HYDRAULIC FACTORS LIMITING THE USE OF SUBIRRIGATION IN FINE TEXTURED SOILS

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ABSTRACT

Subirrigation is a method of supplying water directly to the plant root zone under the ground surface by means of subsurfce drains which are also used to remove excess water from the root zone. Subsurface drainage systems are used to maintain appropriate levels of soil moisture in the root zone of a crop by managing the water table. Subirrigation is seen as being an economic alternative to conventional sprinkler irrigation systems on dairy farms where mole drainage systems are already installed. However, information on subirrigation of these fine textured soils is very limited. The primary focus of this study was to evaluate the hydraulic parameters limiting the use of subirrigation in fine textured soils.

A field experiment was carried out on the Massey University No. 4 Dairy Farm in Palmerston North. During the study, a subsurface tile drainage system, with mole channels, was used to subirrigate 1248 m^2 of Tokomaru silt loam soil. The depth of irrigation applied was 185.71mm (232 m^3 of water added to the system). Time Domain Reflectometry (TDR) was used to measure the soil moisture content to a depth of 400mm at three positions, 5 m away from the drainage lateral and at three control points in an adjacent unirrigated plot. A theoretical daily water balance was developed for the irrigated plot and unirrigated control, based on the available weather data.

The results from field experiment showed that sufficient water did not move from the drainage lateral to the moles. Reasons for this may include: (a) Not enough water applied, (b) Not enough pressure head was available to force water from the drainage lateral to the moles or (c) hydraulic conductivity of the backfill was too low.

Having identified, from the field experiment, that the hydraulic connection between the lateral and mole was a potential problem, a bin model experiment was carried out in the hydraulic laboratory of the Agricultural Engineering Department. Two different backfill materials (gravel and tokomaru silt loam soil) were used with two mole positions in the bin relative to the drainage lateral. The flow rate and head losses through the system were measured for different applied pressure heads. The saturated hydraulic conductivity (K_{sat}) of the backfill materials were measured in the laboratory and were measured other relevant physical properties (bulk density, particle density and porosity).

The bin model experiment showed that flow rate through the system increases as the pressure head increases for both gravel and Tokomaru silt loam soil backfills. The flow rate with gravel backfill was eight times more than the flow rate with Tokomaru silt loam soil.

For a gravel backfill the efficiency of hydraulic connection between the lateral and moles must only be in the order of 2 to 3% for successful subirrigation. With a backfill of Tokomaru silt loam the efficiency of connection must be 10 to 20%. This may not be achieved in the field as the hydraulic conductivity of the backfill will be of a similar magnitude to the surrounding soil leading to significant water losses vertically downward as well as horizontally.

It is recommended that further field studies be conducted using gravel backfill. Further laboratory studies using other alternative backfill materials are also suggested.

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INTRODUCTION AND OBJECTIVES

1.1 The New Zealand Situation

Agricultural land drainage is of prime importance in New Zealand. It permits rapid removal of excess water during autumn, winter and spring when rainfall exceeds evapotranspiration demand. As a consequence of the use of drainage, large areas have become more productive and soil trafficability has been improved, particularly on heavy soils in areas such as the Waikato, Manawatu, and Southland. In New Zealand, subsurface tile drainage systems with mole channels are mostly used on dairy farms, on heavier soils. Commonly, pipe trenches are backfilled with the material that has been removed from them, which is a mixture of topsoil and subsoil. However, this is not necessarily the best treatment, and circumstances may require that some other material be introduced as a backfill.

In summer, most areas of New Zealand suffer from a water deficit, as evapotranspiration rates are high and rainfall is less consistent. Thus irrigation has become a common practice on arable farms and horticulture units. In recent years irrigation has become more common on dairy farms, many of which are situated on heavier soils which require drainage.

1.2 Subirrigation Systems

For centuries, throughout the world, agricultural producers have used underground drainage pipe systems to improve crop production by removing excess water from the soil profile within the root zone. Agricultural producers and scientists have recently shown underground drainage pipe systems can also be used to provide water to crops during rainfall deficit periods and improve production by reducing the deficit water stress. Drainage systems, that have the capability of removing the subsurface water when the root zone is too wet for optimum production, and of providing subsurface water to prevent the root zone from drying, are called **subirrigation systems.** They are recommended for flat humid areas where the installation of subsurface drainage systems is mandatory in any realistic farming enterprise. The transformation of a subsurface drainage system into a dual-purpose drainage/subirrigation systems has, so far, been confined to medium and coarse textured soils. This method, though practised in some parts of the U.S.A. and Canada, has not yet received general acceptance in New Zealand because of a lack of information about the installation and design criteria.

1.2.1 Principle of Operation

Subsurface drainage systems are used to maintain soil water in the root zone of a crop by managing the water table. The water table is lowered during the drainage season to provide more trafficable conditions and reduce root pruning caused by saturation of the root zone (see figure-1.1).

During subirrigation the water table is raised to maintain an adequate water supply in the root zone of the soil (see figure-1.2). The management of the water table in winter and summer must be finely tuned to ensure that an adequate balance and control is achieved.

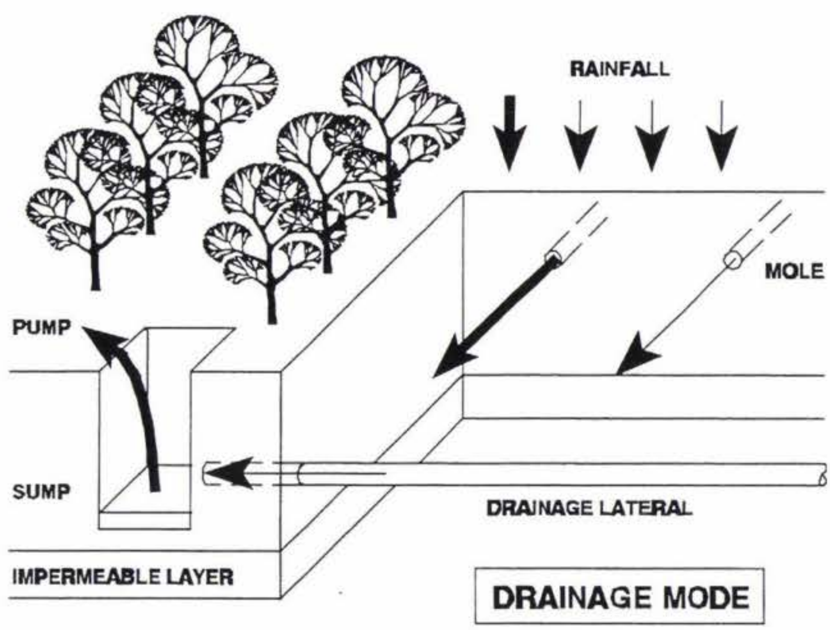

Figure-1.1: Subsurface drainage system working in drainage mode.

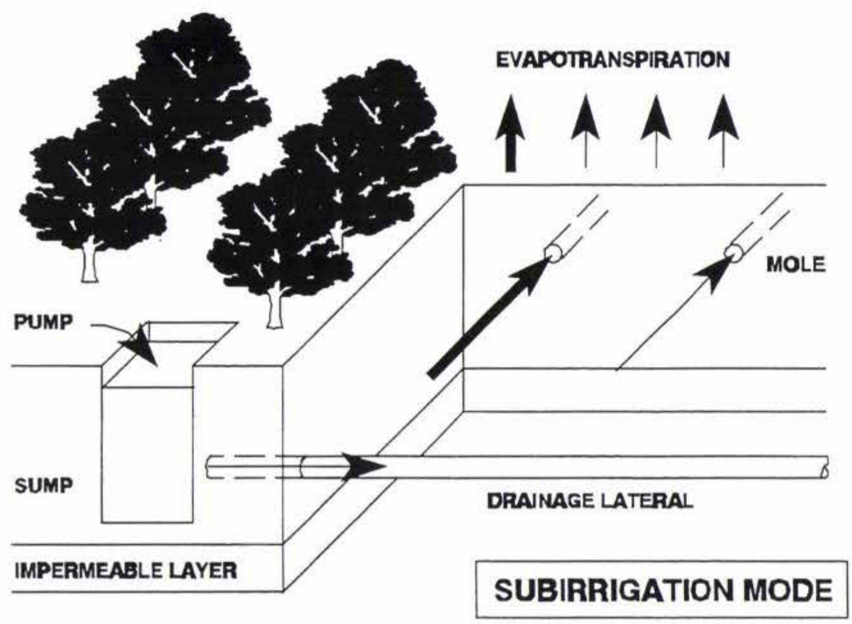

Figure-1.2: Subsurface drainage system working in subirrigation mode.

