablet-based AR systems were found to impose less physical and mental demand on excavation professionals compared to OST devices. Additionally, section 4.4.6 revealed that affordability, which is defined as the cost of devices and training, was a significant barrier to AR adoption. In a similar way, previous studies show that tablets are perceived as more accessible and affordable (Kolaei *et al.*, 2022). And, choosing tablets because of familiarity and not restricting the field of view (see figure 4.9) is in line with existing studies (Stoltz *et al.*, 2017; Abbas *et al.*, 2020; Qin *et al.*, 2021; Xiang *et al*., 2021). These insights directly influenced the decision to use tablets for the experimental phase.

Other interview findings further shaped the experimental study phase. Section 4.4.5 highlighted that professionals require pipe specifications to be visible in the AR environment. In response, the experimental phase incorporated Cross-Sectional and Combination AR visualisation methods to address this need. These methods display a perpendicular cross-sectional plane on the pipes, making pipe dimensions and depth intuitively accessible. Thus, the interview phase not only validated the need to compare specific AR visualisation techniques but also ensured that the selected methods addressed key informational requirements of the industry.

Building on these insights, the experimental study tested four AR visualisation methods: X-Ray, Shadow, Cross-Sectional, and a newly developed Combination method. The study applied the theory of affordances and NASA task load to evaluate the effectiveness. Cross-validation between qualitative and quantitative findings strengthened the confidence in the results: both data sets indicated that X-Ray and Combination methods were the most effective. Participants favoured X-Ray for its simplicity and clarity, especially in fast-paced scenarios, while the Combination method was better suited for complex tasks requiring more spatial context. This aligns with Behzadan *et al.* (2015) and Kim *et al.* (2017), who reported that X-Ray style overlays reduce cognitive burden and speed target identification, and with Chu *et al.* (2020), who showed that combining cues improves spatial comprehension in complex scenes. By contrast, Shadow consistently under-performed in our experiment converging with Muthalif *et al.* (2022b) on depth-judgement and cognitive demand limits for shadow view.

The qualitative responses from the post-experiment open-ended questions closely aligned with the quantitative findings, demonstrating a strong consistency across methods. Both data sources confirmed that the Shadow visualisation method consistently underperformed. The results also highlighted a significant relationship between AR familiarity and task load: participants who were more familiar with AR reported lower task load scores. This underscores the importance of training and prior exposure in supporting the effective adoption of AR systems within HCI contexts.

In addition, older participants generally reported lower sensory and cognitive affordances along with higher task load, suggesting that AR visualisations may be more mentally demanding and less intuitive for this demographic. These findings emphasise the need to consider age-related differences in perception and information processing when designing AR interfaces. Improving the adaptability and clarity of AR systems for older professionals could help promote broader and more inclusive adoption in the construction sector.

Overall, these insights contribute to HCI research by reinforcing the importance of designing user-centred systems that accommodate a wide range of user needs and abilities. The findings also advance the application of the Theory of Affordances and Task Load in the construction industry by demonstrating how different AR visualisation methods offer varying levels of users' feedback. The results support the theory's premise that effective design should align with users' abilities. Furthermore, this study extends existing HCI research by applying these theories in a novel domain, where spatial awareness plays a critical role.

This research offers several practical implications for construction stakeholders. VST devices, such as tablets, are more appropriate for excavation sites compared to OST devices because they are easier to use, more affordable, and already familiar to many workers. Although a formal economic analysis was beyond the scope of this study, the relative affordability of VST device should be considered alongside the of utility strikes. The UK Government's Geospatial Commission (2021) estimates that accidental strikes on underground pipes and cables impose around £2.4 billion per year in total economic costs across the UK. In this context, even a modest reduction in incidents achieved by AR could offset device and training cost, suggesting a favourable cost–benefit balance for early adoption.

In terms of visualisation methods, the X-Ray approach is well-suited for quick, on-site assessments, while the Combination method is more effective for complex excavation scenarios that require detailed spatial planning. For AR integration to be successful, it is essential to address issues related to accessibility and training. The findings showed that participants with prior AR experience reported significantly lower task load. Furthermore, the quality of as-built data and the accuracy of utility drawings remain key challenges. To maximise the potential of AR systems, they must be integrated with real-time or verified utility databases.

This study adopted a pragmatic research approach, with each phase building iteratively on the findings of the previous one. The qualitative feedback from industry participants was not merely descriptive but played a role in shaping both the selection of devices and the design of visualisation methods used in the experimental phase. The alignment between industry expectations and experimental outcomes highlights that user-centred design is essential for effective AR adoption. Future researchers could build on this work by exploring AR systems on active excavation sites to validate the findings. Longitudinal studies could also examine how familiarity with AR develops over time and how it influences safety outcomes. Further research might extend this work into multi-user AR environments to explore collaborative excavation planning. Another important direction would be integrating AR systems with dynamic data sources such as real-time sensor input or a utility network. In conclusion, this research contributes both theoretically and practically to construction safety by demonstrating how AR can be effectively integrated into excavation workflows to reduce underground utility strikes. By aligning technology with user capabilities and industry needs, the study offers a practical framework for safer, smarter, and more efficient excavation practices.

6.1 Contributions

This research makes contributions to the fields of HCI, construction safety, digital technology adoption, and spatial visualisation, particularly within the context of underground utility strike prevention. By focusing on AR and its potential to enhance spatial understanding on excavation sites, the study advances both theoretical knowledge and practical implications in a domain that has received limited attention in the current literature.

From a theoretical perspective, the study extends existing literature by shifting the focus of AR toward a more specific and high-risk activity, which is the prevention of underground utility strikes. While earlier studies have explored the role of AR in training and hazard detection, they have rarely addressed its use in locating underground utilities in the excavation industry. This thesis fills that gap by examining how AR can effectively be adopted as a real-time decision support system in excavation work. This study also provides a structured framework for evaluating AR interfaces in construction contexts, potentially applicable to other domains.

Methodologically, the research presents a structured, mixed-methods approach that moves from systematic review to industry engagement and controlled experimentation. This progression from broad conceptual exploration to empirical analysis demonstrates how AR can be evaluated both in terms of practical adoption and technical performance. The use of semi-structured interviews allowed for the identification of industry needs and expectations, while the experimental phase introduced a comparison of four AR visualisation methods.

In terms of practical impact, the research provides actionable insights for AR developers, industry professionals, and policymakers. It identifies the usability features and hardware preferences that matter most to excavation professionals. Notably, the preference for VST devices is due to their familiarity and practicality in field environments. Moreover, the findings highlight the importance of accessibility, affordability, and ease of use when considering AR adoption in construction workflows. By identifying effective visualisation methods like X-Ray and Combination, the research guides AR tool development for excavation tasks.

In sum, this thesis contributes to filling the gap between technological innovation and industry adoption in construction safety. It offers a foundation for understanding how AR can support safer excavation practices, thereby reducing the risk of underground utility strikes and contributing to a more informed, responsive, and technologically integrated excavation.

6.2 Limitations

Several limitations should be acknowledged. First, the experimental study was conducted in a controlled environment at a single location, which may not fully capture the complex and dynamic conditions of excavation sites. Findings were generated under controlled conditions; the adoption of AR on excavation sites may depend on real-world factors not fully captured here. Weather and lighting can affect visibility; bright sun can increase screen glare and reduce contrast, while rain, dust, and cold can impair touch interaction and degrade battery performance. These conditions may alter perceived affordances and task load. Additionally, the participant pool consisted mainly of individuals with construction backgrounds, a relatively narrow age range, and predominantly postgraduate education. The sample was drawn from New Zealand and should be treated as a boundary condition for interpreting the findings. Construction practices, regulatory settings, and technology readiness differ across regions; therefore, the generalisability of the results beyond New Zealand is uncertain.

Second, the study focused on AR visualisation using a single VST device. As such, the analysis considered sensory, cognitive, and functional affordances; physical affordances were not examined. Device comparisons between OST and VST were therefore outside scope, and potential safety or health issues associated with OST (e.g., motion sickness, eye strain) were not evaluated.

Third, the evaluation centred on individual use rather than collaborative or multi-user interactions, even though excavation tasks are frequently team-based. Anchoring methods were not the primary focus, the study prioritised visualisation design over comparative anchoring techniques.

Fourth, while user experience was assessed using affordance ratings and task load, other performance indicators were only partially incorporated. The experimental scenarios also did not vary the depth, size, or configuration of underground utilities, factors that may influence perceived affordances and task load.

Finally, interview insights indicate that professionals continue to rely on established practices (e.g., GPR, hydro excavation, hand digging). This study did not empirically evaluate how AR integrates with these workflows, nor did it test role-specific customisation of interfaces.

6.3 Future Research

Future work should address external validity through field studies in active excavation environments, sampling across diverse professional roles, age bands, and educational backgrounds, and testing under varied environmental conditions, time pressure, and physical constraints. Longitudinal designs are recommended to examine learning curves, changes in efficiency, retention of spatial understanding, and user adaptation over extended periods.

Comparative device research should evaluate OST versus VST in live settings to quantify the impact of physical affordances on interaction, task performance, and preference, while also assessing health and safety considerations (e.g., motion sickness, eye strain, PPE compatibility). Future studies should also explore multi-user and collaborative AR scenarios, as well as the performance implications of different anchoring systems.

Evaluation metrics should be broadened to include response times, error/accuracy rates, and behavioural indicators alongside subjective measures. Scenario complexity should be increased by systematically varying utility depth, size, and configuration, and by incorporating more complex task sequences.

Given industry practice, research should investigate hybrid workflows in which AR complements detection and verification (e.g., GPR, and potholing), including data-quality signalling and uncertainty visualisation. Finally, studies should examine customisable and role-adaptive interfaces that accommodate differing user expectations, task demands, and utility characteristics, and should replicate the work in regions beyond New Zealand to test broader applicability across organisational, cultural, and regulatory contexts.

6.4 Final Remarks

This doctoral research journey has advanced knowledge in the domain of AR for underground utilities and also significantly shaped the researcher's understanding of how technologies can be integrated into high-risk industries like excavation. Initially, AR appeared to be a promising visual enhancement tool. However, through this journey, the researcher's perspective has evolved to appreciate AR as a complex social-technical system, which must align with user needs, site constraints and workflows to be effective.

Looking ahead, the researcher believes AR has strong potential to improve safety and performance in high-risk industries, especially when systems are designed to be adaptable, support collaboration, and align with users' cognitive processes and work environments. The future of AR in construction will likely involve adaptive interfaces, multi-user environments, and seamless integration with existing technologies. As the line between digital and physical workspaces becomes less clear, the lessons from this research can help guide the design of safer, easier-to-use, and more practical AR systems that meet the needs of different users working in complex environments.

References

(2022), "Common Ground Alliance- Damage Information Reporting Tool", available at https://dirt.commongroundalliance.com/2022-DIRT-Report (accessed).

Abbas, A., Seo, J. and Kim, M. (2020). Impact of Mobile Augmented Reality System on Cognitive Behavior and Performance during Rebar Inspection Tasks, Journal of Computing in Civil Engineering, Vol. 34 No. 6, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000931.

Abebe, Y. and Tesfamariam, S. (2020). Underground sewer networks renewal complexity assessment and trenchless technology: A Bayesian belief network and GIS framework, Journal of Pipeline Systems Engineering and Practice, Vol. 11 No. 2, p. 04019058, https://doi.org/10.1061/(ASCE)PS.1949-1204.0000441.

Ahn, S., Han, S. and Al-Hussein, M. (2019). 2D drawing visualization framework for applying projection-based augmented reality in a panelized construction manufacturing facility: Proof of concept, Journal of Computing in Civil Engineering, Vol. 33 No. 5, p. 04019032, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000843.

Al-Bayati, A.J. (2021). Infrastructure Damage Prevention Approaches in the United States, in Pipelines 2021, pp. 102-108, https://doi.org/10.1061/9780784483619.011.

Al-Bayati, A.J. and Panzer, L. (2020). Reducing damages to underground utilities: Importance of stakeholders' behaviors, Journal of Construction Engineering and Management, Vol. 146 No. 9, p. 04020107, https://doi-org.ezproxy.massey.ac.nz/10.1061/(ASCE)CO.1943-7862.0001899.

Albahbah, M., Kıvrak, S. and Arslan, G. (2021). Application areas of augmented reality and virtual reality in construction project management: A scoping review, J. Constr. Eng. Manag. Innov, Vol. 4 pp. 151-172, https://doi.org/10.31462/jcemi.2021.03151172.

Alice Cleland, I.K., Simon Leong, Satnam Singh, and Eric Wu (2022). Building and construction sector trends annual report, p. 54, Wellington, available at https://www.mbie.govt.nz/building-and-energy/building/building-system-insights-programme/sector-trends-reporting/biannual-snapshots/november-2022/

Amin, D. and Govilkar, S. (2015). Comparative study of augmented reality SDKs, International Journal on Computational Science & Applications, Vol. 5 No. 1, pp. 11-26, https://doi.org/10.5121/ijcsa.2015.5102

Anchuela, Ó.P., Casas-Sainz, A., Soriano, M. and Pocoví-Juan, A. (2009). Mapping subsurface karst features with GPR: results and limitations, Environmental Geology, Vol. 58 pp. 391-399, https://doi.org/10.1007/s00254-008-1603-7.

Asadzadeh, A., Arashpour, M., Li, H., Ngo, T., Bab-Hadiashar, A. and Rashidi, A. (2020). Sensor-based safety management, *Automation in Construction,* Vol. 113 p. 103128, https://doi.org/10.1016/j.autcon.2020.103128.

Baek, F., Ha, I. and Kim, H. (2019). Augmented reality system for facility management using image-based indoor localization, *Automation in Construction,* Vol. 99 pp. 18-26, https://doi.org/10.1016/j.autcon.2018.11.034.

Baek, J. and Choi, Y. (2020). Smart glasses-based personnel proximity warning system for improving pedestrian safety in construction and mining sites, *International Journal of Environmental Research and Public Health,* Vol. 17 No. 4, p. 1422, https://doi.org/10.3390/ijerph17041422.

Baumeister, J., Ssin, S.Y., ElSayed, N.A., Dorrian, J., Webb, D.P., Walsh, J.A., Simon, T.M., Irlitti, A., Smith, R.T. and Kohler, M. (2017). Cognitive cost of using augmented reality displays, *IEEE transactions on visualization and computer graphics,* Vol. 23 No. 11, pp. 2378-2388, https://doi.org/10.1109/TVCG.2017.2735098.

Behzadan, A.H., Dong, S. and Kamat, V.R. (2015). Augmented reality visualization: A review of civil infrastructure system applications, *Advanced Engineering Informatics,* Vol. 29 No. 2, pp. 252-267, https://doi.org/10.1016/j.aei.2015.03.005.

Behzadan, A.H. and Kamat, V.R. (2007). Georeferenced registration of construction graphics in mobile outdoor augmented reality, *Journal of Computing in Civil Engineering,* Vol. 21 No. 4, pp. 247-258, https://doi.org/10.1061/(ASCE)0887-3801(2007)21:4(247).

Behzadan, A.H., Timm, B.W. and Kamat, V.R. (2008). General-purpose modular hardware and software framework for mobile outdoor augmented reality applications in engineering, *Advanced Engineering Informatics,* Vol. 22 No. 1, pp. 90-105, https://doi.org/10.1016/j.aei.2007.08.005.

Bell, E., Harley, B. and Bryman, A. (2022). Business research methods, Oxford university press, 0198869444.