Water movement in a subirrigation system can be characterised by two processes; an active process and a passive process. In the active process, water moves horizontally (lateral movement) through the soil profile. This can be achieved by raising the water table, and providing a head of water which exerts pressure over a wide area of influence. The coarser the subsoil, the more effectively will water move through the soil profile, and more area can be irrigated. In the passive process, water moves vertically upward through the soil profile into the plant root-zone by capillary action. The rate of capillary action depends upon the soil texture, and surface water removed by evapotranspiration. Capillary rise is greatest in coarse textured soils.

1.2.2 Requirements for Subirrigation

Subirrigation systems are most suited to the areas with the following natural requirements (Fox et al., 1956):

(1) Humid areas
(2) Uniform flat topography
(3) Uniform subsoil
(4) A plentiful supply of water to maintain the artificially raised water table.
(5) Surface soil must be uniform texture, deep and highly permeable.
(6) Both the soil and water used for subirrigation must be relatively free of salts.
(7) There must be high water table or a **tight** or restricted layer in the soil profile upon which a perched or temporary water table can be developed at some depth below the normal root zone of the crops.

In addition the following are also necessary.

(8) Checks in the drains may be necessary for proper control of water table.
(9) Adjacent fields should be levelled.

1.2.3 Advantages of subirrigation

Subirrigation systems have the following advantages: (Fox et al., 1956):

(1) Can be used on soils having relatively low water holding capacities and high intake rate.

(2) Labour requirements are low.

(3) Weed seed are not carried over the surface of the land by irrigation water to germinate and grow. Thus, weed control is simpler under subirrigation.

(4) Does not interfere with tillage practices. Cultivation is not necessary for furrowing out or preparing the land to convey the water.

(5) Consumptive use of water is economical.

(6) High crop yields are possible.

(7) Irrigation may be accomplished without wetting the soil surface, thus permitting other farm operations such as pesticide applications or cultivations to be done simultaneously with irrigation.

1.2.4 Disadvantage of subirrigation

Disadvantages of subirrigation are as follows:

(1) Requires an unusual combination of natural conditions.

(2) Full cooperation of neighbours is required.

(3) Only water supplies of good quality should be used.

(4) Soils can become saline without careful control and adequate drainage. Drainage costs may be high.

(5) High fertility levels may be difficult to maintain.

(6) Choice of crops may be somewhat limited.

(7) Extra pumping costs may be required for irrigation due to having to raise water table in the sump to irrigate.

(8) Initial investment may be high.

1.3 Problem Statement

On most New Zealand dairy farms a reduction in milk production is observed in mid to late summer. This arises due to a reduction in pasture growth as a result of reduced soil moisture availability. In order to alleviate this drop off in production farmers must either supply cows with supplementary feed or boost pasture growth with irrigation. Sprinkler irrigation has become popular, particularly in Northland, where the local dairy company is encouraging its practice to boost milk yields and smooth out its milk processing requirements.

In many situations, dairy farms are situated on clay soils which have been mole drained to improve winter pasture production and prevent soil structure damage due to pugging. The Manawatu is a prime example but drainage is also extensively used in other areas such as the Waikato, and Southland. Where a drainage system is present on a dairy farm and the introduction of irrigation is being considered, the question arises as to whether it may be possible to use the drainage system to provide subirrigation rather than installing a conventional overhead sprinkler irrigation systems.

The problem statement is therefore "Would a subirrigation system be practical and economically more beneficial than a conventional irrigation system?"

Traditionally subirrigation has not been practised on clay soils due to their low permeability. Thus there is little or no information available on the feasibility of its use in these situations. To the best of my knowledge, subsurface tile drainage systems, with mole channels, in clay soils have not been tested in field or laboratory conditions anywhere.

1.4 Aim of the Study

The primary aim of this study was "To identify and investigate the hydraulic factors which may limit the use of subirrigation in clay soils".

The study was set out in two phases. The first phase was a field trial and the objectives of phase I were:

a) to identify whether subirrigation would work in a pilot scale study,
b) and if not, what appeared to be the major impediments.

Having identified that the connection between mole and lateral was a potential problem further investigations were carried out using a laboratory scale model.

The specific objectives of phase II were to evaluate the:

1) Effect of backfill material on the rate of flow through the system.
2) Effect of pressure head available on the rate of flow through the system.
3) Effect of the geometry of components on the rate of flow through the system.

1.5 Approach of Analysis

Approach for phase I

A subsurface tile drainage system, with mole channels, was used for this purpose. The objective was achieved by measuring the soil moisture content of the soil at different depths and places in the field using Time Domain Reflectometry (TDR).

Approach for phase II

These objectives were achieved by measuring the rate of flow through the system by changing the backfill material, pressure head available, and geometry of the system components, using a specially constructed soil bin in the laboratory.

1.6 Outline of the Thesis

In chapter 2 the relevant literature on drainage and subirrigation is reviewed. The method, results and discussion of the field experiment are described in chapter 3. In chapter 4 the construction of the soil bin model in the laboratory is described and determination of the head flow relationships for various arrangements of backfill and mole position is discussed. Experiments to measure the saturated hydraulic conductivity of possible backfill materials are also presented in chapter 4. In chapter 5 the overall results obtained from the field experiment and laboratory experiment are discussed. Chapter 6 contains the conclusions and recommendations for future research. Determination of relevant physical characteristics of backfill materials are presented in the appendices.

Chapter 2

LITERATURE REVIEW

In a review of the design of subirrigation systems, Fox et al. (1956), reported on the design features, requirements, advantages, disadvantages of subirrigation. They defined subirrigation as "a method of irrigation where the water supply for the crop comes from underneath the surface of land. It depends on creating an artificial water table and maintaining it at some predetermined depth below the ground surface. Moisture then reaches the plants roots through capillary movement upward. This method requires that the depth to the water be subjected to rigid control; otherwise, the depth can become too small or too great and either retard growth or stop it completely."

2.1 Design Features and Criteria for Subirrigation System

As a basis for design of a subirrigation system, reported by Fox et al. (1956), it is necessary to determine the substrata conditions by means of test boring. These boring should be tied to common datums and the boring logs and sample analyzed to obtained the following information : (a) the topography of the restricting layer (b) the contours of the natural water table, and (c) the hydraulic conductivity of the various strata above the restricting layer.

Israelsen and Vaughan (1962) have stated that success in irrigation through underground conduits depends upon soil conditions that permits free lateral movement of water, rapid capillary movement in the root zone, and a restricted downward movement in the subsoil. An unlined distribution system has the additional requirement that soil conditions permit the formation of a continuously stable mole.

There are two basic design criteria for subirrigation-drainage systems. First, the system must be capable of moving water to the root zone of the crop at a rate sufficient to supply the plant requirements during peak use periods, and second the system must be capable of draining excess water from the soil to prevent crop damage due to poor aeration. Because of the high water tables maintained with this type of irrigation, and of occasional periods of heavy rainfall during the irrigation seasons, it is extremely important to provide adequate drainage in these water management systems. While drainage requirements of crops are difficult to define quantitatively, adequate drainage in humid regions can probably best be provided by designing for a given rate of water-table drawdown (Schwab et al., 1966.). Although Childs (1960) and others have shown that the assumption of a constant drainable porosity can lead to significant errors, the concept can be used to predict water table drawdown with an accuracy which is probably sufficient for design purposes.

Tang and Skaggs (1980) showed that the effect of deeper drains increases with the hydraulic conductivity and thickness of the bottom layer. They concluded that, where possible, drains should be placed at the interface or in the top of the high conductivity layer.