Bello, A.O., Khan, A.A., Idris, A. and Awwal, H.M. (2024). Barriers to modular construction systems implementation in developing countries' architecture, engineering and construction industry, *Engineering, Construction and Architectural Management,* Vol. 31 No. 8, pp. 3148-3164.

Bernardini, G., Lovreglio, R., Quagliarini, E. and D'Orazio, M. (2023). Can active and passive wayfinding systems support fire evacuation in buildings? Insights from a virtual reality-based experiment, *Journal of Building Engineering,* Vol. 74 p. 106778, https://doi.org/10.1016/j.jobe.2023.106778.

Billinghurst, M., Clark, A. and Lee, G. (2015). A survey of augmented reality, *Foundations and Trends® in Human–Computer Interaction,* Vol. 8 No. 2-3, pp. 73-272, https://doi.org/10.1561/1100000049

Billinghurst, M. and Kato, H. (2002). Collaborative augmented reality, *Communications of the ACM,* Vol. 45 No. 7, pp. 64-70, https://doi.org/10.1145/514236.514265

Bird, J.M., Smart, P.A., Harris, D.J., Phillips, L.A., Giannachi, G. and Vine, S.J. (2023). A magic leap in tourism: Intended and realized experience of head-mounted augmented reality in a museum context, Journal of Travel Research, Vol. 62 No. 7, pp. 1427-1447, https://doi.org/10.1177/00472875221134031.

Bokhari, H.R., Lee, D., Khan, N. and Park, C. Inspection of Discrepancies in Construction Temporary Safety Structures through Augmented Reality, IAARC Publications, pp. 193-198, https://doi.org/10.22260/ISARC2020/0029

Bottani, E. and Vignali, G. (2019). Augmented reality technology in the manufacturing industry: A review of the last decade, IISE Transactions, Vol. 51 No. 3, pp. 284-310, https://doi.org/10.1080/24725854.2018.1493244.

Bryman, A. (2016). Social research methods, Oxford university press, 0199689458.

Cai, J., Li, S. and Cai, H. Accurate mapping of underground utilities: An information fusion approach based on Dempster-Shafer theory, pp. 712-721, https://doi.org/10.1061/9780784481295.071

Carmigniani, J., Furht, B., Anisetti, M., Ceravolo, P., Damiani, E. and Ivkovic, M. (2011). Augmented reality technologies, systems and applications, Multimedia tools and applications, Vol. 51 No. 1, pp. 341-377, https://doi.org/10.1007/s11042-010-0660-6.

Chen, H., Hou, L., Zhang, G.K. and Moon, S. (2021). Development of BIM, IoT and AR/VR technologies for fire safety and upskilling, Automation in Construction, Vol. 125 p. 103631, https://doi.org/10.1016/j.autcon.2021.103631.

Chen, J., Granier, X., Lin, N. and Peng, Q. On-line visualization of underground structures using context features, pp. 167-170, https://doi.org/10.1145/1889863.1889898

Chi, H.-L., Kang, S.-C. and Wang, X. (2013). Research trends and opportunities of augmented reality applications in architecture, engineering, and construction, Automation in Construction, Vol. 33 pp. 116-122, https://doi.org/10.1016/j.autcon.2012.12.017.

Chi, H.-L., Kim, M.-K., Liu, K.-Z., Thedja, J., Seo, J. and Lee, D.-E. (2022). Rebar inspection integrating augmented reality and laser scanning, Automation in Construction, Vol. 136 p. 104183, https://doi.org/10.1016/j.autcon.2022.104183.

Chittaro, L. and Sioni, R. (2015). Serious games for emergency preparedness: Evaluation of an interactive vs. a non-interactive simulation of a terror attack, Computers in Human Behavior, Vol. 50 pp. 508-519, https://doi.org/10.1016/j.chb.2015.03.074.

Chu, C.-H., Liao, C.-J. and Lin, S.-C. (2020). Comparing augmented reality-assisted assembly functions—a case study on Dougong structure, Applied Sciences, Vol. 10 No. 10, p. 3383, https://doi.org/10.3390/app10103383.

Chu, M., Matthews, J. and Love, P.E. (2018). Integrating mobile building information modelling and augmented reality systems: an experimental study, Automation in Construction, Vol. 85 pp. 305-316, https://doi.org/10.1016/j.autcon.2017.10.032.

Coglianese, C., Nash, J. and Olmstead, T. (2003). Performance-based regulation: Prospects and limitations in health, safety, and environmental protection, Administrative Law Review, Vol. 55 p. 705, available at: https://www.jstor.org/stable/40712156.

Crapper, M., Fell, M. and Gammoh, I. (2014). Earthworks risk assessment on a heritage railway, Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, Vol. 167 No. 4, pp. 344-356, https://doi.org/10.1680/geng.12.00099

Creswell, J.W. and Creswell, J.D. (2017). Research design: Qualitative, quantitative, and mixed methods approaches, Sage publications, ISBN:1506386717.

da Silva, F.P. (2014). Mental workload, task demand and driving performance: what relation?, Procedia-Social and Behavioral Sciences, Vol. 162 pp. 310-319, https://doi.org/10.1016/j.sbspro.2014.12.212.

Dai, F., Olorunfemi, A., Peng, W., Cao, D. and Luo, X. (2021). Can mixed reality enhance safety communication on construction sites? An industry perspective, Safety Science, Vol. 133 p. 105009, https://doi.org/10.1016/j.ssci.2020.105009.

De Crescenzio, F., Fantini, M., Persiani, F., Di Stefano, L., Azzari, P. and Salti, S. (2010). Augmented reality for aircraft maintenance training and operations support, IEEE Computer Graphics and Applications, Vol. 31 No. 1, pp. 96-101, https://doi.org/10.1109/MCG.2011.4

De Reu, J., De Smedt, P., Herremans, D., Van Meirvenne, M., Laloo, P. and De Clercq, W. (2014). On introducing an image-based 3D reconstruction method in archaeological excavation practice, Journal of Archaeological Science, Vol. 41 pp. 251-262, https://doi.org/10.1016/j.jas.2013.08.020.

DiBenedetto, S., Mochny, H. and Hanson, D. (2010). Pipeline case histories with 2D and 3D underground imaging, in Pipelines 2010: Climbing New Peaks to Infrastructure Reliability: Renew, Rehab, and Reinvest, pp. 1038-1047, https://doi.org/10.1061/41138(386)99

Doan, D.T., GhaffarianHoseini, A., Naismith, N., Ghaffarianhoseini, A., Zhang, T. and Tookey, J. (2020). Examining critical perspectives on building information modelling (BIM) adoption in New Zealand, Smart and Sustainable Built Environment, https://doi.org/10.1108/SASBE-04-2020-0043.

Donaldson, Lex. The contingency theory of organizations. Sage, 2001.

Doolani, S., Wessels, C., Kanal, V., Sevastopoulos, C., Jaiswal, A., Nambiappan, H. and Makedon, F. (2020). A review of extended reality (xr) technologies for manufacturing training, Technologies, Vol. 8 No. 4, p. 77, https://doi.org/10.3390/technologies8040077.

Dunn, O.J. (1961). Multiple comparisons among means, Journal of the American statistical association, Vol. 56 No. 293, pp. 52-64, https://doi.org/10.1080/01621459.1961.10482090.

Dunston, P.S. (2008). Identification of application areas for Augmented Reality in industrial construction based on technology suitability, Automation in Construction, Vol. 17 No. 7, pp. 882-894, https://doi.org/10.1016/j.autcon.2008.02.012.

Dunston, P.S. and Wang, X. (2005). Mixed reality-based visualization interfaces for architecture, engineering, and construction industry, Journal of Construction Engineering and Management, Vol. 131 No. 12, pp. 1301-1309, https://doi.org/10.1061/(ASCE)0733-9364(2005)131:12(130.

Eiris, R., Gheisari, M. and Esmaeili, B. (2018). PARS: Using augmented 360-degree panoramas of reality for construction safety training, International Journal of Environmental Research and Public Health, Vol. 15 No. 11, p. 2452, https://doi.org/10.3390/ijerph15112452.

El Jazzar, M., Urban, H., Schranz, C. and Nassereddine, H. Construction 4.0: A Roadmap to Shaping the Future of Construction, IAARC Publications, pp. 1314-1321, https://doi.org/10.22260/ISARC2020/0180

ElMenshawy, M. and Marzouk, M. (2021). Automated BIM schedule generation approach for solving time–cost trade-off problems, Engineering, Construction and Architectural Management, https://doi.org/10.1108/ECAM-08-2020-0652.

Eren, M.T. and Balcisoy, S. (2018). Evaluation of X-ray visualization techniques for vertical depth judgments in underground exploration, The Visual Computer, Vol. 34 No. 3, pp. 405-416, https://doi.org/10.1007/s00371-016-1346-5.

Farrag, K. and Guerrero Merino, M. An Assessment of Utilities Locating Practices and Excavation Damage, American Society of Mechanical Engineers, p. V003T004A018, https://doi.org/10.1115/ipc2022-81580

Fazel, A. and Izadi, A. (2018). An interactive augmented reality tool for constructing free-form modular surfaces, Automation in Construction, Vol. 85 pp. 135-145, https://doi.org/10.1016/j.autcon.2017.10.015.

Fellows, R.F. and Liu, A.M. (2021). Research methods for construction, John Wiley & Sons, 1119814758.

Fenais, A., Ariaratnam, S.T., Ayer, S.K. and Smilovsky, N. (2019). Integrating geographic information systems and augmented reality for mapping underground utilities, Infrastructures, Vol. 4 No. 4, p. 60, https://doi.org/10.3390/infrastructures4040060.

Fenais, A., Ariaratnam, S.T. and Smilovsky, N. (2020a). Assessing the Accuracy of an Outdoor Augmented Reality Solution for Mapping Underground Utilities, Journal of Pipeline Systems Engineering and Practice, Vol. 11 No. 3, p. 04020029, https://doi.org/10.1061/(ASCE)PS.1949-1204.0000474.

Fenais, A., Smilovsky, N. and Ariaratnam, S.T. (2018a). Using augmented reality in horizontal directional drilling to reduce the risk of utility damages, in Pipelines 2018: Utility Engineering, Surveying, and Multidisciplinary Topics, American Society of Civil Engineers Reston, VA, pp. 290-298, https://doi.org/10.1061/9780784481660.032.

Fenais, A., Smilovsky, N., Ariaratnam, S.T. and Ayer, S.K. A meta-analysis of augmented reality challenges in the underground utility construction industry, pp. 80-89,

Fenais, A.S., Ariaratnam, S.T., Ayer, S.K. and Smilovsky, N. (2020b). A review of augmented reality applied to underground construction, Journal of Information Technology in Construction, Vol. 25 pp. 308-324, https://doi.org/10.36680/J.ITCON.2020.018.

Feng, D., Wang, X. and Zhang, B. (2019). Improving reconstruction of tunnel lining defects from ground-penetrating radar profiles by multi-scale inversion and bi-parametric full-waveform inversion, Advanced Engineering Informatics, Vol. 41 p. 100931, https://doi.org/10.1016/j.aei.2019.100931.

Feng, Z., González, V.A., Amor, R., Lovreglio, R. and Cabrera-Guerrero, G. (2018). Immersive virtual reality serious games for evacuation training and research: A systematic literature review, Computers & Education, Vol. 127 pp. 252-266, https://doi.org/10.1016/j.compedu.2018.09.002.

Flavián, C., Ibáñez-Sánchez, S. and Orús, C. (2019). The impact of virtual, augmented and mixed reality technologies on the customer experience, Journal of Business Research, Vol. 100 pp. 547-560, https://doi.org/10.1016/j.jbusres.2018.10.050.

Foroughi Sabzevar, M., Gheisari, M. and Lo, L.J. (2021). Improving access to design information of paper-based floor plans using augmented reality, International Journal of Construction Education and Research, Vol. 17 No. 2, pp. 178-198, https://doi.org/10.1080/15578771.2020.1717682.

Funk, M., Kosch, T., Greenwald, S.W. and Schmidt, A. A benchmark for interactive augmented reality instructions for assembly tasks, pp. 253-257, https://doi.org/10.1145/2836041.2836067

Funk, M., Kosch, T. and Schmidt, A. Interactive worker assistance: comparing the effects of in-situ projection, head-mounted displays, tablet, and paper instructions, pp. 934-939, https://doi.org/10.1145/2971648.2971706

Gao, Y., Gonzalez, V.A. and Yiu, T.W. (2019). The effectiveness of traditional tools and computer-aided technologies for health and safety training in the construction sector: A systematic review, Computers & Education, Vol. 138 pp. 101-115, https://doi.org/10.1016/j.compedu.2019.05.003.

Gibson, J. (1977). The theory of affordances, Perceiving, acting and knowing: Towards an ecological psychology/Erlbaum.

Gill, J. and Johnson, P. (2010). Research methods for managers.

Gray, D.E. (2021). Doing research in the real world.

Grote, K., Hubbard, S., Harvey, J. and Rubin, Y. (2005). Evaluation of infiltration in layered pavements using surface GPR reflection techniques, Journal of Applied Geophysics, Vol. 57 No. 2, pp. 129-153, https://doi.org/10.1016/j.jappgeo.2004.10.002.

Guba, E.G. and Lincoln, Y.S. (1994). Competing paradigms in qualitative research, Handbook of qualitative research, Vol. 2 No. 163-194, p. 105.

Guo, H., Li, H., Chan, G. and Skitmore, M. (2012). Using game technologies to improve the safety of construction plant operations, Accident Analysis & Prevention, Vol. 48 pp. 204-213, https://doi.org/10.1016/j.aap.2011.06.002.

Guo, H., Yu, Y. and Skitmore, M. (2017a). Visualization technology-based construction safety management: A review, Automation in Construction, Vol. 73 pp. 135-144, https://doi.org/10.1016/j.autcon.2016.10.004.

Guo, H., Yu, Y., Xiang, T., Li, H. and Zhang, D. (2017b). The availability of wearable-device-based physical data for the measurement of construction workers' psychological status on site: From the perspective of safety management, Automation in Construction, Vol. 82 pp. 207-217, https://doi.org/10.1016/j.autcon.2017.06.001.

Hall, J., Hammerschmidt, J., Goglia, J., Black Jr, G. and Carmody, C. (1998). Natural gas pipeline rupture and subsequent explosion, Washington, DC: National Transportation Safety Board.

Hanafi, H.F., Wahab, M.H.A., Selamat, A.Z., Khairani, M.Z., Idrus, S.Z.S. and Adnan, M.H. Technology acceptance of a mobile augmented reality learning application among primary school students: A focus on the moderating effects of gender, AIP Publishing, https://doi.org/10.1063/5.0127739

Hao, T., Rogers, C., Metje, N., Chapman, D., Muggleton, J., Foo, K., Wang, P., Pennock, S.R., Atkins, P. and Swingler, S. (2012). Condition assessment of the buried utility service infrastructure, Tunnelling and Underground Space Technology, Vol. 28 pp. 331-344, https://doi.org/10.1016/j.tust.2011.10.011.

Harikrishnan, A., Abdallah, A.S., Ayer, S.K., El Asmar, M. and Tang, P. (2021). Feasibility of augmented reality technology for communication in the construction industry, Advanced Engineering Informatics, Vol. 50 p. 101363, https://doi.org/10.1016/j.aei.2021.101363.

Harris, D., Wilson, M. and Vine, S. (2020). Development and validation of a simulation workload measure: the simulation task load index (SIM-TLX), Virtual Reality, Vol. 24 No. 4, pp. 557-566, https://doi.org/10.1007/s10055-019-00422-9.

Harvey, J., Bolam, H., Gregory, D. and Erdos, G. (2001). The effectiveness of training to change safety culture and attitudes within a highly regulated environment, Personnel Review, https://doi.org/10.1108/EUM0000000005976.