Skaggs (1981) stated that subsurface drainage systems can sometimes be designed to perform both drainage and irrigation functions. In such systems, subirrigation is practised by submerging the drainage outlets so that the water table in the field is raised to a position that will supply water to the growing crop. During periods of high rainfall the outlet water level may be lowered to facilitate rapid drainage and prevent crop damage due to excessive soil water. He mentioned that, if the system is properly designed, it may be possible to operate the system continuously without changing the outlet water level except for infrequent, large storm events. This combination subirrigation and drainage system has many advantages over alternative water management methods for certain soils and conditions.

2.1.1 Critical factor in the design of subirrigation systems

According to Skaggs (1981), the most critical factor in the design of a subirrigation system is the determination of the drain spacing and depth necessary to supply water during dry periods and removes excess water during wet periods. The required drain spacing depends upon soil parameters such as hydraulic conductivity, profile depth and water table depth that should be maintained during the growing season. The optimum water table depth depends again on soil properties, the crop to be grown and climatological factors, which are a function of location. Therefore, soil, crop and climatological factors should all be considered for the design of subirrigation system. He also stated that water moves laterally into the profile by saturated flow; then vertically from the water table by unsaturated flow to the root zone or to the surface where it leaves the profile as ET.

2.1.2 Lateral Spacing

Skaggs et al. (1973) conducted a field experiments on a subirrigation drainage system to determine the applicability of four drain spacing equations for a shallow sandy loam soil with tile drains spaced at three intervals. The water table drawdown following subirrigation and rainfall events were measured for drain spacing of 7.5 m, 15 m and 30 m. Drains spacings were calculated using four theoretical equations and were compared to the actual spacings. The results of the experiments showed that for soils with shallow water tables, the application of rainfall will results in a sharp rise of the water table elevation. The total rise and response time of the water table will depend on its initial depth, the rate and amount of rainfall, and the soil hydraulic properties. When the effective hydraulic conductivities were determined from water table drawdown measurements for the 15 m spacing, the order of preference of four equations tested was Hammad (1962), Bouwer and Van Schilfgaarde (1963), Van Schilfgaarde (1970), and Glover (Dumm, 1954). However, it was concluded that if the conductivity is determined from soil cores or other independent measurements, the Hammad equation will not give a reliable prediction of the drain spacing for shallow soils. In either case, the reliability of the other three equations could probably be improved for shallow soils if a better procedure for compensating for convergence near the drain tube were available. Greater accuracy can be obtained in all of the above equations by evaluating the drainable porosity based on the initial and final water table depths rather than using a constant drainable porosity value.

Doty and Parsons (1978) reported that a "water mound" can be built by controlling the head above the drain outlet, and they presented the approximate shape of the mound above three tile spacings, the water and head requirements, and the yield responses to the tile depths and spacings. They designed and instrumented a controlled and reversible drainage (CaRD) system which was operated for 2 years, when the rainfall was below normal in 1975 and above normal in 1976.

Doty et al. (1975) reported satisfactory results from drain line spacing 40 m or more in sandy soils. Doty and Parsons (1978) studied the irrigation water requirements for subirrigation-drainage system, and showed that tile spacing had little effect on crop yield. In 1977, the selected plots yields were 3.2, 3.4, and 3.2 tons/ha for 8, 16, and 32 m spacings respectively.

Skaggs (1981) identified and discussed the approximate methods for calculating the position and shape of the water table during steady state subirrigation. Transient conditions were also considered. Methods were presented for predicting, in terms of certain design parameters, the time required to raise the water table for certain initial and boundary conditions. Results of analyses for steady state, transient and continuous operation of several alternative designs for both conventional drainage and subirrigation drainage systems were presented. The results showed that both subirrigation and drainage requirements could be satisfied with an 18 m drain spacing, while a 25 m spacing would be satisfactory for conventional drainage alone.

2.2 Life of Mole Drains

In some cases, water is introduced into the soil profile through the drains or "mole drains". The use of the tile drains for this purpose is limited because of high installation costs. Also maintenance costs may be high because of the tendency for such drains to silt up. Mole drains can be used successfully in certain organic soils under special conditions such as exist in the Florida Everglades. Mole drains are formed by drawing 150 mm bullet shaped cylinders through the soil. Under Florida Everglade conditions, the resulting hole is about 113 mm in diameter and the effective life of the mole drains is 5 to 8 years, as reported by Stephen (1955).

Sommerfieldt (1983) studied the effects of soil moisture and texture on the force required to install mole drains and the stability of the drains after installation in the laboratory, and the result explained the differences in mole drain performance at two field sites in southern Alberta. He concluded that for effective durable drains, the soil should contain sufficient clay to be cohesive and plastic (texture; clay loam or finer) and the moisture content should be at or above the plastic limits (50% of the field capacity) during installation. The force required to install the drains depended on both texture and moisture. Below the plastic limit, less force was required in the loam than in the fine textured soils, while at moisture level above the plastic limits more force was required in the loam than in the fine textured soils. He also concluded that failure of the moles to function as drains in a clay loam at one field location and to function in a clay loam at another location is attributed to their respective soil moisture content at time of installing the moles.

Nicholson (1946) reported that the effective life of mole drains varies from days to decades, and averages 10-15 years. Moles often fail to function as drains. Childs (1942) indicated that unsuitable soil conditions such as sand pockets and dry soil at the time of moling are causes for failure. He recognized organic matter and clay as factors that add required stability to the soil, yet some soils with 60% clay content were unstable.

Hobbs and Laliberte (1967) in a study of shallow moles for irrigation, reported that the soil tended to shatter rather than compact when the soil moisture content was below 50% of the available soil moisture range. Raadsma (1974) reported that the soil in which the mole is placed should contain sufficient moisture to be cohesive and plastic to allow the channel to be shaped without cracking or sealing of the channel walls. He did not identify what the minimum moisture content should be.

2.3 Locations of the subirrigation practice

In both humid and semiarid areas, there are number of locations in the United States where subirrigation is practised. Baker (1982) reported that the most extensive systems are found in Netherlands, and in New Zealand the Waikato peats have been controlled using subirrigation techniques. Hagan et al. (1967) have reported the use and development of subirrigation systems in humid, semi arid, and arid regions of the world.

2.3.1 Subirrigation in humid regions

Some of the more extensive subirrigation systems in humid regions of the world are found in the Netherlands. The climate, topography and soils of the Zuiderzee Polders necessitates that drainage facilities be utilized for sustained crop production. However, in summer when evaporation exceeds rainfall, irrigation is a supplementary expedient on coarser textured soils. Soil water deficiencies during periods of insufficient or too intermittent rainfall often result in wilting of the crop or reduce production. In the USA, Florida has two extensive areas where conditions are suitable for subirrigation: The Everglades and the Flatwoods of the Coastal Plain. Until recent years, these lands were either too wet or too dry for good crop production. Water table control through subirrigation and drainage has increased production several hundred percent (Stephen, 1955).

In certain areas of Great Lakes states of Michigan, Minnesota, Indiana, and Ohio, USA a practice of "controlled drainage" is used which in effect is a subirrigation practice. In this high rainfall area, the proper water table elevation is maintained by control structures in the drainage channels. Ordinarily, additional irrigation water is not used. Salinization of soils, an ever present danger where subirrigation is practised in arid and semi-arid regions, does not occur under climatic and drainage conditions in the Netherlands or in humid regions as a whole. Any tendency to salinization resulting from the upward movement of the water during the growing season is entirely overcome by the downward movement of the water during winter or noncropped season (Kalisvaart, 1958).

2.3.2 Developing Subirrigation in humid regions

Basic for design of good subirrigation system are surveys of soils, hydrology, and topography. It must be possible to decide from the surveys if the soils need irrigation and if they are suitable for it. For this decision the system design features, as described in section 2.1, must be kept in mind.

2.3.3 Subirrigation in arid and semiarid regions

In arid areas of the world there is only limited practice of subirrigation and this has been developed largely through trial and error. There are number of locations in the USA where subirrigation is practised in semiarid and arid regions. Some of the most notable are found in California, Idaho, Colorado, Utah and Wyoming. Approximately

160,000 acres of low-lying delta lands and islands are subirrigated successfully in the Sacramento-San Joaquin Delta of California. Before being reclaimed by diking, these tracts were flooded each year by high waters from the rivers. By diking and installing a drainage system, it is possible to maintain the water table at the desired elevation in the peats soils either by pumping from the drains to river or discharging water by gravity from the river to the feeder ditches as required. On the upper Snake River in Idaho there is an area of some 28,000 acres known as the Egin Bench which is sub-irrigated. The land slopes uniformly at about 0.2% and the soils are extremely permeable overlying impervious lava rock. A description of the area is given by Clinton (1948).