Hasan, S.M., Lee, K., Moon, D., Kwon, S., Jinwoo, S. and Lee, S. (2021). Augmented reality and digital twin system for interaction with construction machinery, Journal of Asian Architecture and Building Engineering, pp. 1-12, https://doi.org/10.1080/13467581.2020.1869557.

Hasanzadeh, S. and De La Garza, J.M. (2020). Productivity-safety model: debunking the myth of the productivity-safety divide through a mixed-reality residential roofing task, Journal of Construction Engineering and Management, Vol. 146 No. 11, p. 04020124, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001916.

Hoover, M., Miller, J., Gilbert, S. and Winer, E. (2020). Measuring the performance impact of using the microsoft hololens 1 to provide guided assembly work instructions, Journal of Computing and Information Science in Engineering, Vol. 20 No. 6, p. 061001, https://doi.org/10.1115/1.4046006.

Hou, L., Chi, H.-L., Tarng, W., Chai, J., Panuwatwanich, K. and Wang, X. (2017). A framework of innovative learning for skill development in complex operational tasks, Automation in Construction, Vol. 83 pp. 29-40, https://doi.org/10.1016/j.autcon.2017.07.001.

Hou, L. and Wang, X. (2013). A study on the benefits of augmented reality in retaining working memory in assembly tasks: A focus on differences in gender, Automation in Construction, Vol. 32 pp. 38-45, https://doi.org/10.1016/j.autcon.2012.12.007.

Hou, L., Wang, Y., Wang, X., Maynard, N., Cameron, I.T., Zhang, S. and Jiao, Y. (2014). Combining photogrammetry and augmented reality towards an integrated facility management system for the oil industry, *Proceedings of the IEEE*, Vol. 102 No. 2, pp. 204-220, https://doi.org/10.1109/JPROC.2013.2295327.

Hsu, H. and Hsieh, S. Applying Augmented Reality Technique to Support On-site Rebar Inspection, IAARC Publications, pp. 1312-1318, https://doi.org/10.22260/ISARC2019/0176

Jian, M.-S., Wang, Y.-C., Wu, B.-H. and Cheng, Y.-E. Hybrid cloud computing for user location-aware augmented reality construction, IEEE, Chuncheon, Korea (South), pp. 190-194, https://doi.org/10.23919/ICACT.2018.8323692

Kamat, V.R. and El-Tawil, S. Rapid post-disaster evaluation of building damage using augmented situational visualization, pp. 1-10, https://doi.org/10.1061/40754(183)122

Kanangkaew, S., Jokkaw, N. and Tongthong, T. (2023). A real-time fire evacuation system based on the integration of building information modeling and augmented reality, *Journal of Building Engineering*, Vol. 67 p. 105883, https://doi.org/10.1016/j.jobe.2023.105883.

Kaufeld, M., Mundt, M., Forst, S. and Hecht, H. (2022). Optical see-through augmented reality can induce severe motion sickness, *Displays*, Vol. 74 p. 102283, https://doi.org/10.1016/j.displa.2022.102283.

Ketokivi, M. and Mantere, S. (2010). Two strategies for inductive reasoning in organizational research, *Academy of management review*, Vol. 35 No. 2, pp. 315-333.

Khairadeen Ali, A., Lee, O.J., Lee, D. and Park, C. (2021). Remote Indoor Construction Progress Monitoring Using Extended Reality, *Sustainability*, Vol. 13 No. 4, p. 2290, https://doi.org/10.3390/su13042290.

Khorrami Shad, H., Feng, Z., Paes, D., Yiu, T.W. and Lovreglio, R. (2025). Augmented Reality Applications for the Excavation Industry: Locating and Protecting Underground Utilities, *Journal of Pipeline Systems Engineering and Practice*, Vol. 16 No. 1, p. 04024072, https://doi.org/10.1061/JPSEA2.PSENG-1652.

Khorrami Shad, H., Tak Wing Yiu, K., Lovreglio, R. and Feng, Z. (2022). State-of-the-art analysis of the integration of augmented reality with construction technologies to improve construction safety, *Smart and Sustainable Built Environment*, https://doi.org/10.1108/SASBE-07-2022-0151.

Kim, B., Kim, C. and Kim, H. (2012). Interactive modeler for construction equipment operation using augmented reality, *Journal of Computing in Civil Engineering*, Vol. 26 No. 3, pp. 331-341, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000137.

Kim, K., Billinghurst, M., Bruder, G., Duh, H.B.-L. and Welch, G.F. (2018). Revisiting trends in augmented reality research: A review of the 2nd decade of ISMAR (2008–2017), *IEEE transactions on visualization and computer graphics*, Vol. 24 No. 11, pp. 2947-2962, https://doi.org/10.1109/TVCG.2018.2868591.

Kim, K., Kim, H. and Kim, H. (2017). Image-based construction hazard avoidance system using augmented reality in wearable device, Automation in Construction, Vol. 83 pp. 390-403, https://doi.org/10.1016/j.autcon.2017.06.014.

Kim, M.-K., Cheng, J.C., Sohn, H. and Chang, C.-C. (2015). A framework for dimensional and surface quality assessment of precast concrete elements using BIM and 3D laser scanning, Automation in Construction, Vol. 49 pp. 225-238, https://doi.org/10.1016/j.autcon.2014.07.010.

Kim, M.-K., Sohn, H. and Chang, C.-C. (2014). Automated dimensional quality assessment of precast concrete panels using terrestrial laser scanning, Automation in Construction, Vol. 45 pp. 163-177, https://doi.org/10.1016/j.autcon.2014.05.015.

Kim, M.-K., Wang, Q., Park, J.-W., Cheng, J.C., Sohn, H. and Chang, C.-C. (2016). Automated dimensional quality assurance of full-scale precast concrete elements using laser scanning and BIM, Automation in Construction, Vol. 72 pp. 102-114, https://doi.org/10.1016/j.autcon.2016.08.035.

Kivrak, S. and Arslan, G. (2019). Using augmented reality to facilitate construction site activities, in Advances in informatics and computing in civil and construction engineering, Springer, pp. 215-221, https://doi.org/10.1007/978-3-030-00220-6_26.

Klinc, R. and Turk, Ž. (2019). Construction 4.0–digital transformation of one of the oldest industries, Economic and Business Review, Vol. 21 No. 3, pp. 393-410, https://doi.org/10.15458/ebr.92.

Knight, A. and Ruddock, L. (2009). Advanced research methods in the built environment, John Wiley & Sons, 144430951X.

Koch, C., Neges, M., König, M. and Abramovici, M. (2014). Natural markers for augmented reality-based indoor navigation and facility maintenance, Automation in Construction, Vol. 48 pp. 18-30, https://doi.org/10.1016/j.autcon.2014.08.009.

Kolaei, A.Z., Hedayati, E., Khanzadi, M. and Amiri, G.G. (2022). Challenges and opportunities of augmented reality during the construction phase, Automation in Construction, Vol. 143 p. 104586, https://doi.org/10.1016/j.autcon.2022.104586.

Koo, D.-H. and Ariaratnam, S.T. (2006). Innovative method for assessment of underground sewer pipe condition, Automation in Construction, Vol. 15 No. 4, pp. 479-488, https://doi.org/10.1016/j.autcon.2005.06.007.

Koumpouros, Y. (2024). Revealing the true potential and prospects of augmented reality in education, Smart Learning Environments, Vol. 11 No. 1, p. 2, https://doi.org/10.1186/s40561-023-00288-0.

Kumar, R. (2018). Research methodology: A step-by-step guide for beginners.

Kusumo, C. and Poh, M.E.M. (2022). VR/AR Technology Adoption in Architecture Education: Student Acceptance at Taylor's University, in Handbook of Research on Issues, Challenges, and Opportunities in Sustainable Architecture, IGI Global, pp. 283-297, https://doi.org/10.4018/978-1-6684-5119-9.ch013.

Kwiatek, C., Sharif, M., Li, S., Haas, C. and Walbridge, S. (2019). Impact of augmented reality and spatial cognition on assembly in construction, Automation in Construction, Vol. 108 p. 102935, https://doi.org/10.1016/j.autcon.2019.102935.

Kyaw, A.H., Xu, A.H., Jahn, G., van den Berg, N., Newnham, C. and Zivkovic, S. (2023). Augmented Reality for high precision fabrication of Glued Laminated Timber beams, Automation in Construction, Vol. 152 p. 104912, https://doi.org/10.1016/j.autcon.2023.104912.

Lam, M.C., Sadik, M.J. and Elias, N.F. (2021). The effect of paper-based manual and stereoscopic-based mobile augmented reality systems on knowledge retention, Virtual Reality, Vol. 25 pp. 217-232, https://doi.org/10.1007/s10055-020-00451-9

Lazar, J., Feng, J.H. and Hochheiser, H. (2017). Research methods in human-computer interaction, Morgan Kaufmann, ISBN:0128093439.

Le, Q.T., Pham, H.C., Pedro, A., Park, C.S. and Korea, S. (2015). Application of wearable devices for real time construction safety management, IPC Proceedings, South Korea, pp. 28-31, available at: https://www.researchgate.net/publication/291973303.

Lee, A., Chigira, H., Tang, S.K., Acquah, K. and Ishii, H. AnnoScape: remote collaborative review using live video overlay in shared 3D virtual workspace, pp. 26-29, https://doi.org/10.1145/2659766.2659776

Lee, S. and Akin, Ö. (2011). Augmented reality-based computational fieldwork support for equipment operations and maintenance, Automation in Construction, Vol. 20 No. 4, pp. 338-352, https://doi.org/10.1016/j.autcon.2010.11.004.

Leucci, G., Negri, S., Carrozzo, M.T. and Nuzzo, L. (2002). Use of ground penetrating radar to map subsurface moisture variations in an urban area, Journal of Environmental & Engineering Geophysics, Vol. 7 No. 2, pp. 69-77, https://doi.org/10.4133/JEEG7.2.69.

Li, D. (2020), "1 dead and 7 injured after massive gas explosion destroys houses in Baltimore", available at https://www.nbcnews.com/news/us-news/massive-explosion-rocks-baltimore-neighborhood-n1236278 (accessed).

Li, M., Feng, X. and Han, Y. (2022). Brillouin fiber optic sensors and mobile augmented reality-based digital twins for quantitative safety assessment of underground pipelines, Automation in Construction, Vol. 144 p. 104617, https://doi.org/10.1016/j.autcon.2022.104617.

Li, S., Cai, H. and Kamat, V.R. (2016). Integrating natural language processing and spatial reasoning for utility compliance checking, Journal of Construction Engineering and Management, Vol. 142 No. 12, p. 04016074, https://doi.org/10.1061/(asce)co.1943-7862.0001199

Li, X., Yi, W., Chi, H.-L., Wang, X. and Chan, A.P. (2018). A critical review of virtual and augmented reality (VR/AR) applications in construction safety, Automation in Construction, Vol. 86 pp. 150-162, https://doi.org/10.1016/j.autcon.2017.11.003.

Lin, Z., Petzold, F. and Hsieh, S.-H. 4D-BIM Based Real Time Augmented Reality Navigation System for Tower Crane Operation, American Society of Civil Engineers Reston, VA, pp. 828-836, https://doi.org/10.1061/9780784482865.088

Littell, R.C., Pendergast, J. and Natarajan, R. (2000). Modelling covariance structure in the analysis of repeated measures data, Statistics in Medicine, Vol. 19 No. 13, pp. 1793-1819, https://doi.org/10.1002/0470023724.ch1c(ii).

Liu, D., Ham, Y., Kim, J. and Park, H., 2022, May. Towards a collaborative future in construction robotics: A human-centered study in a multi-user immersive operation and communication system for excavation. In The 2022 International Conference on Robotics and Automation (ICRA).

Liu, F. and Seipel, S. (2018). Precision study on augmented reality-based visual guidance for facility management tasks, Automation in Construction, Vol. 90 pp. 79-90, https://doi.org/10.1016/j.autcon.2018.02.020.

Lovreglio, R. and Kinateder, M. (2020). Augmented reality for pedestrian evacuation research: promises and limitations, Safety Science, Vol. 128 p. 104750, https://doi.org/10.1016/j.ssci.2020.104750.

Lovreglio, R., Paes, D., Feng, Z. and Zhao, X. (2024). Digital Technologies for Fire Evacuations, in Intelligent Building Fire Safety and Smart Firefighting, Springer, pp. 439-454, https://doi.org/10.1007/978-3-031-48161-1_18.

Makhataeva, Z. and Varol, H.A. (2020). Augmented reality for robotics: A review, Robotics, Vol. 9 No. 2, p. 21, https://doi.org/10.3390/robotics9020021.

Makkonen, H., Johnston, W.J. and Javalgi, R.R.G. (2016). A behavioral approach to organizational innovation adoption, Journal of Business Research, Vol. 69 No. 7, pp. 2480-2489, https://doi.org/10.1016/j.jbusres.2016.02.017.

Makransky, G. and Petersen, G.B. (2019). Investigating the process of learning with desktop virtual reality: A structural equation modeling approach, Computers & Education, Vol. 134 pp. 15-30, https://doi.org/10.1016/j.compedu.2019.02.002.

Maksoud, S.A.a. (2022). An Industry Practice Guide for Underground Cable Fault-Finding in the Low Voltage Distribution Network, https://doi.org/10.1109/ACCESS.2022.3186352.

Malek, K. and Moreu, F. (2022). Realtime conversion of cracks from pixel to engineering scale using Augmented Reality, Automation in Construction, Vol. 143 p. 104542, https://doi.org/10.1016/j.autcon.2022.104542.

Maree, S., Rotimi, F.E. and Rotimi, J.O.B. (2021). The primacy of as-built drawings in the management of underground utility operations: A New Zealand study, Buildings, Vol. 11 No. 9, p. 399, https://doi.org/10.3390/buildings11090399.

McCullagh, P. (2019). Generalized linear models, Routledge, https://doi.org/10.1201/9780203753736, 0203753739.

Microsoft (2022), "Mixed Reality Feature Tool for Unity", available at https://learn.microsoft.com/en-us/windows/mixed-reality/develop/unity/welcome-to-mr-feature-tool (accessed).

Milgram, P. and Kishino, F. (1994). A taxonomy of mixed reality visual displays, IEICE TRANSACTIONS on Information and Systems, Vol. 77 No. 12, pp. 1321-1329, available at: https://www.researchgate.net/publication/231514051.

Mizuno, Y., Kato, H. and Nishida, S. Outdoor augmented reality for direct display of hazard information, IEEE, pp. 831-836, available at: https://ieeexplore-ieee-org.ezproxy.massey.ac.nz/abstract/document/1491519.

Moghaddam, M., Wilson, N.C., Modestino, A.S., Jona, K. and Marsella, S.C. (2021). Exploring augmented reality for worker assistance versus training, Advanced Engineering Informatics, Vol. 50 p. 101410, https://doi.org/10.1016/j.aei.2021.101410.

Moher, D., Liberati, A., Tetzlaff, J. and Altman, D.G. (2010). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement, Int J Surg, Vol. 8 No. 5, pp. 336-341, https://doi.org/10.1371/journal.pmed.1000097.

Moore, H.F. and Gheisari, M. (2019). A review of virtual and mixed reality applications in construction safety literature, Safety, Vol. 5 No. 3, p. 51, https://doi.org/10.3390/safety5030051.

Murphy, J.P. and Murphy, A.R. (1990). Pragmatism: From peirce to davidson.