The San Luis Valley of Colorado is one of the most extensive sub-irrigated area in the western USA containing 135,000 acres. This area, part of which is on the headwaters of the Rio Grande River, has surface soils that are slightly less permeable than many other subirrigated tracts. Because of the salts in the water supplies used, special practices have been developed to maintain a proper salt balance in the surface soils and to break up the hard salt lens that forms at the point where the ground water table is commonly held.

Along the Platte River in Nebraska, USA are several areas where the natural water table greatly favours the production of alfalfa (Medicago sativa). Many fields in this area are surface irrigated when the alfalfa needs reseeding. On the Eden Valley irrigation project in Wyoming, USA an area of sandy land within one segment of the project has been developed for subirrigation. The high intake rate and low water holding capacity of the soil and the favourable geological and topographic conditions provided the necessary ingredients for a successful subirrigation system (Fox et al., 1956).

2.3.4 Developing Subirrigation in arid and semiarid regions

The one drawback pertaining to arid and semiarid regions is the danger of soil salinization where salts occur either in the soil or irrigation water; hence provision must be made for their removal if the practice of subirrigation is to succeed. Salinization of a soil profile cropped to alfalfa on the Huntley Reclamation project of Wyoming is well illustrated by Campbell et al. (1960). The data showed that "no irrigation treatment" (Subirrigation only) resulted in the increased accumulation of excess salts below 2 ft by the upward movement of soluble salts in the ground water over a 4-year period compared to treatment receiving six irrigations annually, where essentially no accumulation occurred. The salts accumulated at those depths where roots absorbed water for the transpiration, leaving the salt behind. Maximum concentration of salt as measured by the conductivity of the saturated extract was about to 6 to 7 mmhos/cm. In cases like this, it would be necessary to provide drainage and to leach periodically for sustained production of salt sensitive crops.

2.4 Economic, Production and Environmental Impacts of Subirrigation and Controlled Drainage

Broughton (1995) discussed the economic, production and environmental impacts of subirrigation. Subsurface irrigation has resulted in average increase in maize yields of 29% over the six years, 1982 to 1988, in Richelieu County, Quebec, Canada (Drouet, 1989). Maize yield increases in individual years ranged from 12 to 48%. Galganov (1991) found average yield increases of soybean due to subirrigation of approximately 28% in experiments conducted in 1988, 1989 and 1990. Similar yield increases are reported by Evans et al. (1988) for North Carolina.

Whether yield increases of this magnitude provide net economic benefits in any locality depends on the costs of supplying the irrigation water and managing the irrigation systems.

2.4.1 Economic and Production Impacts

The crop production impacts of controlled drainage and subirrigation are primarily effects of increased yield in dry years, or more stability in crop yield from year to year (Rashid-Noah et al., 1987; Volp, 1989). With water management by drainage and subirrigation farmers may achieve more consistent crop yield from their most productive land, so they could make the environmentally desirable decisions of removing the erodible and droughty soils from cultivation to forest and grass crops. This includes soil strips along drainage ditches. Subirrigation and controlled drainage require some management time. This time will likely be less than the time which would be required to cultivate a larger acreage to achieve the same total crop production.

Subirrigation and controlled drainage have economic impacts for society as a whole. By eliminating a major source of crop yield variation between wet, dry and normal years subirrigation/drainage helps to stabilize food availability and reduce the cost of crop insurance. Crop insurance may help to stabilize a farmer's income, but it does not produce food. While subirrigation/drainage will reduce the need for crop insurance it will not remove the need for governmental assistance for relief from disaster such as major floods, hurricanes, tornados, typhoons and crop killing frosts.

Galganov (1991) found that subirrigation caused increased weed growth in soybeans. It appears that more research is needed to find satisfactory methods of weed control in subirrigated crops. Israelsen (1954), has given an account of subirrigation in the Lewiston area in Cache Valley, Utah, located between the Bear and Cub Rivers, comprises a flat table land of deep permeable soils underlain by about 15 feet of clay. Original attempts to irrigate these soils by surface methods resulted in excessive water logging and concentration of salts in the surface soils over parts of the bench. The construction of large open-drains improved, land levelling practices, and the development of better control practices for maintaining the water table at the correct level have made crop production profitable.

There are approximately 3 million acres of minerals and organic soils in the lower coastal plains of North Carolina. These soils, which are common along the southeastern Atlantic coast from Maryland to Florida, have flat slopes, shallow water table, and are usually poorly drained. When properly drained and managed, the soils are very productive and have tremendous capacity for producing food and fibre. For many of the soils in this area, subirrigation through subsurface drains or ditches appears to be feasible, and is attractive from both the standpoint of crop production and efficient water management (Schwab et al., 1966).

Carter et al. (1970) reported favourable yield response of sugar cane to controlled water tables. Lal and Patrick (1965) reported that higher yields were recorded in Louisiana during years when the early part of the cane's growing season was relatively dry. They concluded that cane yields in Louisiana could be increased more by drainage than by irrigation. The relationship of water table to yield of many field crops has been investigated. Doty et al. (1975) found that average yields of field corn increased by 0.5 t/ha for each additional day the water table was maintained at less than 100 cm from the surface in a sandy Coastal Plains soil. Campbell and Seaborne (1972) and many others have shown the best crop response when the water table was maintained between 60 and 100 cm from the surface in lysimeters filled with sandy soils.

In a field experiment, Follet et al. (1974) reported that yields were maximum in plots over a shallow water table, 60 to 90 cm below the surface. Irrigation of the crops over the shallow water table resulted in no increase in yield. These findings showed that controlling the water table could possibly increase the crop production in the Coastal Plains area. According to the U.S. Soil Conservation Services, an estimated 2 million ha of sandy and sandy loam soils in the Southern Coastal Plains have a seasonal high water table that can be controlled. Reicosky et al. (1976) showed that sweet corn produced better yields on chiselled soil when the water table came to within 0.8 m below the surface.

Baker (1982) carried out subsurface irrigation trials in the Battersea area sited on Otukura Silt Loam, and concluded that the pasture cut weights and piezometric readings confirm that subirrigation will give higher pasture dry matter yields compared with non irrigated pasture on similar soils and has the potential to give at least equivalent dry matter yields from the pasture as that of spray irrigated pasture under ideal conditions.

Nemon et al. (1987) conducted an experiment in 1982 and 1983 on flat sandy soils in southern Quebec to study the feasibility of subsurface irrigation in this region. The field experiment was designed on 10ha with two treatments and eight replicates. These treatments consisted of irrigated and nonirrigated maize plots. They found that subirrigation raised the water table satisfactorily to a predicted water table position which resulted in adequate water supply to the crop root zone, and the subsurface irrigation treatment produced grain maize yield twice as high as the nonirrigated treatment.

The cost of separate irrigation and drainage systems can become prohibitive. Worm et al. (1982) reported on the installation, in South Carolina of a complete 22-ha controlled drainage subirrigation system including a deep well at a cost of $939/ha compared to 50 ha centre pivot system at a cost of $1410/ha. They also made an economic evaluation and found that " for the cost and yields observed in this study, the subirrigation-drainage system is more a profitable investment than the centre pivot system." Worm et al. (1982) measured the energy for a centre pivot and subirrigation-drainage system, both pumping from a well, and found that the annual energy cost was about 1.6 times more for the high pressure centre pivot system than for the subirrigation-drainage system in 1980 and 1981.

2.4.2 Environmental Impacts

As indicated by Gilliam and Skaggs (1986) subirrigation/controlled drainage provides environmental benefits to farmers and society. Environmental benefits include:

1. Achieving more complete use of fertilizers by crops.
2. Reduce movement of fertilizer and soil into downstream water bodies.
3. Reducing the quantities of herbicides and pesticides which move off from land into river systems.
4. Stabilizing crop production.
5. Growing more food on good quality flat land and removing erodible land from cultivation to forest, grassland, wildlife habitat and recreational uses.