Muthalif, M., Shojaei, D. and Khoshelham, K. (2022a). Resolving perceptual challenges of visualizing underground utilities in mixed reality, The international archives of the photogrammetry, remote sensing and spatial information sciences, Vol. 48 pp. 101-108, https://doi.org/10.5194/isprs-archives-XLVIII-4-W4-2022-101-2022.

Muthalif, M.Z.A., Shojaei, D. and Khoshelham, K. (2022b). A review of augmented reality visualization methods for subsurface utilities, Advanced Engineering Informatics, Vol. 51 p. 101498, https://doi.org/10.1016/j.aei.2021.101498.

Nakagawa, S. and Schielzeth, H. (2013). A general and simple method for obtaining R2 from generalized linear mixed-effects models, Methods in ecology and evolution, Vol. 4 No. 2, pp. 133-142, https://doi.org/10.1111/j.2041-210x.2012.00261.x.

Neville A. Stanton, P.M.S., Laura A. Rafferty, Guy H. Walker, Chris Baber, Daniel P. Jenkins (2013). Human Factors Methods: A Practical Guide for Engineering and Design, Ashgate London, https://doi.org/10.1201/9781315587394, 9781409457541.

Newman, C., Edwards, D., Martek, I., Lai, J., Thwala, W.D. and Rillie, I. (2020). Industry 4.0 deployment in the construction industry: a bibliometric literature review and UK-based case study, Smart and Sustainable Built Environment, https://doi.org/10.1108/SASBE-02-2020-0016.

Nguyen, N.Q., Cardinell, J., Ramjist, J.M., Lai, P., Dobashi, Y., Guha, D., Androutsos, D. and Yang, V.X. (2020). An augmented reality system characterization of placement accuracy in neurosurgery, Journal of Clinical Neuroscience, Vol. 72 pp. 392-396, https://doi.org/10.1016/j.jocn.2019.12.014.

Ogunseiju, O.R., Olayiwola, J., Akanmu, A.A. and Nnaji, C. (2021). Digital twin-driven framework for improving self-management of ergonomic risks, Smart and Sustainable Built Environment, https://doi.org/10.1108/SASBE-03-2021-0035.

Olander, J., Ronchi, E., Lovreglio, R. and Nilsson, D. (2017). Dissuasive exit signage for building fire evacuation, Applied Ergonomics, Vol. 59 pp. 84-93, https://doi.org/10.1016/j.apergo.2016.08.029.

Olorunfemi, A., Dai, F., Tang, L. and Yoon, Y. Three-dimensional visual and collaborative environment for jobsite risk communication, pp. 345-355, https://doi.org/10.1061/9780784481288.034

Ortega, S., Wendel, J., Santana, J.M., Murshed, S.M., Boates, I., Trujillo, A., Nichersu, A. and Suárez, J.P. (2019). Making the invisible visible—strategies for visualizing underground infrastructures in immersive environments, ISPRS International Journal of Geo-Information, Vol. 8 No. 3, p. 152, https://doi.org/10.3390/ijgi8030152.

Paes, D., Feng, Z., King, M., Shad, H.K., Sasikumar, P., Pujoni, D. and Lovreglio, R. (2024). Optical see-through augmented reality fire safety training for building occupants, Automation in Construction, Vol. 162 p. 105371, https://doi.org/10.1016/j.autcon.2024.105371.

Paes, D., Feng, Z., Mander, S., Datoussaid, S., Descamps, T., Rahouti, A. and Lovreglio, R. (2025). Video see-through augmented reality fire safety training: A comparison with virtual reality and video training, Safety Science, Vol. 184 p. 106714, https://doi.org/10.1016/j.ssci.2024.106714.

Paes, D., Irizarry, J. and Pujoni, D. (2021). An evidence of cognitive benefits from immersive design review: Comparing three-dimensional perception and presence between immersive and non-immersive virtual environments, Automation in Construction, Vol. 130 p. 103849, https://doi.org/10.1016/j.autcon.2021.103849.

Pala, P., Cavallo, V., Dang, N.T., Granie, M.-A., Schneider, S., Maruhn, P. and Bengler, K. (2021). Is the street-crossing behavior with a head-mounted display different from that behavior in a CAVE? A study among young adults and children, Transportation research part F: traffic psychology and behaviour, Vol. 82 pp. 15-31, https://doi.org/10.1016/j.trf.2021.07.016.

Panya, D.S., Kim, T. and Choo, S. (2023). An interactive design change methodology using a BIM-based Virtual Reality and Augmented Reality, Journal of Building Engineering, Vol. 68 p. 106030, https://doi.org/10.1016/j.jobe.2023.106030.

Park, C.-S. and Kim, H.-J. (2013). A framework for construction safety management and visualization system, Automation in Construction, Vol. 33 pp. 95-103, https://doi.org/10.1016/j.autcon.2012.09.012.

Pereira, M., Burns, D., Orfeo, D., Zhang, Y., Jiao, L., Huston, D. and Xia, T. (2020). 3-D multistatic ground penetrating radar imaging for augmented reality visualization, IEEE Transactions on Geoscience and Remote Sensing, Vol. 58 No. 8, pp. 5666-5675, https://doi.org/10.1109/TGRS.2020.2968208.

Pereira, R.E., Gheisari, M. and Esmaeili, B. Using panoramic augmented reality to develop a virtual safety training environment, pp. 29-39, https://doi.org/10.1061/9780784481288.004

Pereira, R.E., Moore, H., Gheisari, M. and Esmaeili, B. (2019). Development and usability testing of a panoramic augmented reality environment for fall hazard safety training, in Advances in informatics and computing in civil and construction engineering, Springer, pp. 271-279, https://doi.org/10.1007/978-3-030-00220-6_33.

Pierdicca, R., Tonetto, F., Paolanti, M., Mameli, M., Rosati, R. and Zingaretti, P. (2024). DeepReality: An open source framework to develop AI-based augmented reality applications, Expert Systems with Applications, Vol. 249 p. 123530, https://doi.org/10.1016/j.eswa.2024.123530.

Piroozfar, P., Judd, A., Boseley, S., Essa, A. and Farr, E.R. Augmented reality for urban utility infrastructure: a UK perspective, Springer, pp. 535-541, https://doi.org/10.1007/978-3-030-48465-1_88

Pozharliev, R., De Angelis, M. and Rossi, D. (2022). The effect of augmented reality versus traditional advertising: a comparison between neurophysiological and self-reported measures, Marketing Letters, Vol. 33 No. 1, pp. 113-128, https://doi.org/10.1007/s11002-021-09573-9

Primer, A.P. (1992). Quantitative methods in psychology, Psychological bulletin, Vol. 112 No. 1,155-159, https://doi.org/10.1037/0033-2909.112.1.155.

Qin, H., Xie, X., Vrugt, J.A., Zeng, K. and Hong, G. (2016). Underground structure defect detection and reconstruction using crosshole GPR and Bayesian waveform inversion, Automation in Construction, Vol. 68 pp. 156-169, https://doi.org/10.1016/j.autcon.2016.03.011.

Qin, Y., Bloomquist, E., Bulbul, T., Gabbard, J. and Tanous, K. (2021). Impact of information display on worker performance for wood frame wall assembly using AR HMD under different task conditions, Advanced Engineering Informatics, Vol. 50 p. 101423, https://doi.org/10.1016/j.aei.2021.101423.

Quezada-Gaibor, D., Torres-Sospedra, J., Nurmi, J., Koucheryavy, Y. and Huerta, J. (2021). Cloud platforms for context-adaptive positioning and localisation in GNSS-denied scenarios—A systematic review, Sensors, Vol. 22 No. 1, p. 110, https://doi.org/10.3390/s22010110.

Radhakrishnan, U., Koumaditis, K. and Chinello, F. (2021). A systematic review of immersive virtual reality for industrial skills training, Behaviour & information technology, Vol. 40 No. 12, pp. 1310-1339, https://doi.org/10.1080/0144929X.2021.1954693.

Rapti, S., Sapounidis, T. and Tselegkaridis, S. (2023). Enriching a traditional learning activity in preschool through augmented reality: Children's and teachers' views, Information, Vol. 14 No. 10, p. 530, https://doi.org/10.3390/info14100530.

Rebol, M., Pietroszek, K., Sikka, N., Ranniger, C., Hood, C., Rutenberg, A., Sasankan, P. and Gütl, C. Evaluating Augmented Reality Communication: How Can We Teach Procedural Skill in AR?, pp. 1-11, https://doi.org/10.1145/3611659.3615685

Rijal, R. (2021). Comparative Study between Hydro and Air Excavation Technologies, https://doi.org/10.7939/r3-sjt8-xs83.

Rolland, J.P. and Fuchs, H. (2000). Optical versus video see-through head-mounted displays in medical visualization, Presence, Vol. 9 No. 3, pp. 287-309, https://doi.org/10.1162/105474600566808.

Ronchi, E. and Nilsson, D. (2013). Traffic information signs, colour scheme of emergency exit portals and acoustic systems for road tunnel emergency evacuations.

Ronchi, E., Nilsson, D., Kojić, S., Eriksson, J., Lovreglio, R., Modig, H. and Walter, A.L. (2016). A virtual reality experiment on flashing lights at emergency exit portals for road tunnel evacuation, Fire Technology, Vol. 52 pp. 623-647, https://doi.org/10.1007/s10694-015-0462-5.

Sabeti, S., Shoghli, O., Baharani, M. and Tabkhi, H. (2021). Toward AI-enabled augmented reality to enhance the safety of highway work zones: Feasibility, requirements, and challenges, Advanced Engineering Informatics, Vol. 50 p. 101429, https://doi.org/10.1016/j.aei.2021.101429.

Sagnard, F., Norgeot, C., Derobert, X., Baltazart, V., Merliot, E., Derkx, F. and Lebental, B. (2016). Utility detection and positioning on the urban site Sense-City using Ground-Penetrating Radar systems, Measurement, Vol. 88 pp. 318-330, https://doi.org/10.1016/j.measurement.2016.03.044.

Saha, S., Mukhopadhyay, S., Mahapatra, U., Bhattacharya, S. and Srivastava, G. (2010). Empirical structure for characterizing metal loss defects from radial magnetic flux leakage signal, Ndt & E International, Vol. 43 No. 6, pp. 507-512, https://doi.org/10.1016/j.ndteint.2010.05.006.

Sangiorgio, V., Martiradonna, S., Fatiguso, F. and Lombillo, I. (2021). Augmented reality based-decision making (AR-DM) to support multi-criteria analysis in constructions, Automation in Construction, Vol. 124 p. 103567, https://doi.org/10.1016/j.autcon.2021.103567.

Saunders, M. (2014). Research Methods for Business Students (6th edn.

Saunders, M. and Tosey, P. (2012). Research Design, Academia.

Schall, G., Mendez, E., Kruijff, E., Veas, E., Junghanns, S., Reitinger, B. and Schmalstieg, D. (2009). Handheld augmented reality for underground infrastructure visualization, Personal and ubiquitous computing, Vol. 13 pp. 281-291, https://doi.org/10.1007/s00779-008-0204-5.

Schall, G., Zollmann, S. and Reitmayr, G. (2013). Smart Vidente: advances in mobile augmented reality for interactive visualization of underground infrastructure, Personal and ubiquitous computing, Vol. 17 pp. 1533-1549, https://doi.org/10.1007/s00779-012-0599-x.

Schmalstieg, D. and Hollerer, T. (2016). Augmented reality: principles and practice, Addison-Wesley Professional, ISBN:0133153207.

Schoch, K. (2020). Case study research, Research design and methods: An applied guide for the scholar-practitioner, Vol. 31 No. 1, pp. 245-258.

Settimi, A., Gamerro, J. and Weinand, Y. (2022). Augmented-reality-assisted timber drilling with smart retrofitted tools, Automation in Construction, Vol. 139 p. 104272, https://doi.org/10.1016/j.autcon.2022.104272.

Shanbari, H., Blinn, N. and Issa, R.R. (2016). Using augmented reality video in enhancing masonry and roof component comprehension for construction management students, Engineering, Construction and Architectural Management, https://doi.org/10.1108/ECAM-01-2016-0028.

Sherratt, F., Crapper, M., Foster-Smith, L. and Walsh, S. (2015). Safety and volunteer construction workers, Construction Management and Economics, Vol. 33 No. 5-6, pp. 361-374, https://doi.org/10.1080/01446193.2015.1024269.

Sidani, A., Dinis, F.M., Duarte, J., Sanhudo, L., Calvetti, D., Baptista, J.S., Martins, J.P. and Soeiro, A. (2021). Recent tools and techniques of BIM-Based Augmented Reality: A systematic review, *Journal of Building Engineering,* Vol. 42 p. 102500, https://doi.org/10.1016/j.jobe.2021.102500.

Singh, G., Ellis, S.R. and Swan, J.E. (2018). The effect of focal distance, age, and brightness on near-field augmented reality depth matching, *IEEE transactions on visualization and computer graphics,* Vol. 26 No. 2, pp. 1385-1398, https://10.1109/TVCG.2018.2869729.

Skulmowski, A. (2023). Guidelines for choosing cognitive load measures in perceptually rich environments, *Mind, Brain, and Education,* Vol. 17 No. 1, pp. 20-28, https://doi.org/10.1111/mbe.12342.

Skulmowski, A. and Xu, K.M. (2022). Understanding cognitive load in digital and online learning: A new perspective on extraneous cognitive load, *Educational psychology review,* Vol. 34 No. 1, pp. 171-196, https://doi.org/10.1007/s10648-021-09624-7.

Solla, M., Pérez-Gracia, V. and Fontul, S. (2021). A review of GPR application on transport infrastructures: Troubleshooting and best practices, *Remote Sensing,* Vol. 13 No. 4, p. 672, https://doi.org/10.3390/rs13040672.

Spink, T. (2020). Strategic geotechnical asset management, *Quarterly Journal of Engineering Geology and Hydrogeology,* Vol. 53 No. 2, pp. 304-320, https://doi.org/10.1144/qjegh2019-014.

Stoltz, M.-H., Giannikas, V., McFarlane, D., Strachan, J., Um, J. and Srinivasan, R. (2017). Augmented reality in warehouse operations: opportunities and barriers, *IFAC-PapersOnLine,* Vol. 50 No. 1, pp. 12979-12984, https://doi.org/10.1016/j.ifacol.2017.08.1807.

Stylianidis, E., Valari, E., Pagani, A., Carrillo, I., Kounoudes, A., Michail, K. and Smagas, K. (2020). Augmented reality geovisualisation for underground utilities, *ournal of Photogrammetry, Remote Sensing and Geoinformation Science,* https://doi.org/10.1007/s41064-020-00108-x.

Su, X., Talmaki, S., Cai, H. and Kamat, V.R. (2013). Uncertainty-aware visualization and proximity monitoring in urban excavation: a geospatial augmented reality approach, *Visualization in engineering,* Vol. 1 No. 1, pp. 1-13, https://doi.org/10.1186/2213-7459-1-2.

Su, Y., Wang, J., Li, D., Wang, X., Hu, L., Yao, Y. and Kang, Y. (2023a). End-to-end deep learning model for underground utilities localization using GPR, *Automation in Construction,* Vol. 149 p. 104776, https://doi.org/10.1016/j.autcon.2023.104776.

Su, Y., Wang, J., Wang, X., Yao, Y. and Shou, W. (2023b). 3D reconstruction in underground utilities, *Automation in Construction,* Vol. 156 p. 105100, https://doi.org/10.1016/j.autcon.2023.105100.

Sun, X., Lee, W.K., Hou, Y. and Pong, P.W. (2014). Underground power cable detection and inspection technology based on magnetic field sensing at ground surface level, *IEEE transactions on magnetics,* Vol. 50 No. 7, pp. 1-5, https://doi.org/10.1109/TMAG.2013.2297195.