2.5 Over Drainage Problem

Controlled water table levels maintained close enough to the soil surface will allow the plant roots to withdraw water from the capillary fringe above the water table and reduce plant-water stress during droughts. As reported by Doty (1973) the farmers, scientists, and the water management engineers have become concerned with over drainage, particulary in sandy soils. In sandy soils of Carolina Bays, soybean yield was two times higher for surface drainage than subsurface drainage. Although extensive drainage is needed in the Florida Everglades for flood control, over-drainage can cause drought which will affect land, wildlife, and towns.

Skaggs (1977) showed that over drainage could occur in Wagram soils (Arenic Paleudults), and stated that, on the average, "a drain spacing of 43 m would result in 34 or more dry days in 1 year out of 5."

2.6 Water Table Management Models

Based on the procedures described by Kirkham (1958) and Van Beer (1976), Skaggs (1978b) developed a computer simulation model called, DRAINMOD, to predict the water table position and soil water content on a day-to-day basis for a long period of climatological record. The use of DRAINMOD for evaluating drainage and subirrigation systems has been described in several papers (Skaggs, 1977; 1978b). Hiller (1969) advanced a method called, Stress day index (SDI), to evaluate the quality of drainage during the growing season, and Ravelo et al. (1978) used this method with DRAINMOD.

Skaggs (1982) tested DRAINMOD using the data from field experiments at three North Carolina locations over a 5-year duration. Based on the results of study, he concluded that DRAINMOD can be used to predict the effect of drainage system design on water table elevations.

Mostaghimi et al. (1985) used DRAINMOD to investigate the suitability of controlled-drainage/subirrigation of corn on claypan soils of the Mid-west, USA which have very low permeability and severely limit root development and water penetration. They used several years of crop, soil and weather data on a claypan soil in Illinois, and simulated various drain spacing and depth combinations for both good and poor surface drainage.

Fouss (1985) described a conceptual method to automatically operate subirrigation-drainage systems. He developed a dynamic simulation model for a "total" soil water management system including an operational-control subroutine, using the simulation model DRAINMOD.

Memon et al. (1986) proposed utilizing the Matrix Flux Potential (MFLP) model for estimating the steady unsaturated flow from a water table and compared this method with the numerical and analytical solutions to the one dimensional, unsaturated flow equation. They concluded that the MFLP model agreed very closely with the analytical and numerical solutions, as well as with laboratory measurements and required less computational time. The MFLP model was suggested for use in soil-water modelling and the design of subirrigation systems.

Tabrizi et al. (1990) developed a water table predicting model by using the NARMAX Modelling (NonLinear Auto Regressive Moving Average model with eXogenous input). They described the identification of both linear and non-linear difference equation models to represent the difference between the three inputs (rainfall, potential evaporation, and ditch water elevation) and the output (water table elevation). They found that the predicted and observed results were comparable to that obtained with the physically based DRAINMOD model.

Workman and Skaggs (1991) evaluated the PREFELO model, used to simulate soil evaporation, plant transpiration, subsurface drainage, subirrigation, infiltration and preferential flow and surface runoff by comparing the simulated midpoint water table depths from Aurora, North Carolina. They also compared the model to simulations by the water management simulation model, DRAINMOD and concluded that there was good agreement between simulated and measured water table depths. Bengtson et al. (1993) developed a Fluctuating Water Table Model (FWTMOD) as a simplified method to predict the daily changes in the water table depth for a subirrigation system.

2.7 Water and Energy Requirements for Surface and Subsurface Irrigation Systems

Massey et al. (1983) designed a subirrigation and sprinkler systems using DRAINMOD (Skaggs, 1978) for three North Carolina soils. The results from their study showed that subirrigation required 4 to 8 cm more water than the sprinkler irrigation when seepage losses and efficiencies were taken into account. Subirrigation requires only 9 and 6 percent of the energy required for sprinkler irrigation systems operated at 340 and 690 kPa (50 and 100 psi), respectively. They found that subirrigation offers good potential for energy savings because, as contrasted to sprinkler irrigation, it does not require delivery of water under pressure. Strickland et al. (1981) found that subirrigation of corn during 1980 required about 70 percent as much energy as a centre pivot system near Orangeburg, South Carolina.

Strickland et al. (1981) compared the water and energy requirements of the subirrigation and centre pivot irrigation. They reported that the total water applied (rainfall and irrigation) to the subirrigation site was approximately 7 cm greater than was applied to the centre pivot site. They showed that subirrigation required only 25% of the energy used by the centre pivot system. Massey et al. (1983) reported that the energy requirements for the sprinkler irrigation ranged from 5 to 12 times more than the subirrigation/drainage system when the water was pumped from 2m below the surface and applied at the pressure of 340 kPa. Energy requirements for a centre pivot ranged from 0.6 to 2.0 times that of controlled drainage and subirrigation system when the water was pumped from a 80 m deep well.

2.8 Effect of Gravel Backfill on Flow Rate

Fausey et al. (1986) conducted a study on a lakebed (Hoytville silty clay loam) soil and measured the drain flow rates from subsurface drains having gravel backfill and mole channels installed above the drain pipes to enhance profile drainage and water movement to the drains and concluded that, the gravel backfill increased the peak flow rates and that the mole channels did not improve water movement to the drains. Saturated hydraulic conductivity measurements revealed a soil layer at the 0.3 to 0.5 m depth having low hydraulic conductivity that restricted downward movement of water.

2.9 Effect of Fabric Wrap Envelope and Drain Slope

The USDA-SCS (1973) recommended that drains be installed on a slope to increase the rate of flow and promote self cleaning as clay and silt sediments carried from the drains. Drain envelopes are also recommended for some soils. Their functions are two fold: (1) to stabilize the soil and inhibit particle movement to the drain, and (2) to provide a highly permeable zone to reduce head losses near the drain. Fabric wrap materials are thought to bridge or cause soil particle to bridge over the corrugation, increasing the effective area over the drain.

Davenport and Skaggs (1990) conducted a field study to determine the effect of fabric wrap envelope and drain slope on the performance of a combination drainage and subirrigation system. The experiment consisted of 32, 102mm diameter drain tubes in two replications of four treatments of 0 and 0.2% slope, with and without fabric wrap envelopes. Flow rates and water table elevations were measured continuously. Results of the study showed that the effect of slope and envelope on drainage and subirrigation varied somewhat depending on field locations. The fabric wrap envelope was effective in increasing the subirrigation rates, but effectiveness decreased with time. Water table response to drainage was also more rapid for the envelope covered drains, in most cases, as indicated by more rapid drawdown after rainfall or subirrigation. Entry resistance was less for drains that had both envelope and slope than for any other treatment. However, resistance changed with time during the four year experiment and head losses near the drains were high, for all cases, for the sandy loam soil. Based on results from subirrigation and drainage, it was concluded that a fabric wrap envelope improved performance of the drains for sandy loam soils. The effect of drain slope was not clear from the experimental data.

2.10 Effect of Hydraulic Conductivity on Yield for Subirrigation System

A simulation study was conducted by Parsons et al. (1990), for a typical drainage system on a Rains sandy loam soil in North Carolina. Simulations were conducted for a range of saturated hydraulic conductivities and to simulate the conventional drainage, controlled drainage, and subirrigation for the 1982-1986 growing seasons, using the water management model WATRCOM (Parson, 1987). The simulations showed that for certain saturated hydraulic conductivities, controlled drainage provides significant yield increases over conventional drainage while reducing the outflow of drainage water from the site. During the dry years controlled drainage increased relative yields over conventional drainage. However, predicted yields were less than those obtained with subirrigation because of drought stresses.

2.11 Head Losses in Subirrigation System

Head losses occur when water flows in a drainage/subirrigation system (Von Hoyningen Huene, 1984). Skaggs (1978) experimentally determined that head losses in a subsurface drainage system occur due to the resistance offered by the drain openings and the convergence of flow lines near drains.