Sutrisna, M. Research methodology in doctoral research: understanding the meaning of conducting qualitative research, pp. 48-57, Talmaki, S. and Kamat, V.R. (2014). Real-time hybrid virtuality for prevention of excavation related utility strikes, Journal of Computing in Civil Engineering, Vol. 28 No. 3, p. 04014001, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000269.

Tan, Y.-C., Chandukala, S.R. and Reddy, S.K. (2022). Augmented reality in retail and its impact on sales, Journal of Marketing, Vol. 86 No. 1, pp. 48-66, https://doi-org.ezproxy.massey.ac.nz/10.1177/0022242921995449.

Tarek, H. and Marzouk, M. (2022). Integrated augmented reality and cloud computing approach for infrastructure utilities maintenance, Journal of Pipeline Systems Engineering and Practice, Vol. 13 No. 1, p. 04021064, https://doi.org/10.1061/(ASCE)PS.1949-1204.0000616.

Tashakkori, A. (2010). SAGE handbook of mixed methods in social & behavioral research, Sage,

Tavares, P., Costa, C.M., Rocha, L., Malaca, P., Costa, P., Moreira, A.P., Sousa, A. and Veiga, G. (2019). Collaborative welding system using BIM for robotic reprogramming and spatial augmented reality, Automation in Construction, Vol. 106 p. 102825, https://doi.org/10.1016/j.autcon.2019.04.020.

Ternier, S., Klemke, R., Kalz, M., Van Ulzen, P. and Specht, M. (2012). ARLearn: Augmented Reality Meets Augmented Virtuality, Journal of Universal Computer Science, Vol. 18 No. 15, pp. 2143-2164, https://doi.org/10.3217/jucs-018-15-2143.

Um, J., min Park, J., yeon Park, S. and Yilmaz, G. (2023). Low-cost mobile augmented reality service for building information modeling, Automation in Construction, Vol. 146 p. 104662, https://doi.org/10.1016/j.autcon.2022.104662.

Uslu, B., Jung, Y.J. and Sinha, S.K. (2016). Underground utility locating technologies for condition assessment and renewal engineering of water pipeline infrastructure systems, Journal of Pipeline Systems Engineering and Practice, Vol. 7 No. 4, p. 04016011, https://doi.org/10.1061/(ASCE)PS.1949-1204.0000221.

Uzairuddin, S. (2021). Risk Assessment in Deep Excavations and their Effect on Surrounding Structures: A review, https://doi.org/10.31224/osf.io/zv9xy

Wang, M., Hu, D., Chen, J. and Li, S. (2023). Underground infrastructure detection and localization using deep learning enabled radargram inversion and vision based mapping, Automation in Construction, Vol. 154 p. 105004, https://doi.org/10.1016/j.autcon.2023.105004.

Wang, Q., Kim, M.-K., Cheng, J.C. and Sohn, H. (2016). Automated quality assessment of precast concrete elements with geometry irregularities using terrestrial laser scanning, Automation in Construction, Vol. 68 pp. 170-182, https://doi.org/10.1016/j.autcon.2016.03.014.

Wang, X. and Dunston, P.S. (2007). Design, strategies, and issues towards an augmented reality-based construction training platform, Journal of information technology in construction (ITcon), Vol. 12 No. 25, pp. 363-380, available at: https://www.itcon.org/2007/25.

Wang, X., Truijens, M., Hou, L., Wang, Y. and Zhou, Y. (2014). Integrating Augmented Reality with Building Information Modeling: Onsite construction process controlling for liquefied natural gas industry, Automation in Construction, Vol. 40 pp. 96-105, https://doi.org/10.1016/j.autcon.2013.12.003.

Wen, J., Gheisari, M., Jain, S., Zhang, Y. and Minchin, R.E. (2021). Using cloud-based augmented reality to 3D-enable the 2D drawings of AISC steel sculpture: a plan-reading educational experiment, Journal of Civil Engineering Education, Vol. 147 No. 3, p. 04021006, https://doi.org/10.1061/(ASCE)EI.2643-9115.0000046.

West, B.T., Welch, K.B. and Galecki, A.T. (2022). Linear mixed models: a practical guide using statistical software, Chapman and Hall/CRC, https://doi.org/10.1201/9781003181064, 1003181066.

Wolf, M., Teizer, J., Wolf, B., Bükrü, S. and Solberg, A. (2022). Investigating hazard recognition in augmented virtuality for personalized feedback in construction safety education and training, Advanced Engineering Informatics, Vol. 51 p. 101469, https://doi.org/10.1016/j.aei.2021.101469.

Wu, J., Bai, Y., Fang, W., Zhou, R., Reniers, G. and Khakzad, N. (2021). An Integrated Quantitative Risk Assessment Method for Urban Underground Utility Tunnels, Reliability Engineering & System Safety, Vol. 213 p. 107792, https://doi.org/10.1016/j.ress.2021.107792.

Wu, S., Hou, L., Chen, H., Zhang, G.K., Zou, Y. and Tushar, Q. (2023). Cognitive ergonomics-based Augmented Reality application for construction performance, Automation in Construction, Vol. 149 p. 104802, https://doi.org/10.1016/j.autcon.2023.104802.

Wu, S., Hou, L., Zhang, G.K. and Chen, H. (2022). Real-time mixed reality-based visual warning for construction workforce safety, Automation in Construction, Vol. 139 p. 104252, https://doi.org/10.1016/j.autcon.2022.104252.

Xiang, S., Wang, R. and Feng, C. Towards Mobile Projective AR for Construction Co-Robots, IAARC Publications, pp. 1106-1113, https://doi.org/10.22260/ISARC2019/0147

Xiang, S., Wang, R. and Feng, C. (2021). Mobile projective augmented reality for collaborative robots in construction, Automation in Construction, Vol. 127 p. 103704, https://doi.org/10.1016/j.autcon.2021.103704.

Xu, Z., Feng, Z., Jelodar, M.B. and Guo, B.H. (2024). Augmented reality applications in construction productivity: A systematic literature review, Advanced Engineering Informatics, Vol. 62 p. 102798, https://doi.org/10.1016/j.aei.2024.102798.

Yang, D., de Vries, B. and van der Schaft, L. (2021). The construction workers' preference and acceptance of innovations in data provision: A stated choice experiment study in the Netherlands, Journal of Building Engineering, Vol. 35 p. 101970, https://doi.org/10.1016/j.jobe.2020.101970.

Yeh, K.-C., Tsai, M.-H. and Kang, S.-C. (2012). On-site building information retrieval by using projection-based augmented reality, Journal of Computing in Civil Engineering, Vol. 26 No. 3, pp. 342-355, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000156.

Yin, R.K. (2012). Case study methods.

Yip, J., Wong, S.-H., Yick, K.-L., Chan, K. and Wong, K.-H. (2019). Improving quality of teaching and learning in classes by using augmented reality video, Computers & Education, Vol. 128 pp. 88-101, https://doi.org/10.1016/j.compedu.2018.09.014.

Yoon, S., Wang, Q. and Sohn, H. (2018). Optimal placement of precast bridge deck slabs with respect to precast girders using 3D laser scanning, Automation in Construction, Vol. 86 pp. 81-98, https://doi.org/10.1016/j.autcon.2017.11.004.

Zhang, J., Xia, X., Liu, R. and Li, N. (2021). Enhancing human indoor cognitive map development and wayfinding performance with immersive augmented reality-based navigation systems, Advanced Engineering Informatics, Vol. 50 p. 101432, https://doi.org/10.1016/j.aei.2021.101432.

Zhang, Y., Zhang, H. and Chen, X. Augmented Reality Technology: Research Situation and Key Technologies, Springer, pp. 986-1004, https://doi.org/10.1007/978-981-32-9437-0_102

Zhang, Z. and Pan, W. (2021). Multi-criteria decision analysis for tower crane layout planning in high-rise modular integrated construction, Automation in Construction, Vol. 127 p. 103709, https://doi.org/10.1016/j.autcon.2021.103709.

Zhou, C., Ding, L., Zhou, Y. and Luo, H. (2018). Topological mapping and assessment of multiple settlement time series in deep excavation: a complex network perspective, Advanced Engineering Informatics, Vol. 36 pp. 1-19, https://doi.org/10.1016/j.aei.2018.02.005.

Zhou, Y., Ding, L. and Chen, L. (2013). Application of 4D visualization technology for safety management in metro construction, Automation in Construction, Vol. 34 pp. 25-36, https://doi.org/10.1016/j.autcon.2012.10.011.

Zhou, Y., Luo, H. and Yang, Y. (2017). Implementation of augmented reality for segment displacement inspection during tunneling construction, Automation in Construction, Vol. 82 pp. 112-121, https://doi.org/10.1016/j.autcon.2017.02.007.

Ziegler, J. (1996). Interactive techniques, ACM Computing Surveys (CSUR), Vol. 28 No. 1, pp. 185-187, https://doi.org/10.1145/234313.234392.

Appendices

Appendix 1: Ethics Approval

Appendix 2: List of trial orders for each participant

Appendix 3: The Conference Paper Presented at the AUBEA Conference 2023

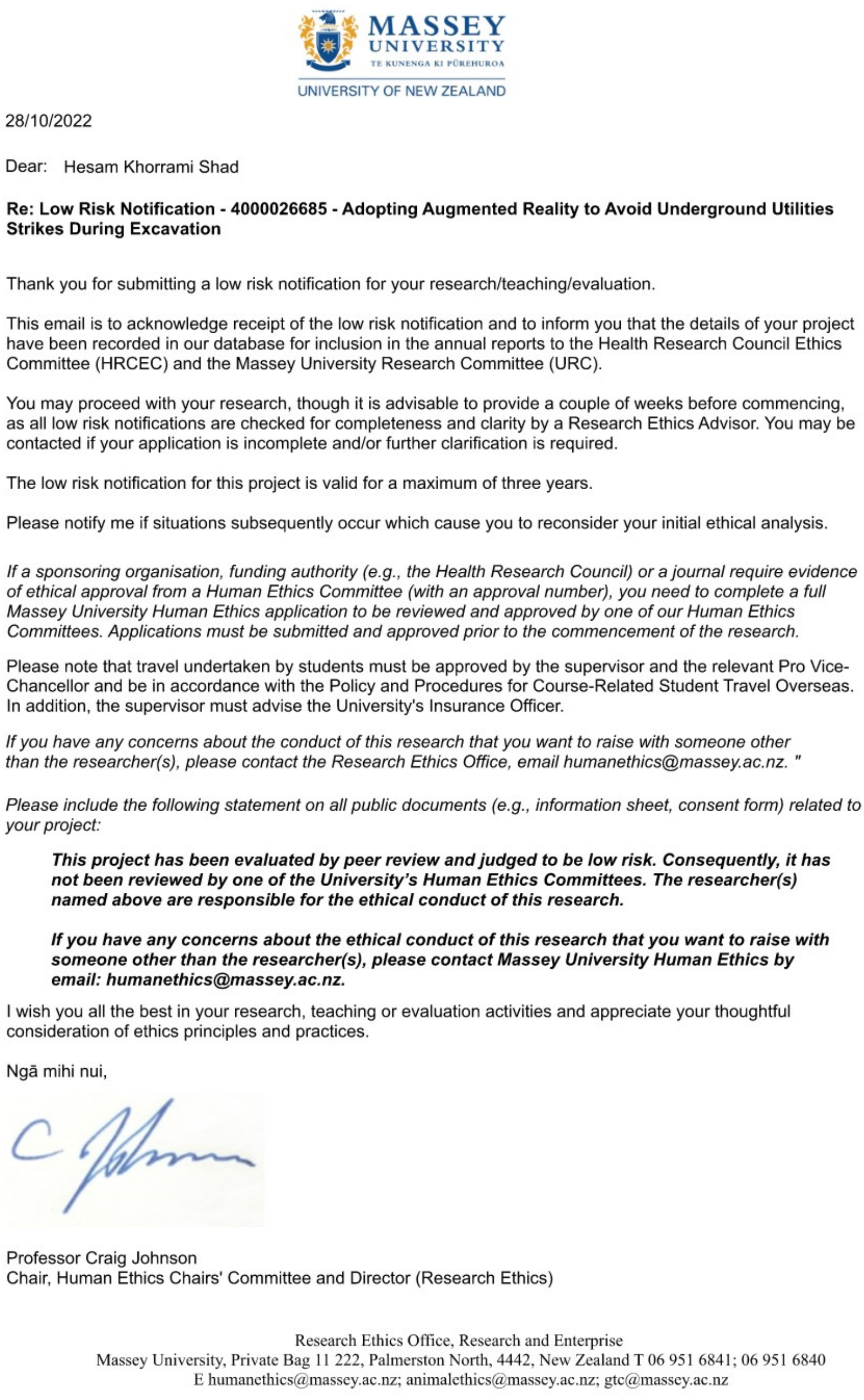
Appendix 4: Semi-Structured Interview

Appendix 5: Experimental Study

Appendix 6: Statement of contribution Forms

Appendix 1

Ethics Approval



MASSEY
UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

28/10/2022

Dear: Hesam Khorrami Shad

Re: Low Risk Notification - 4000026685 - Adopting Augmented Reality to Avoid Underground Utilities Strikes During Excavation

Thank you for submitting a low risk notification for your research/teaching/evaluation.

This email is to acknowledge receipt of the low risk notification and to inform you that the details of your project have been recorded in our database for inclusion in the annual reports to the Health Research Council Ethics Committee (HRCEC) and the Massey University Research Committee (URC).

You may proceed with your research, though it is advisable to provide a couple of weeks before commencing, as all low risk notifications are checked for completeness and clarity by a Research Ethics Advisor. You may be contacted if your application is incomplete and/or further clarification is required.

The low risk notification for this project is valid for a maximum of three years.

Please notify me if situations subsequently occur which cause you to reconsider your initial ethical analysis.

If a sponsoring organisation, funding authority (e.g., the Health Research Council) or a journal require evidence of ethical approval from a Human Ethics Committee (with an approval number), you need to complete a full Massey University Human Ethics application to be reviewed and approved by one of our Human Ethics Committees. Applications must be submitted and approved prior to the commencement of the research.

Please note that travel undertaken by students must be approved by the supervisor and the relevant Pro Vice-Chancellor and be in accordance with the Policy and Procedures for Course-Related Student Travel Overseas. In addition, the supervisor must advise the University's Insurance Officer.

If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher(s), please contact the Research Ethics Office, email humanethics@massey.ac.nz. "

Please include the following statement on all public documents (e.g., information sheet, consent form) related to your project:

> ***This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named above are responsible for the ethical conduct of this research.***
>
> ***If you have any concerns about the ethical conduct of this research that you want to raise with someone other than the researcher(s), please contact Massey University Human Ethics by email: humanethics@massey.ac.nz.***

I wish you all the best in your research, teaching or evaluation activities and appreciate your thoughtful consideration of ethics principles and practices.