Bournival et al. (1987) measured the head losses in a subirrigation system on a sandy loam soil in south Quebec, including entrance head loss in drain pipes, exit head loss from perforations in the pipe and the divergence head loss in the soil around drain pipes. The head losses were found to be a function of the flow rate in the subirrigation system. They concluded that to overcome the head losses of a subirrigation system in loamy sand soils in Quebec, water level in the control chamber should be maintained at least 55 cm higher than the desired field water table level. The exit head loss from perforations in pipes was found to be the most significant head loss in the subirrigation system. It was 75% of the total head loss in the subirrigation system. It follows that future field and laboratory measurements should be made to determine the exit head loss for different drainage pipes, with and without drain envelopes. They concluded that measurements of head loss in the subirrigation system has a great practical significance because it determines the water level to be maintained in the control chamber. In some cases, the water level in the control chamber might have to be maintained at an elevation higher than the soil surface to provide the desirable head above drainage pipes.

Skaggs (1991) reported that conventional theory for predicting water table response to drainage and subirrigation generally assumes that the water table elevation directly over the drain is equal to the pressure head in the drain. This is contrary to the field measurements which show head losses near the drain may be significant. Solutions of his study showed that head losses near the drain make up a relatively large percentage of the total head losses for the subirrigation with narrow drain spacings. As a percentage of the total, the radial head loss near the drain increases with increasing hydraulic conductivity and profile depth, and with decreasing drain spacing. This partially explains differences between relatively flat water table profiles measured in the field and steeper profiles predicted by the previous theory. Results from his study showed that use of the conventional "Hooghoudt equivalent depth" method of correcting for convergence near the drain may lead to significant errors in predicted water table elevations and flow rates for the subirrigation. Finally, the methods presented provides a mean of correcting for convergence head losses when the drain rests on, or is very close to, the impermeable layer.

2.12 Subirrigation in Fine Textured Soils

Carter et al. (1983) tested a water management system on silty clay and silt loam soils in Louisiana, consisting of subsurface drained, bordered plots which were connected by pipe to a water level control sump. They concluded from these results that the system could be used effectively to manipulate the water table in the soil tested. The test results reported in this paper showed that the water management system concept works in silt loam soil and silty clay; it removes water from the soil profile during wet periods and adds water to the soil profile during droughts. They also reported that, the key to obtain maximum benefits from this system, is management - knowing when to activate the system for drainage and for subirrigation.

Rauch and Nelson (1984) investigated the benefits of water management systems on claypan soils of Missouri. They reported that subirrigation improved alfalfa yield by 2.5 times over that of non-irrigated plots. However, the slow permeability of the claypan layer restricted the lateral water flow in the soil and subirrigation moved less than 2 meters away from the trench. It should be noted that they used a 15 m spacing between the drains used for subirrigation and that their results were based on only one year of data collection.

Cyr and Prashar (1985), investigated the possible changes in soil structure as caused by subirrigation in clay and clay-loam soils and also investigated their effects on the performance of a subsurface drainage system in Quebec city (Canada), where subirrigation systems have been recommended only on medium or coarse-textured soils. They concluded that there is a significant difference in the rates of infiltration at the soil surface and percolation in the soil profile between drainage and subirrigation on a clay soil. To what extent it really matters in the design of a subirrigation system is unclear. They also concluded that only a field scale study will enable us to better understand the soil physics during subirrigation and till that time, the design of subirrigation systems on clay soils should be done with caution.

Visser (1991) set out a field experiment in the Ysselmeer polder project in 1964 on a loamy to clayey soil in the east Flavoland polder. He studied the relationship between subirrigation levels of 0.40, 0.70, 1.00 and 1.30m below soil surface and the soil structure, soil compaction, hydrological conductivity in the drain trench, nitrogen management, root development, growth of grass and growth & production of apple trees during a period of 12 years. His results showed that optimum values were different for each subsequent parameter. Soil compaction was worse at high ground water levels, nitrogen management was maximal at 1.30m ground water level and soil subsidence and crack formation were maximal at the deeper ground water levels. The overall conclusion of his study was that subirrigation in a clay soil is possible. However, profits will highly depend on climate and type of crop.

Chapter 3

FIELD EXPERIMENT

This chapter describes the site layout, climate, soil type, and methods used for a field experiment designed to identify whether subirrigation would work on a clay soil and if not what were the major impediments.

3.1 Objectives

The objectives of this field experiment were:

a) to identify whether subirrigation would work in a pilot scale study,

b) and if not, what appeared to be the major impediments.

3.2 Description of Site

The site on which this work was carried was relatively flat terrace land situated on the Massey University No. 4 Dairy Farm in the Soil Science Department's experimental drainage plots. The site had not had any recent fertilizer application, had been under perennial ryegrass and white clover pasture for several years, and been periodically grazed by sheep.

3.2.1 Soil type

The soil in the plot area was classified as Tokomaru silt loam soil. It is the one of the most important soils in the New Zealand sequence. In New Zealand the soil is classified as a moderately gleyed, originally forest melanized, central yellow-grey earth. In the Federal Republic of Germany it would rank as a strongly developed Pseudogley, in the World Soil Map probably as a planosol, while in U.S.D.A. Comprehensive System it would be classed as an Alfisol (Fragiaqualf) (Pollok, 1975). The morphological properties of the soil described by Pollok (1975) show that the soil consists of 30 cm of relatively well structured silt loam A horizon, a compact clay loam B horizon to 70 cm, and a very compact silt loam fragipan below that. The compact nature of the B horizon was also observed by Scotter et al. (1979a). The existence of the fragipan impedes the movement of percolating water, and as a result a perched water table normally occurs during winter and spring, causing waterlogging. The soil profile is depicted in figure (3.1). Detailed information on the soil site and profile description in available in Pollok (1975). Information relevant to this study is summarized below:

1. The medium textured upper horizons. Slight yellowish red rusting around plant roots in the Ah1 and Ah2 horizons develops into dark reddish brown and dusky red reticulate mottling in the ABg horizon. Slightly imperfect internal drainage and moist. Ironstone concretions may be present.
2. The strongly developed, heavy textured, highly mottled pseudogley horizon, Btg. In the natural state this becomes very wet and sticky in winter and sets hard and dry in summer. Old bush roots are still clearly in evidence and soft ironstone concretions are in the process of developing out of the strong brown mottled areas. Imperfect internal drainage; moist and slightly uneven boundary.
3. The classic fragipan lying beneath the pseudogley horizon, lighter in texture, but setting extremely hard and compact in summer and only wetting up

slowly in winter. Impressive coarse polygonal structures, separated by clearly defined cracks filled with pale-grey soil, are developed in the fragipan. The only escape for water, which perches above the fragipan in winter-time, is down the soil-filled cracks. The saturated soil in the cracks then has the consistency of a colloidal gel.

4. The gradual loss of compaction as the fragipan gives way to the 1 Cwg1 horizon beneath.

Tokomaru silt loam soils are poorly drained soils with high water tables for long periods during most years. Surface drainage is also poor due to flat topography (less than 1% slope). The impermeable layer (Fragipan) underlies the entire area and seals the artesian water in the aquifer system. This impeding layer, which is located about 1.00 - 1.5m below the soil surface also prevents percolation. Existence of this impeding layer along with the flat topography makes the study site suitable for subirrigation.

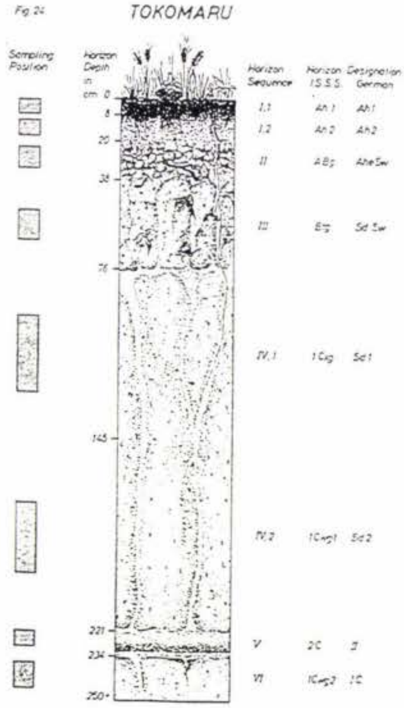

Figure-3.1: A drawing showing the profile of tokomaru silt loam soil (Pollok, 1975).