Ngā mihi nui,

Professor Craig Johnson
Chair, Human Ethics Chairs' Committee and Director (Research Ethics)

Research Ethics Office, Research and Enterprise
Massey University, Private Bag 11 222, Palmerston North, 4442, New Zealand T 06 951 6841; 06 951 6840
E humanethics@massey.ac.nz; animalethics@massey.ac.nz; gtc@massey.ac.nz

Appendix 2

List of trial orders for each participant

Participant ID	Trial Order	Participant ID	Trial Order
P01	Shadow, X-Ray, Combination, Cross-Sectional	P31	X-Ray, Shadow, Combination, Cross-Sectional
P02	Shadow, X-Ray, Cross-Sectional, Combination	P32	X-Ray, Shadow, Cross-Sectional, Combination
P03	X-Ray, Combination, Cross-Sectional, Shadow	P33	Cross-Sectional, Shadow, Combination, X-Ray
P04	X-Ray, Combination, Shadow, Cross-Sectional	P34	Cross-Sectional, Shadow, X-Ray, Combination
P05	X-Ray, Cross-Sectional, Combination, Shadow	P35	Cross-Sectional, X-Ray, Combination, Shadow
P06	X-Ray, Cross-Sectional, Shadow, Combination	P36	Cross-Sectional, X-Ray, Shadow, Combination
P07	X-Ray, Shadow, Combination, Cross-Sectional	P37	Shadow, Combination, Cross-Sectional, X-Ray
P08	X-Ray, Shadow, Cross-Sectional, Combination	P38	Shadow, Combination, X-Ray, Cross-Sectional
P09	Cross-Sectional, Shadow, X-Ray, Combination	P39	Shadow, Cross-Sectional, Combination, X-Ray
P10	Cross-Sectional, Shadow, Combination, X-Ray	P40	Shadow, Cross-Sectional, X-Ray, Combination
P11	Cross-Sectional, X-Ray, Shadow, Combination	P41	Combination, Cross-Sectional, Shadow, X-Ray
P12	Cross-Sectional, X-Ray, Combination, Shadow	P42	Combination, Cross-Sectional, X-Ray, Shadow
P13	Shadow, Combination, Cross-Sectional, X-Ray	P43	Combination, Shadow, Cross-Sectional, X-Ray
P14	Shadow, Combination, X-Ray, Cross-Sectional	P44	Combination, Shadow, X-Ray, Cross-Sectional
P15	Shadow, Cross-Sectional, Combination, X-Ray	P45	Combination, X-Ray, Cross-Sectional, Shadow
P16	Shadow, Cross-Sectional, X-Ray, Combination	P46	Combination, X-Ray, Shadow, Cross-Sectional
P17	Combination, Cross-Sectional, Shadow, X-Ray	P47	Cross-Sectional, Combination, Shadow, X-Ray
P18	Combination, Cross-Sectional, X-Ray, Shadow	P48	Cross-Sectional, Combination, X-Ray, Shadow
P19	Combination, Shadow, Cross-Sectional, X-Ray	P49	Shadow, X-Ray, Combination, Cross-Sectional
P20	Combination, Shadow, X-Ray, Cross-Sectional	P50	Shadow, X-Ray, Cross-Sectional, Combination
P21	Combination, X-Ray, Cross-Sectional, Shadow	P51	X-Ray, Combination, Cross-Sectional, Shadow
P22	Combination, X-Ray, Shadow, Cross-Sectional	P52	X-Ray, Combination, Shadow, Cross-Sectional
P23	Cross-Sectional, Combination, Shadow, X-Ray	P53	X-Ray, Cross-Sectional, Combination, Shadow
P24	Cross-Sectional, Combination, X-Ray, Shadow	P54	X-Ray, Cross-Sectional, Shadow, Combination
P25	Shadow, X-Ray, Combination, Cross-Sectional	P55	X-Ray, Shadow, Combination, Cross-Sectional
P26	Shadow, X-Ray, Cross-Sectional, Combination	P56	X-Ray, Shadow, Cross-Sectional, Combination
P27	X-Ray, Combination, Cross-Sectional, Shadow	P57	Cross-Sectional, Shadow, Combination, X-Ray
P28	X-Ray, Combination, Shadow, Cross-Sectional	P58	Cross-Sectional, Shadow, X-Ray, Combination
P29	X-Ray, Cross-Sectional, Combination, Shadow	P59	Cross-Sectional, X-Ray, Combination, Shadow
P30	X-Ray, Cross-Sectional, Shadow, Combination	P60	Cross-Sectional, X-Ray, Shadow, Combination

Appendix 3

The Conference Paper Presented at the AUBEA Conference 2023

Augmented reality for the excavation industry: needs, expectations, and challenges

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Zhenan Feng, Senior Lecturer, Massey University, New Zealand

Daniel Paes, Senior Lecturer, Massey University, New Zealand

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Abstract:

The construction industry constantly explores innovative solutions to improve safety and productivity and to cut costs and time. Augmented Reality (AR) is one of the emerging technologies that can strongly impact the construction industry. This paper presents the preliminary results of a study focusing on the excavation industry's needs, expectations and challenges regarding AR applications. Sixteen (16) professionals from the New Zealand excavation industry were interviewed to share their perspectives. The interview was structured into several sections: demographics, industrial experience, common practices for preventing underground utility strikes during excavation, ranking identified limitations and risks associated with excavation works and providing recommendations to mitigate them. During the interview, participants were exposed to AR prototypes. Following the hands-on experience with the prototypes, the interviews concluded with discussions on the industry needs and expectations associated with their AR experience. This research suggests that the primary risks during excavation are injuries to workers and the potential risk of striking buried utilities. Moreover, there was a high expectation of accuracy from an AR system for future development.

Keywords:

Augmented reality, excavation works, underground construction, utilities

Introduction

Underground utilities constitute an integral component of the infrastructural services that sustain societal functions (Fenais *et al.*, 2018b). Today, these utilities span millions of miles worldwide and cater to the core necessities of urban life, including sewer pipelines, telecommunication cables, and supplies of electricity, gas, and water, thereby facilitating the uninterrupted flow of energy, information, and urban logistics (Wu *et al.*, 2021). However, the societal and economic repercussions of excavation damage to these utilities are substantial (Wu *et al.*, 2021). The principal threat to the integrity of underground utilities stems from strikes during excavation (Talmaki and Kamat, 2014).

In St. Cloud, Minnesota, U.S., in December 1998, a high-pressure gas line was struck while installing a utility pole support anchor, leading to four deaths, several severe injuries, and the destruction of six buildings (Hall *et al.*, 1998). Such incidents underscore the importance of treating underground utilities as nationally critical infrastructures (Hall *et al.*, 1998).

Against this backdrop, innovative technologies like AR are gaining momentum to enhance the safety conditions for construction workers (Hou *et al.*, 2014; Khorrami Shad *et al.*, 2022). By overlaying digital data onto the real world, AR enhances the real environment with virtual data, facilitating seamless communication among construction site workers regardless of geographic location (Moore and Gheisari, 2019). However, despite these benefits, construction professionals are reluctant to adopt such frontier technologies (Makkonen *et al.*, 2016), indicating a compelling need to understand the underlying reasons for this resistance. On the other hand, it is important to use existing resources and technologies in a smart way, facilitate information sharing, and ensure efficient communication during underground works (Fenais *et al.*, 2020b).

This study aims to contribute to this effort by highlighting the significance of AR in improving performance in excavation, providing a knowledge base for its implementation, and fostering a safer work environment for the industry.

Literature Review

Several studies have endeavoured to integrate underground utility mapping with AR technology to enhance the safety and improve the productivity of earthwork activities (Su *et al.*, 2013; Fenais *et al.*, 2018a; Fenais *et al.*, 2019; Fenais *et al.*, 2020a). For instance, a study by Su *et al.* (2013) assessed the technical feasibility of employing AR visualisation techniques during active excavation operations. Additionally, three other studies explored the potential of AR in mitigating the risks associated with utility strikes during directional drilling procedures (Fenais *et al.*, 2018a; Fenais *et al.*, 2019; Fenais *et al.*, 2020a). In this vein, three studies developed an innovative prototype employing an AR system to plot the layout of underground utilities, harnessing the capabilities of Geographic Information Systems (GIS) for data collection and storage (Fenais *et al.*, 2018a; Fenais *et al.*, 2019; Fenais *et al.*, 2020a). The findings of these studies collectively suggest that AR holds promise as a viable and secure method for data visualisation in underground utility operations.

A review of the existing academic literature reveals a limited number of studies investigating the use of AR technology to prevent strikes on underground utilities during excavation works. These studies primarily focus on the precision and accuracy of smartphones in handling data related to underground utilities (Khorrami Shad *et al.*, 2022). However, findings from these studies highlight a significant constraint: the lack of precision in the smartphone GPS systems has made them unsuitable for application in the underground construction sector (Fenais *et al.*, 2020a). Moreover, these studies fail to address expectations from industrial perspectives for AR adoption.

The present study aspires to bridge the gap by gathering and analysing the needs and expectations of the industry concerning the adoption of AR technology to prevent underground utility strikes during excavation operations.

Research Method

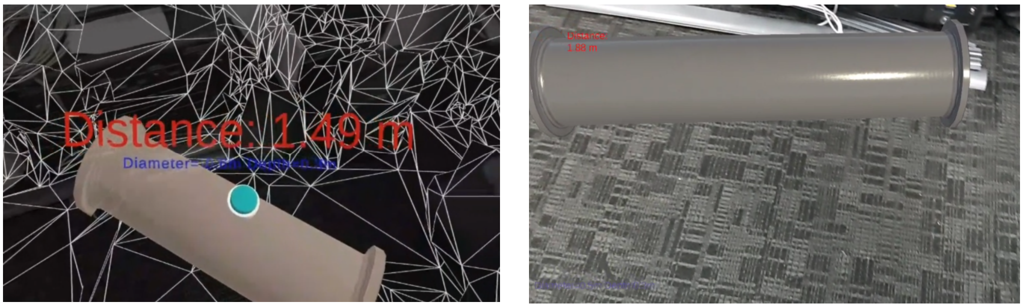
This study employed an empirical research approach, a research method widely used in various fields to gain an in-depth understanding of complex issues (Creswell and Creswell, 2017). The aim was to discern the needs, expectations, and challenges faced by the excavation industry concerning the application of AR.

Our research sample comprised professionals actively engaged in the New Zealand excavation industry. We utilised a purposeful sampling strategy (Palinkas *et al.*, 2015) to recruit 16 professionals from diverse roles within the industry, ensuring a balanced and comprehensive understanding of the industry's viewpoint. These participants ranged from plant managers, senior project managers and site engineers to forepersons, encompassing a broad spectrum of perspectives.

We utilised qualitative and quantitative research designs to gain detailed insights into the participants' perspectives. We employed a semi-structured interview format (DiCicco-Bloom and Crabtree, 2006), enabling us to delve deeper into areas of interest and seek clarifications when necessary.

The first section of the interview gathered demographic data and information about the participants' professional backgrounds. This section contains five items to gather information on the participants' characteristics and their experience in excavation. These items include gender, educational background, age, duration of involvement in the excavation field, and their present professional position. This information was crucial for contextualising the insights gained from the interviews (Yiu *et al.*, 2023). The second section delved into the participants' industrial experience, particularly their common practices for preventing underground utility strikes during excavation. Then, the limitations and risks associated with current excavation practices have been explored. Participants were asked to rank these in order of importance or severity. This section also includes discussions on potential mitigation strategies.

To provide the participants with a practical understanding of AR capabilities, we offered a hands-on experience with AR prototypes; these prototypes consist of augmenting an underground pipeline to show the professionals how AR works (see figure 1). The final section of the interview revolved around discussing the industry's needs and expectations for AR technology. This portion delves into what participants anticipate from such a prototype. Open-ended queries are crafted to obtain their specific needs and their expected data presentation.



(a) (b)

Figure 1. Screenshots of the AR environment: (a) OST device, (b) VST device (by authors)

The data collected from the interviews were transcribed and coded to identify common themes and patterns. The research method aligns with a similar study (Zhang and Pan, 2021). These themes were then analysed to extract key findings and recommendations.

Findings and Discussion

Participant Demographics and Background

Our study encompassed a set of 16 industry professionals from the excavation sector, consisting of fourteen males and two females. The educational backgrounds varied among the participants, with four holding no university degrees, four having diplomas, four possessing undergraduate degrees, and four boasting postgraduate qualifications. Their ages spanned from 25 to 61 years, averaging 39.8 years. These professionals brought a wealth of experience to our study, with tenures in the excavation field ranging from 2.5 years to an impressive 40 years, with a mean experience of 16.6 years. Figure 2 illustrates the current roles of the participants.

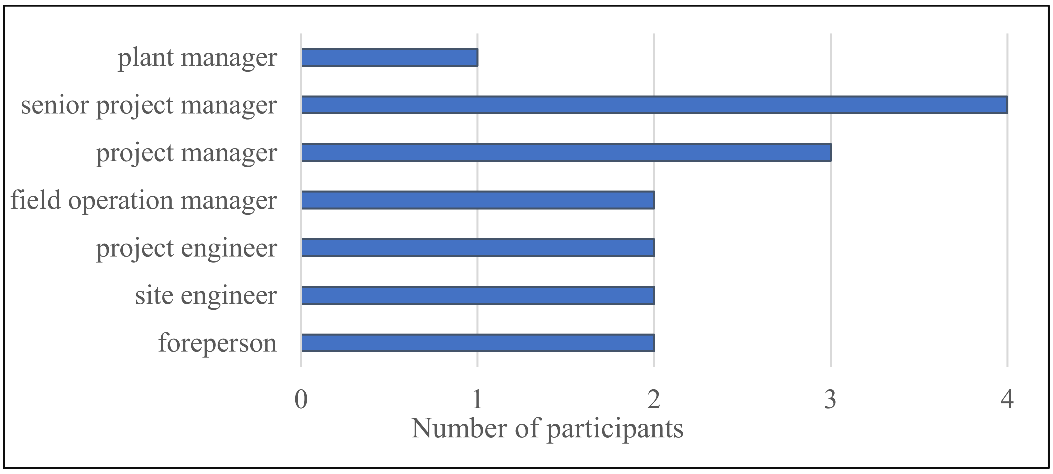


Figure 2: Participants' current roles

Earthwork Practices and Challenges

We probed into the current measures employed by the participants to prevent damage to underground utilities during excavation. The unanimous response indicated the usage of maps and plans to identify underground utilities before commencing excavation. The participants also unanimously reported using hydro excavation, which employs high-pressure water to excavate soil and debris around underground utilities, thereby averting physical contact and potential damage. A significant majority, 15 out of 16, reported resorting to hand-digging techniques for more precise excavation in areas with underground utilities. The same number reported using non-destructive testing methods, such as Ground Penetrating Radar (GPR), to locate underground utilities. Conversely, only two participants reported employing Cable Avoidance Tools (CAT) and Genny Scans to help avert strikes to underground utilities, particularly live cables, during excavation works.

The participants then ranked various limitations they encountered during excavation works. Figure 3 shows these rankings, highlighting that the most prevalent issues were the lack of information about existing buried utilities and the lack of vertical accuracy due to further changes of elevation that are not captured in the original as-built drawings. Additional limitations identified by the participants included poor communication and limited workspace.

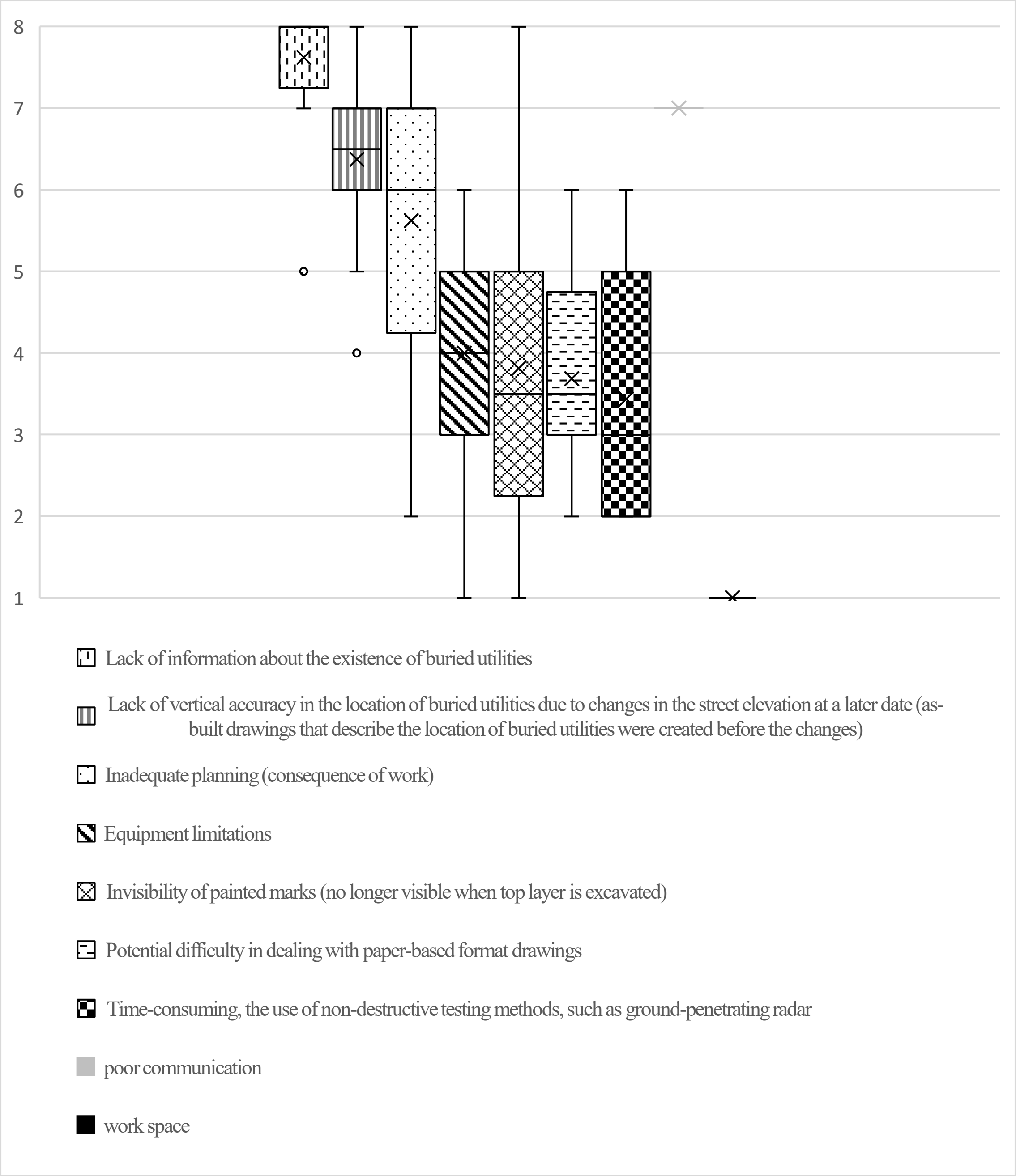


Figure 3: Limitations in excavation works

When asked how these critical limitations could be mitigated, 13 out of 16 participants suggested using GPR, hydro excavation, and potholing.

Risks associated with excavation work were then ranked by participants, as demonstrated in figure 4, with the risk of injuries or fatalities to construction professionals and bystanders being identified as the most severe. The following was the risk of striking underground utilities. The mitigation strategies proposed for these risks included efficient traffic management systems and using GPR, hydro excavation, and potholing.

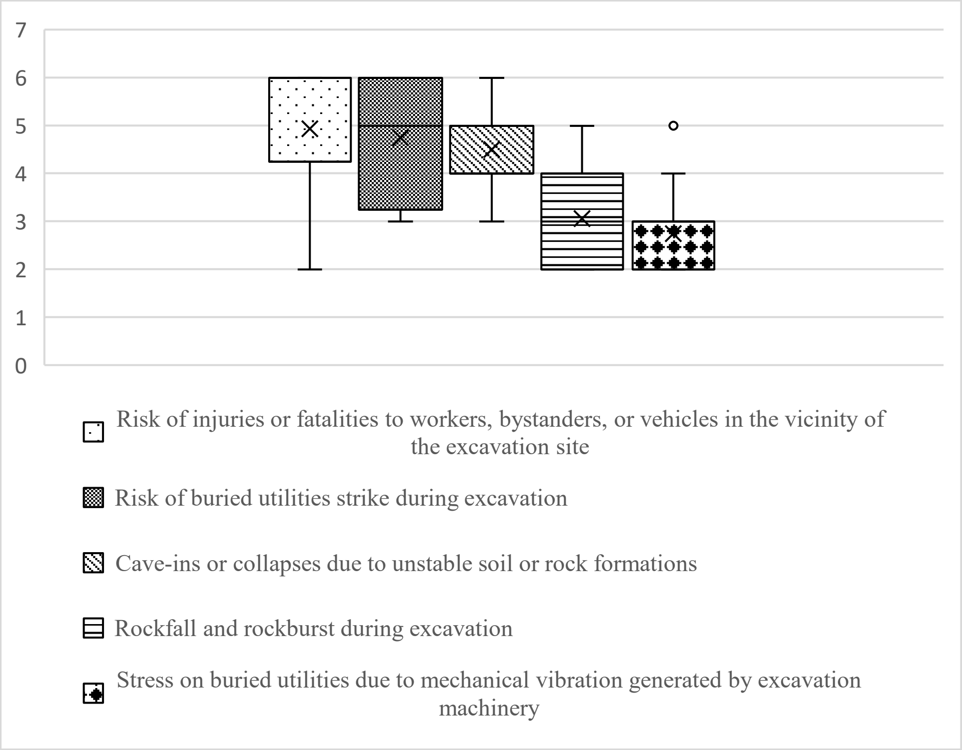


Figure 4: Risks in excavation works

AR System Expectations

We then moved on to gauge the participants' familiarity with AR technology. At this stage, participants were told that car reverse cameras or Pokémon GO are common applications of AR. Nine had a regular level of familiarity, four reported frequent use, while three rarely interacted with AR in their daily life. Then, we asked them to experience AR technology to familiarise them. Then, we asked them one open-ended question: What would be your demands and expectations of an AR system for daily excavation works for identifying and locating underground utilities?

The participants' responses highlighted several vital expectations and requirements for an effective AR system for excavation. A recurring theme among most participants was the demand for accuracy. They underscored the need for an AR system to precisely identify and locate underground utilities, thereby reducing the risk of potential damage. For instance, one site manager remarked, "*Without pinpoint accuracy, the entire exercise becomes moot. The AR system needs to tell us exactly where the utilities are*."

Another common expectation was the ease of use. A few participants stated that the AR system must be user-friendly, with a gentle learning curve, to ensure rapid adoption within the industry. A site engineer shared, "*The last thing we need is a complicated system that requires extensive training. It has to be intuitive and straightforward*."

Several participants also highlighted the importance of cost efficiency. They expressed the need for affordable AR devices and maintenance to ensure the technology is accessible to companies of varying scales. "*AR technology sounds promising, but it won't make sense for us if it's not economically viable*," one of the respondents pointed out.

The speed of processing was another expectation that emerged from the interviews. A participant emphasised the need for swift responses from the AR system to maintain the pace of work. "*Time is always of the essence in our industry. The AR system should provide us with immediate, real-time information*," they said.

These responses provide crucial insights into the expectations and demands of industry professionals for the adoption and effective utilisation of AR systems in the excavation industry. By focusing on these critical aspects – accuracy, ease of use, cost-efficiency, and speed – developers can better tailor AR solutions to meet the industry's needs.

Conclusion and Further Research

This study investigated the expectations and demands of industry professionals concerning the adoption and utilisation of AR technology in the excavation field. Key areas of interest that emerged from the interviews included the need for accuracy in identifying and locating underground utilities, ease of use of the AR system, cost-efficiency of the technology, and the speed at which the system processes information. These critical elements must be considered when developing AR systems for the industry, as they directly align with the industry's requirements for efficient excavation practices.

However, participants did not mention any concern regarding the safety rules and regulations associated with AR systems. This area is significant given the potential risks associated with AR technology in excavation operations (Sabeti *et al.*, 2021; Zoleykani *et al.*, 2023). Future research should delve into this aspect, outlining necessary safety protocols and measures to ensure the secure operation of AR systems in this setting.

Moreover, this study has opened avenues for future research to enhance the application of AR technology in the excavation industry. One such area is the physical and mental demands of using AR systems. Understanding these demands can provide insights into developing user-friendly interfaces that minimise strain and maximise productivity.

Furthermore, a comparative study between OST and VST AR systems from the excavation industry's perspective can shed light on the advantages and limitations of each system in this particular context. Such a comparison with a bigger sample size can help industry professionals make informed decisions about the most suitable AR system for their specific needs and guide developers in tailoring AR solutions to meet these needs.

In conclusion, the insights from this study provide valuable direction for the ongoing development and refinement of AR systems in the excavation industry. By addressing industry professionals' specific needs and expectations, AR technology can be positioned to enhance safety and efficiency in excavation practices significantly. The outlined directions for future research underscore the potential of AR technology to transform the excavation industry, with wide-ranging implications for construction safety and productivity.

References

Creswell, J.W. and Creswell, J.D. (2017). Research design: Qualitative, quantitative, and mixed methods approaches, Sage publications, ISBN:1506386717.

DiCicco-Bloom, B. and Crabtree, B.F. (2006). The qualitative research interview, Medical education, Vol. 40 No. 4, pp. 314-321.

Fenais, A., Ariaratnam, S.T., Ayer, S.K. and Smilovsky, N. (2019). Integrating geographic information systems and augmented reality for mapping underground utilities, Infrastructures, Vol. 4 No. 4, p. 60, https://doi.org/10.3390/infrastructures4040060.

Fenais, A., Ariaratnam, S.T. and Smilovsky, N. (2020a). Assessing the Accuracy of an Outdoor Augmented Reality Solution for Mapping Underground Utilities, Journal of Pipeline Systems Engineering and Practice, Vol. 11 No. 3, p. 04020029, https://doi.org/10.1061/(ASCE)PS.1949-1204.0000474.

Fenais, A., Smilovsky, N. and Ariaratnam, S.T. (2018a). Using augmented reality in horizontal directional drilling to reduce the risk of utility damages, in Pipelines 2018: Utility Engineering, Surveying, and Multidisciplinary Topics, American Society of Civil Engineers Reston, VA, pp. 290-298, https://doi.org/10.1061/9780784481660.032.

Fenais, A., Smilovsky, N., Ariaratnam, S.T. and Ayer, S.K. (2018). A meta-analysis of augmented reality challenges in the underground utility construction industry, pp. 80-89, https://doi.org/10.1061/9780784481295.009

Fenais, A.S., Ariaratnam, S.T., Ayer, S.K. and Smilovsky, N. (2020b). A review of augmented reality applied to underground construction, Journal of Information Technology in Construction, Vol. 25 pp. 308-324, https://doi.org/10.36680/J.ITCON.2020.018.

Hall, J., Hammerschmidt, J., Goglia, J., Black Jr, G. and Carmody, C. (1998). Natural gas pipeline rupture and subsequent explosion, Washington, DC: National Transportation Safety Board.

Hou, L., Wang, Y., Wang, X., Maynard, N., Cameron, I.T., Zhang, S. and Jiao, Y. (2014). Combining photogrammetry and augmented reality towards an integrated facility management system for the oil industry, Proceedings of the IEEE, Vol. 102 No. 2, pp. 204-220, https://doi.org/10.1109/JPROC.2013.2295327.

Khorrami Shad, H., Tak Wing Yiu, K., Lovreglio, R. and Feng, Z. (2022). State-of-the-art analysis of the integration of augmented reality with construction technologies to improve construction safety, Smart and Sustainable Built Environment, https://doi.org/10.1108/SASBE-07-2022-0151.

Makkonen, H., Johnston, W.J. and Javalgi, R.R.G. (2016). A behavioral approach to organizational innovation adoption, Journal of Business Research, Vol. 69 No. 7, pp. 2480-2489, https://doi.org/10.1016/j.jbusres.2016.02.017.

Moore, H.F. and Gheisari, M. (2019). A review of virtual and mixed reality applications in construction safety literature, Safety, Vol. 5 No. 3, p. 51, https://doi.org/10.3390/safety5030051.

Palinkas, L.A., Horwitz, S.M., Green, C.A., Wisdom, J.P., Duan, N. and Hoagwood, K. (2015). Purposeful sampling for qualitative data collection and analysis in mixed method implementation research, Administration and policy in mental health and mental health services research, Vol. 42 pp. 533-544.

Sabeti, S., Shoghli, O., Baharani, M. and Tabkhi, H. (2021). Toward AI-enabled augmented reality to enhance the safety of highway work zones: Feasibility, requirements, and challenges, Advanced Engineering Informatics, Vol. 50 p. 101429, https://doi.org/10.1016/j.aei.2021.101429.

Su, X., Talmaki, S., Cai, H. and Kamat, V.R. (2013). Uncertainty-aware visualisation and proximity monitoring in urban excavation: a geospatial augmented reality approach, Visualisation in engineering, Vol. 1 No. 1, pp. 1-13, https://doi.org/10.1186/2213-7459-1-2.

Talmaki, S. and Kamat, V.R. (2014). Real-time hybrid virtuality for prevention of excavation related utility strikes, Journal of Computing in Civil Engineering, Vol. 28 No. 3, p. 04014001, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000269.

Wu, J., Bai, Y., Fang, W., Zhou, R., Reniers, G. and Khakzad, N. (2021). An Integrated Quantitative Risk Assessment Method for Urban Underground Utility Tunnels, Reliability Engineering & System Safety, Vol. 213 p. 107792, https://doi.org/10.1016/j.ress.2021.107792.

Yiu, T.W., Wu, R.W., Jelodar, M.B., Lovreglio, R., Ali, N.A., Guo, B.H. and Ghodrati, N. (2023). Are You Ready to be Monitored at Work?–A Study of Real-time Employee Monitoring Technologies Adoption for New Zealand Construction Industry from Legal, Ethical and Behavioural Perspectives.

Zhang, Z. and Pan, W. (2021). Multi-criteria decision analysis for tower crane layout planning in high-rise modular integrated construction, Automation in Construction, Vol. 127 p. 103709.

Zoleykani, M.J., Abbasianjahromi, H., Banihashemi, S., Tabadkani, S.A. and Hajirasouli, A. (2023). Extended reality (XR) technologies in the construction safety: systematic review and analysis, Construction Innovation, https://doi.org/10.1108/CI-05-2022-0131.

Appendix 4

Semi-Structured Interview

School of Built Environment

College of Sciences

School of Built Environment
Quadrangle Building A
Albany campus, Auckland 0632
New Zealand

PARTICIPANT INFORMATION SHEET

Name of Principal Researcher:	**Hesam Khorrami Shad**
Research Project Title:	**Adopting Augmented Reality to Avoid Underground Utilities Strikes During Excavation**
Research Supervisors:	**A/Prof Ruggiero Lovreglio** **Prof Kenneth Tak Wing Yiu** **Dr Zhenan Feng** **Dr Daniel Paes**

Purpose of this Participant Information Sheet (PIS)

The purpose of this Participant Information Sheet (PIS) is to invite you to participate in a semi-structured interview for the abovementioned research currently undertaken for a PhD study at Massey University. The research aims to introduce effective underground utility damage prevention practices by locating underground utilities via AR technologies.