3.2.2 Climate

The mean temperature for the month of February and March, when the experiment was carried out, was 17.6 °C and 16.4 °C respectively. The total rainfall and pan evapotranspiration *(ET)* were 160 mm and 135 mm respectively.

The mean annual rainfall at the site is 995 millimetres. This is relatively evenly distributed over the winter months, but the distribution over the spring, summer and autumn periods is subject to fluctuation, with occasional severe droughts developing in summer, early autumn, and in late spring as shown in the figure (3.2). [Data taken from New Zealand Met Service Misc publication 177, 1980]. The mean annual evapotranspiration is 1069 millimetres. The mean annual temperature is 12.9 °C.

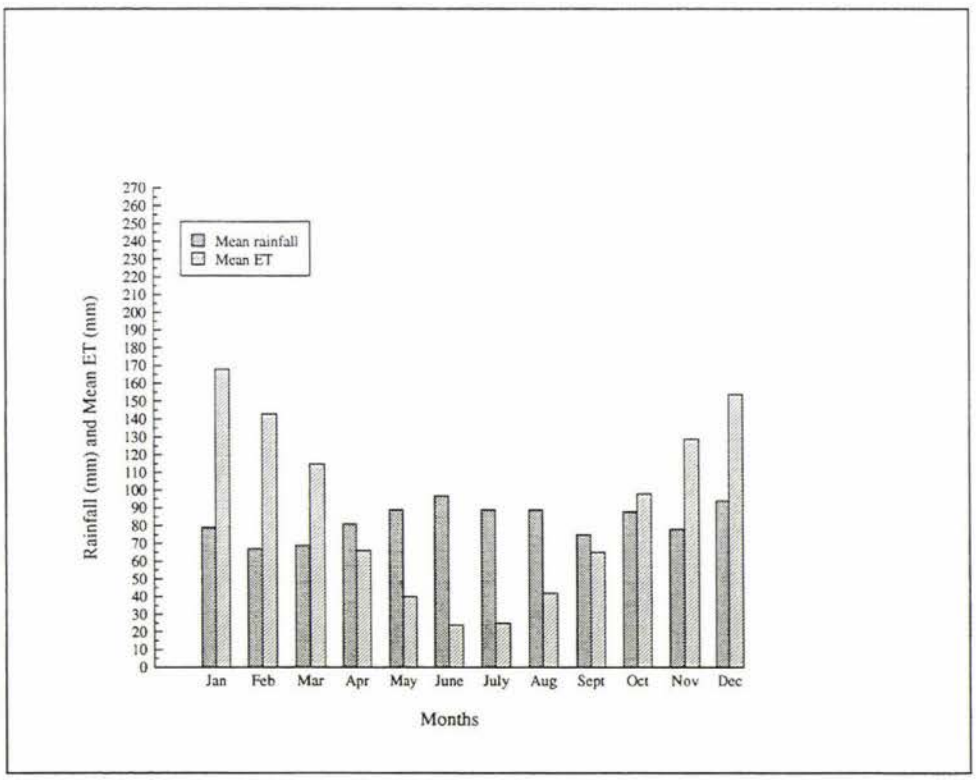

Figure-3.2: A graph showing the long term rainfall and evapotranspiration pattern in Palmerston North.

It is clear from figure (3.2) that the mean evapotranspiration *(ET)* is high in summer, early autumn, and in late spring. Thus there is deficit and irrigation is required during this period to maintain potential rates of evapotranspiration.

3.2.3 Existing drainage system

The test site was divided into two plots each having a subsurface tile drainage system with mole drains. To alleviate water logging problems, mole drains, which are a relatively inexpensive form of drainage particularly suited to fine textured soils with an impermeable subsoil, were installed in these two paddocks in 1975. The paddocks were remoled in the spring of 1986. The moles were 75 mm in diameter (Horne, 1985), were pulled at a depth of approximately 0.45 m, at a spacing 2 m, on a gradient of 1%. Flow from the mole drains was intercepted by 100 mm diameter tile drains laid perpendicular to the moles, at a depth of approximately 0.75 m, with a minimum grade of 0.4%. There were two sumps of size 1.2m by 2.0m by 1.5m, for each plot which collected water from the tile drains. Backfill above the tile drain was the topsoil removed during trenching, which ensured that the low permeability of the subsoil did not affect flow from the moles to the tile drains. The experimental site consisted of 0.2475 ha of pasture grown land with almost zero slope.

3.3 Trial Site and Equipment Set up

3.3.1 Site layout

The trial consisted of one subirrigated plot of 1248 m^2 area and an adjacent control plot which was not irrigated. Figure (3.3) shows the layout of the subirrigated trial that was installed in December 1994 using the existing drainage plots.

3.3.2 Sump

The 3.6 m^3 sump was used to subirrigate the system. It was lined with polyethylene plastic sheets to make sure there was no leakage from the sides or bottom.

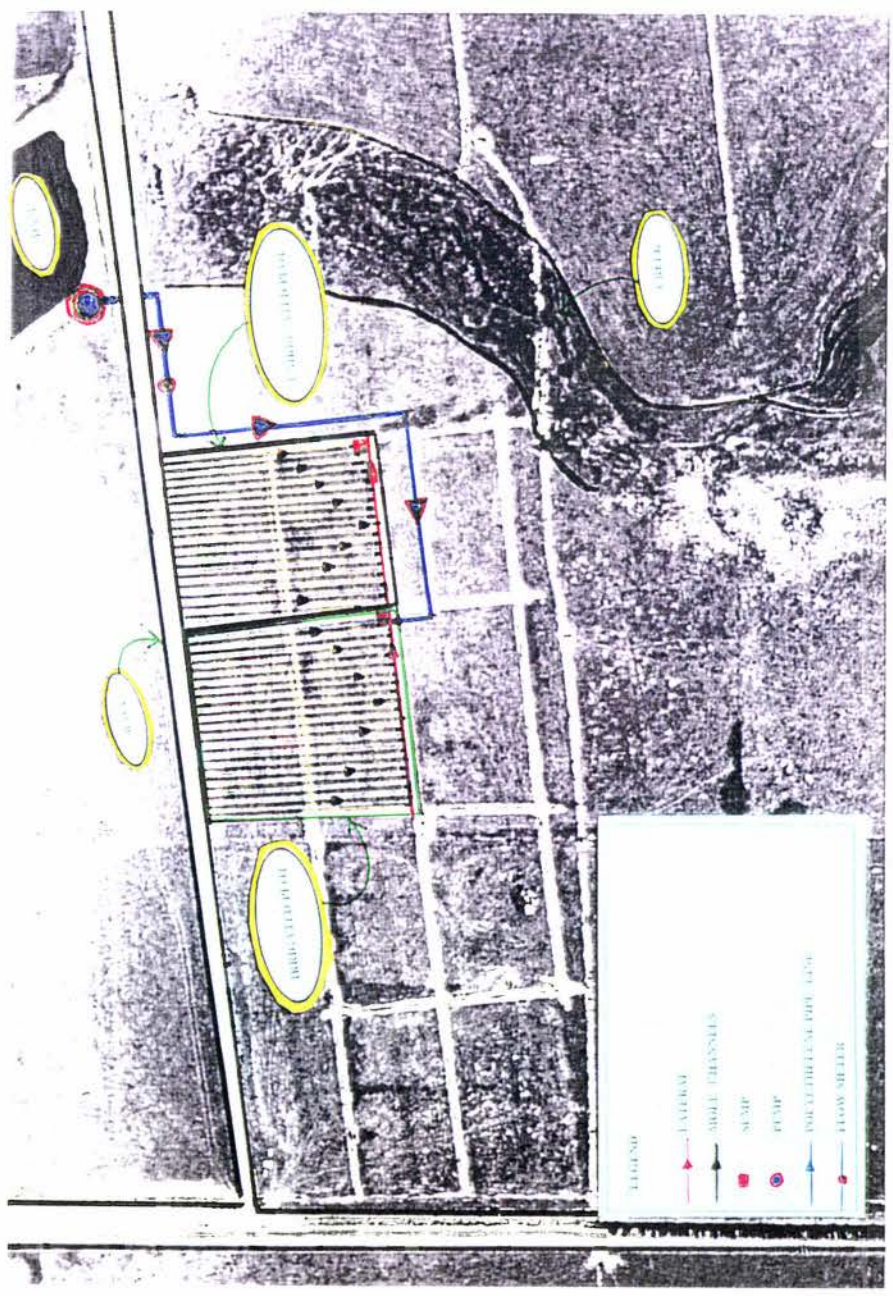

Figure-3.3: An aerial photograph of the trial site.