Project Description

The research endeavours to introduce effective underground utility damage prevention practices by locating underground utilities via AR technologies. In this stage, we aim to identify the limitations and challenges facing primary excavation methods within the New Zealand construction industry and define the industry's needs to design a technology-based solution. The questions include open-ended and closed-ended but are carefully predetermined.

Participation and Withdrawal

The goal is for you to provide some information regarding your experience in the excavation industry. Also, you will try AR technology as a part of the interview and provide us with your feedback. If you decide to participate in this research, you also have the right to withdraw from participation at any time without any explanation.

Data Collection

You will be interviewed as part of the data collection process and should answer based on your knowledge and expertise. The average interview time is 30 minutes. Please be aware that the survey is anonymous, and individual data will not be identifiable. The audio in the semi-structured interview will be recorded to avoid missing data. The information gathered through this interview will be securely kept, and only the appropriate researchers can access it. All data collected will be stored in an electronic file on password-protected computers. Data might be used in conferences, academic publications, or presentations. However, organisations, individuals or individual responses will not be identified in any of these. All reports/results will be based on the overall results of the research.

You can withdraw your interview data should you no longer wish to participate up to the point of data analysis. Should you wish to withdraw, you must notify the researchers before data analysis, and your data will be deleted immediately.

The interview process will NOT involve any physical changes to the environment in which the participants interact. You can withdraw at any point if you feel unwell.

Confidentiality and Anonymity

Confidentiality is of the utmost importance in all stages of this research. All data will be anonymised. This will include removing any names or other potentially identifying information you may mention in your interview. No individual data will be described or released in any form, and only aggregate data will be presented in any reports based on this data. If you are an employee of an organisation, your employer has given permission for employees to participate, but you will not be notified of your specific participation and will not be provided with individual employee data.

Interview Procedure

The interview guideline is structured into three main sections: participants' background, experience with AR within a tablet and HoloLens, questions related to AR experience in the second section, and your expectations. It should take no longer than 30 minutes to answer.

Ethics Notification

This project has been evaluated by peer review and is judged as low risk. The Ethics notification number for this project is 4000026685, and the low-risk notification is valid for three years, effective from October 2022.

If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher, please get in touch with Prof. Craig Johnson, Director – Ethics, telephone at 063569099 ext. 85271, email: C.B.Johnson@massey.ac.nz.

Funding

The researcher has been awarded the Massey University Doctoral Scholarship for three years.

CONSENT FORM

THIS FORM WILL BE HELD FOR A PERIOD OF 6 YEARS

Project: Adopting Augmented Reality to Avoid Underground Utilities Strikes During Excavation

STATEMENT OF CONSENT

If you wish to take part in this study, please read the following carefully and sign in the space provided

- I am voluntarily taking part in this interview. I understand that I do not have to take part, and I can stop and withdraw my consent at any time up to three weeks from today.
- I have read the Information Sheet.
- I am aware that the semi-structured interview will be audio recorded.
- I understand that the data I provide is confidential and that I will not be identified in any publications of findings from this research.
- I have been able to ask any questions I might have, and I understand that I am free to contact the researcher with any questions I may have.

Signature:		Date:	
Full Name:			

The Ethics notification number for this project is 4000026685.

If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher, please get in touch with Prof. Craig Johnson, Director – Ethics, telephone at 063569099 ext. 85271, email: C.B.Johnson@massey.ac.nz.

If you have any queries, please contact;

Researcher's Name and Contact Details Hesam Khorrami Shad, PhD student, School of Built Environment Email: HKhorrami@massey.ac.nz Phone: +64 20 41 97 4268	**Supervisor's Name and Contact Details** Dr. Ruggiero Lovreglio School of Built Environment Email: R.Lovreglio@massey.ac.nz

Thank you for your time and your kind support!

Participant's Background

Gender

☐ Man ☐ Woman ☐ Non-binary/Third gender ☐ Prefer not to say

Education

☐ No university degree ☐ Diploma ☐ Undergraduate ☐ Postgraduate

Age

The number of years of experience in excavation and earthwork activities

Current role and how many years

Earthwork Questions

What measures do you currently implement to prevent damage to underground utilities during excavation works?

The use of maps and plans to identify the location of underground utilities before excavation works commence (before you dig)

Hand digging techniques, which allow for more precise excavation in areas where underground utilities are present

The use of non-destructive testing methods, such as ground penetrating radar, to locate underground utilities

Hydro excavation or suction using high-pressure water or air to excavate soil and debris around underground utilities while avoiding physical contact that may cause damage.

Any other practices?

Please rank from 1 to 8 the below-mentioned limitations in excavation works (1 means the most critical limitation)

Invisibility of painted marks (no longer visible when the top layer is excavated)

Lack of information about the existence of buried utilities

Lack of vertical accuracy in the location of buried utilities due to changes in the street elevation at a later date (as-built drawings that describe the location of buried utilities were created before the changes)

Potential difficulty in dealing with paper-based format drawings

Equipment limitations

Inadequate planning (consequence of work)

Time-consuming, the use of non-destructive testing methods, such as ground-penetrating radar

Any other limitations?

How can the most critical limitation be mitigated?

Please rank from 1 to 6 the below-mentioned risks in excavation works (1 means the most severe risk)

Risk of a buried utilities strike during excavation

Cave-ins or collapses due to unstable soil or rock formations

Stress on buried utilities due to mechanical vibration generated by excavation machinery

Risk of injuries or fatalities to workers, bystanders, or vehicles in the vicinity of the excavation site

Rockfall and rockburst during excavation

Any other risks?

How can the most critical risk be mitigated?

How often do you use Augmented Reality technology in daily life? (Car reverse camera, Instagram face filters, and Pokémon Go are some examples of AR)

☐ never ☐ rarely ☐ occasionally ☐ regularly

Now you will be experiencing AR within a tablet and HoloLens

Exploratory AR Questions

How mentally demanding was AR within the HoloLens system?

☐ very low ☐ low ☐ somewhat low ☐ neither ☐ somewhat high ☐ high ☐ very high

How mentally demanding was AR within the tablet system

☐ very low ☐ low ☐ somewhat low ☐ neither ☐ somewhat high ☐ high ☐ very high

How physically demanding was AR within the HoloLens system

☐ very low ☐ low ☐ somewhat low ☐ neither ☐ somewhat high ☐ high ☐ very high

How physically demanding was AR within the tablet system

☐ very low ☐ low ☐ somewhat low ☐ neither ☐ somewhat high ☐ high ☐ very high

I believe AR technology with the tablet system could be a better alternative to traditional paper-based drawing methods for identifying and locating underground utilities.

☐ Strongly disagree ☐ somewhat disagree ☐ neither agree nor disagree ☐ somewhat agree ☐ strongly agree

I believe AR technology with the HoloLens system could be a better alternative to traditional paper-based drawings methods for identifying and locating underground utilities

☐ Strongly disagree ☐ somewhat disagree ☐ neither agree nor disagree ☐ somewhat agree ☐ strongly agree

Which one (tablet or HoloLens) do you think would be more suitable for daily excavation works and why?

____

What would be your demands and expectations of an AR system for daily excavation works to identify and locate underground utilities?

What kind of information would be relevant to be shown in an AR system for daily excavation works?

What are the top three reasons AR has not yet been adopted for excavation works in the construction industry?

Appendix 5

Experimental Study

School of Built Environment

College of Sciences

School of Built Environment
Quadrangle Building A
Albany campus, Auckland 0632
New Zealand

PARTICIPANT INFORMATION SHEET

Name of Principal Researcher:	**Hesam Khorrami Shad**
Research Project Title:	**A Comparison of AR Solutions for Underground Utility Visualisation**
Research Supervisors:	**A/Prof Ruggiero Lovreglio** **Prof Kenneth Tak Wing Yiu** **Dr Zhenan Feng** **Dr Daniel Paes**

Purpose of this Participant Information Sheet (PIS)

The purpose of this Participant Information Sheet (PIS) is to invite you to participate in an experiment for the abovementioned research currently undertaken for a PhD study at Massey University. The research aims to introduce effective underground utility damage prevention practices by locating underground utilities via AR technologies.

Project Description

The research endeavours to compare different AR solutions for underground utility visualisation. In this stage, we aim to identify the pros and cons of each visualisation solution for underground utilities. The questions include open-ended and closed-ended but are carefully predetermined.

Participation and Withdrawal

The goal is for you to provide some information regarding your experience in the excavation industry. Also, you will try AR technology as a part of the experiment and provide us with your feedback. If you decide to participate in this research, you also have the right to withdraw from participation at any time without any explanation.

Data Collection (6 years)

You will be exposed to an experiment as part of the data collection process and should answer based on your knowledge and expertise. The average time is 30 minutes. Please be aware that the survey is anonymous, and individual data will not be identifiable. The audio in the experiment will be recorded to avoid missing data. The information gathered through this experiment will be securely kept, and only the appropriate researchers can access it. All data collected will be stored in an electronic file on Massey-monitored computers. Data might be used in conferences, academic publications, or presentations. However, organisations, individuals or individual responses will not be identified in any of these. All reports/results will be based on the overall results of the research.

You can withdraw your experiment data should you no longer wish to participate up to the point of data analysis. Should you wish to withdraw, you must notify the researchers before data analysis, and your data will be deleted immediately.

The experiment process will NOT involve any physical changes to the environment in which the participants interact. You can withdraw at any point if you feel unwell.

Confidentiality and Anonymity

Confidentiality is of the utmost importance in all stages of this research. All data will be anonymised. This will include removing any names or other potentially identifying information you may mention in your experiment. No individual data will be described or released in any form, and only aggregate data will be presented in any reports based on this data. If you are an employee of an organisation, your employer has given permission for employees to participate but will not be notified of your specific participation and will not be provided with individual employee data.

Experiment Procedure

The experiment is structured into three main sections: participants' background, experiencing AR, and the questions related to AR experience. It should take no longer than 30 minutes to answer.

Ethics Notification

This project has been evaluated by peer review and is judged as low risk. The Ethics notification number for this project is 4000026685, and the low-risk notification is valid for three years, effective from October 2022.

If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher, please get in touch with Prof. Craig Johnson, Director – Ethics, telephone at 063569099 ext. 85271, email: C.B.Johnson@massey.ac.nz.

Funding

The researcher has been awarded the Massey University Doctoral Scholarship for three years.

CONSENT FORM

THIS FORM WILL BE HELD FOR A PERIOD OF 6 YEARS

Project: A Comparison Study of AR Solutions for Underground Utility Visualisation

STATEMENT OF CONSENT

If you wish to take part in this study, please read the following carefully and sign in the space provided

- I am voluntarily taking part in this experiment. I can stop, pause, or withdraw my consent at any time up to three weeks from today.
- I have read the Participant Information Sheet.
- I am aware that the experiment involves audio recording.
- I understand that the data I provide is confidential and that I will not be identified in any publications of findings from this research.
- I have been able to ask any questions I might have, and I understand that I am free to contact the researcher with any questions I may have.

Signature:		Date:	
Full Name:			

The Ethics notification number for this project is 4000026685.

If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher, please get in touch with Prof. Craig Johnson, Director – Ethics, telephone at 063569099 ext. 85271, email: C.B.Johnson@massey.ac.nz.

If you have any queries, please contact;

Researcher's Name and Contact Details	**Supervisor's Name and Contact Details**
Hesam Khorrami Shad, PhD student,	Dr. Ruggiero Lovreglio
School of Built Environment	School of Built Environment
Email: HKhorrami@massey.ac.nz	Email: R.Lovreglio@massey.ac.nz
Phone: +64 20 41 97 4268	

Thank you for your time and your kind support!

Demographics:

Participant's Background

Gender

☐ Man ☐ Woman ☐ Non-binary/Third gender ☐ Prefer not to say

Education

☐ No university degree ☐ Diploma ☐ Undergraduate ☐ Postgraduate

Age:

Background:

☐ Construction-related ☐ Non-Construction

Occupation:

How often do you use Augmented Reality technology in daily life? (Car reverse camera, Instagram face filters, and Pokémon Go are some examples of AR)

☐ Never ☐ Rarely ☐ Occasionally ☐ Regularly

Questionnaire:

No.	Questions	Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree
1	It is easy for me to understand that virtual objects represent pipelines	☐	☐	☐	☐	☐	☐	☐
2	It is easy for me to notice the pipelines	☐	☐	☐	☐	☐	☐	☐
3	It is easy for me to understand that the pipelines are underground	☐	☐	☐	☐	☐	☐	☐
4	It is easy for me to understand the vertical position of the pipelines	☐	☐	☐	☐	☐	☐	☐
5	It is easy for me to understand the horizontal position of the pipelines	☐	☐	☐	☐	☐	☐	☐
6	This system will make it easier to identify pipeline position in excavation tasks.	☐	☐	☐	☐	☐	☐	☐
7	This system will reduce the risk of damage to pipeline during excavation tasks	☐	☐	☐	☐	☐	☐	☐

Please evaluate the procedure by marking "X" at the point which best fits your experience. The scale ranges from "Very low" on the left to "Very high" on the right.

1. Mental Demand

How mentally fatiguing was the task?

2. Physical Demand

How physically fatiguing was the task?

3. Frustration

How insecure, discouraged, irritated, stressed or annoyed were you?

4. Task Complexity

How complex was the task?

5. Visual perception strain

How uncomfortable/irritating were the visual aspects of the task?

Open-ended Questions:

1. **Which system do you think is the best and why?**

2. **What do you recommend to improve our system?**

Appendix 6

Statement of contribution Forms

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Hesam Khorrami Shad
Name and title of main supervisor:	Professor Ruggiero Lovreglio
In which chapter is the manuscript/published work?	Chapter 3

Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:[1]

Student Contribution: Formulating the research questions, conducting literature review, synthesizing key findings, and drafting the manuscript.
Members of Supervisory Team Contribution: Designing the project, reviewing the methodology, participation in drafting and revising the manuscript, and approval of the final manuscript.

Please select one of the following three options:

● **The manuscript/published work is published or in press**

Please provide the full reference of the research output:

Khorrami Shad, H., Tak Wing Yiu, K., Lovreglio, R., & Feng, Z. (2024). State-of-the-art analysis of the integration of augmented reality with construction technologies to improve construction safety. Smart and Sustainable Built Environment, 13(6), 1434-1449.

○ **The manuscript is currently under review for publication**

Please provide the name of the journal:

○ **It is intended that the manuscript will be published, but it has not yet been submitted to a journal**

Student's signature:	Hesam Khorrami Shad	Main supervisor's signature:	Ruggiero Lovreglio Digitally signed by Ruggiero Lovreglio DN: OU=SBE, O=Massey University, CN=Ruggiero Lovreglio, E=r.lovreglio@massey.ac.nz Reason: I am the author of this document Location: Washington DC, US Date: 2025.04.07 09:11:27+12'00' Foxit PDF Reader Version: 2024.3.0

This form should be placed at the beginning of each relevant thesis chapter.

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[1] Refer to the Massey University Publishing and Authorship guidelines (OneMassey for staff, Stream for students) and/ or Contributor Roles Taxonomy (CRediT) guidelines for guidance.

1

Doctoral Research Committee
May 2023

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

GRADUATE
RESEARCH
SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Hesam Khorrami Shad
Name and title of main supervisor:	Professor Ruggiero Lovreglio
In which chapter is the manuscript/published work?	Chapter 4

Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:[1]

Student Contribution: Formulating the research questions, conducting literature review, developing the prototype, conducting the interview, and writing the manuscript.
Members of Supervisory Team Contribution: Finalizing the research questions, designing the interview process, reviewing the research method, participation in drafting and revising the manuscript, and approval of the final manuscript.

Please select one of the following three options:

● **The manuscript/published work is published or in press**

Please provide the full reference of the research output:

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