3.3.3 Pump

An engine driven centrifugal pump, Homelite model AP220, with a capacity of 31,800 litres/hour with a working head of upto 33.5m was used.

3.3.4 Flow meter

A Kent flow meter, was used to measure the amount of water added to the system during each irrigation cycle.

3.3.5 Time Domain Reflectometry probes

Twelve sets of TDR probes (400mm in length) were installed in the irrigated field to a depth of 400mm. Three groups, each with four sets of probes were placed parallel to the lateral at 4.5m, 22.5m and 40.5m from the sump, and 5m away from the lateral. Within each group the four sets of probes were placed at 50cm centres to span a mole. Each set consisted of two probes 50mm apart. Three sets of probes were also installed randomly in the control plot to the same depth.

3.3.6 Observation wells

Two observation wells 1.5m and 1.0m deep were installed close to the sump and at the end of the lateral respectively. A water level recorder was used to measure the water table in the soil profile.

3.4 Method

Subirrigation was carried out by pumping water from a storage dam into the sump. The experiment was carried out for 33 days (from Feb 16 to Mar 20, 1995). The total depth of irrigation applied was 185.71 mm (232 m^3 of water added to the system).

Actual irrigation times and amounts are given in table (3.1).

Soil moisture content measurements (percentage volumetric base) were made using the portable TDR (Time Domain Reflectometry) measurement system from the permanently installed probes in the irrigated and unirrigated (control) plots. A theoretical daily water balance, with and without irrigation, was developed for the irrigated plot and unirrigated (control) plot based on the available weather data as shown in the table (3.1). The soil moisture content was determined on a daily base using the water balance equation (3.1).

$$SMC_i = SMC_{i-1} + R + I - ET_{crop} \tag{3.1}$$

where

SMC_i	= soil moisture content of the present day (mm)
SMC_{i-1}	= soil moisture content of the previous day (mm)
ET_{crop}	= ET_{pan} x crop factor, crop evapotranspiration (mm)
ET_{pan}	= measured pan evaporation (mm)
R	= daily rainfall (mm)
I	= daily irrigation applied (mm)

Daily rainfall and pan evapotranspiration data was taken from the nearby AgResearch weather station. Crop factors of 0.7, 0.6, 0.5, 0.4, and 0.3 were tried. A crop factor of 0.4 was found to give the best fit between predicted and observed data. This low value does not seem unreasonable given the very dry conditions.

Before irrigation the measured soil moisture content in the control plot was 12.7 % by volume. This was used as a base to determine the initial soil moisture content in millimetres. The soil moisture content, in percent by volume, was determined using the equation (3.2).

$$SMC\ (\%) = \{SMC\ (mm)\ /\ Effective\ depth\} \times 100 \qquad (3.2)$$

The effective depth used was 400 mm.

At the end of the trial visual inspection was carried out by excavating above the lateral and along side a mole channel.

3.5 Results

The average of all twelve readings of soil moisture content were taken. The results of the theoretical daily water balance for the irrigated and the unirrigated control are shown in the table (3.1). Table (3.2) shows the predicted and measured soil moisture contents on a percentage basis, for the irrigated plot and the unirrigated control. The results are plotted together versus time in days in figure (3.4).

The observation wells remained dry throughout the experiment.

Date 1995	Rain (mm)	Pan ET (mm)	ETcrop (mm)	Irrigation (mm)	SMC (irrig) (mm)	SMC (unirrig) (mm)
Feb 15					50.8	50.8
Feb 16	0.0	6.2	2.5	11.4	59.7	48.3
Feb 17	0.0	6.8	2.7	15.8	72.8	45.6
Feb 18	0.0	4.7	1.9	0.0	70.9	43.7
Feb 19	0.0	4.1	1.6	0.0	69.3	42.1
Feb 20	16.7	4.7	1.9	11.7	95.8	56.9
Feb 21	8.8	3.8	1.5	0.0	103.1	64.2
Feb 22	2.8	0.6	0.2	0.0	105.7	66.7
Feb 23	26.3	3.1	1.2	4.2	135.0	91.8
Feb 24	2.3	3.0	1.2	0.0	136.1	92.9
Feb 25	0.0	3.7	1.5	0.0	134.6	91.4
Feb 26	0.0	5.7	2.3	0.0	132.3	89.1
Feb 27	0.0	6.0	2.4	9.3	139.2	86.7
Feb 28	0.0	4.0	1.6	21.2	158.8	85.1
Mar 01	0.3	3.2	1.3	14.2	172.1	84.2
Mar 02	0.0	6.0	2.4	19.3	189.0	81.8
Mar 03	5.9	0.0	0.0	0.0	194.9	87.7
Mar 04	0.0	4.9	2.0	0.0	192.9	85.7
Mar 05	0.0	4.7	1.9	0.0	191.0	83.8
Mar 06	0.0	3.2	1.3	16.7	206.4	82.5
Mar 07	0.0	4.8	1.9	19.8	224.3	80.6
Mar 08	0.0	4.6	1.8	18.8	241.2	78.8
Mar 09	0.0	5.6	2.2	18.3	257.3	76.5
Mar 10	5.1	5.1	2.0	4.9	265.3	79.6
Mar 11	0.0	6.2	2.5	0.0	262.8	77.1
Mar 12	20.4	3.7	1.5	0.0	281.8	96.0
Mar 13	7.0	5.0	2.0	0.0	286.8	101.0
Mar 14	0.0	5.9	2.4	0.0	284.4	98.7
Mar 15	25.3	2.8	1.1	0.0	308.6	122.9
Mar 16	7.8	2.0	0.8	0.0	315.6	129.9
Mar 17	1.1	1.1	0.4	0.0	316.2	130.5
Mar 18	1.1	2.7	1.1	0.0	316.3	130.5
Mar 19	5.2	2.6	1.0	0.0	320.4	134.7
Mar 20	24.0	4.0	1.6	0.0	342.8	157.1
Total	160.1	134.5	53.8	185.7	6583.3	2904.3

Table 3.1: A table showing the theoretical water balance on daily basis.

Date 1995	Predicted SMC(irrig) (%)	Predicted SMC(unirrig) (%)	Measured SMC(irrig) (%)	Measured SMC(control) (%)
Feb 15	12.70	12.70	14.66	12.70
Feb 16	14.92	12.08	16.18	13.06
Feb 17	18.20	11.40	16.23	12.03
Feb 18	17.73	10.93	14.67	13.06
Feb 19	17.32	10.52	14.15	12.73
Feb 20	23.96	14.22	14.74	13.13
Feb 21	25.78	16.05		
Feb 22	26.42	16.69		
Feb 23	33.74	22.95		
Feb 24	34.02	23.23		
Feb 25	33.65	22.86		
Feb 26	33.08	22.29		
Feb 27	34.81	1.68	25.34	26.66
Feb 28	39.70	21.29	22.48	25.63
Mar 01	43.02	21.04	20.75	24.63
Mar 02	47.25	20.44	20.64	24.36
Mar 03	48.72	21.91	19.20	23.93
Mar 04	48.23	21.43		
Mar 05	47.76	20.96		
Mar 06	51.60	20.64	19.10	22.33
Mar 07	56.07	20.16	18.12	23.70
Mar 08	60.31	19.70	21.26	19.26
Mar 09	64.33	19.14	17.24	21.40
Mar 10	66.33	19.90	17.00	20.23
Mar 11	65.71	19.28		
Mar 12	70.44	24.01		
Mar 13	71.69	25.26		
Mar 14	71.10	24.67	25.22	28.63
Mar 15	77.14	30.72		
Mar 16	78.89	32.47	34.07	38.30
Mar 17	79.06	32.63		
Mar 18	79.06	32.64		
Mar 19	80.10	33.68		
Mar 20	85.70	39.28	29.86	33.60

Table 3.2: A table showing the measured and predicted soil moisture content (%) in the irrigated and unirrigated plots.

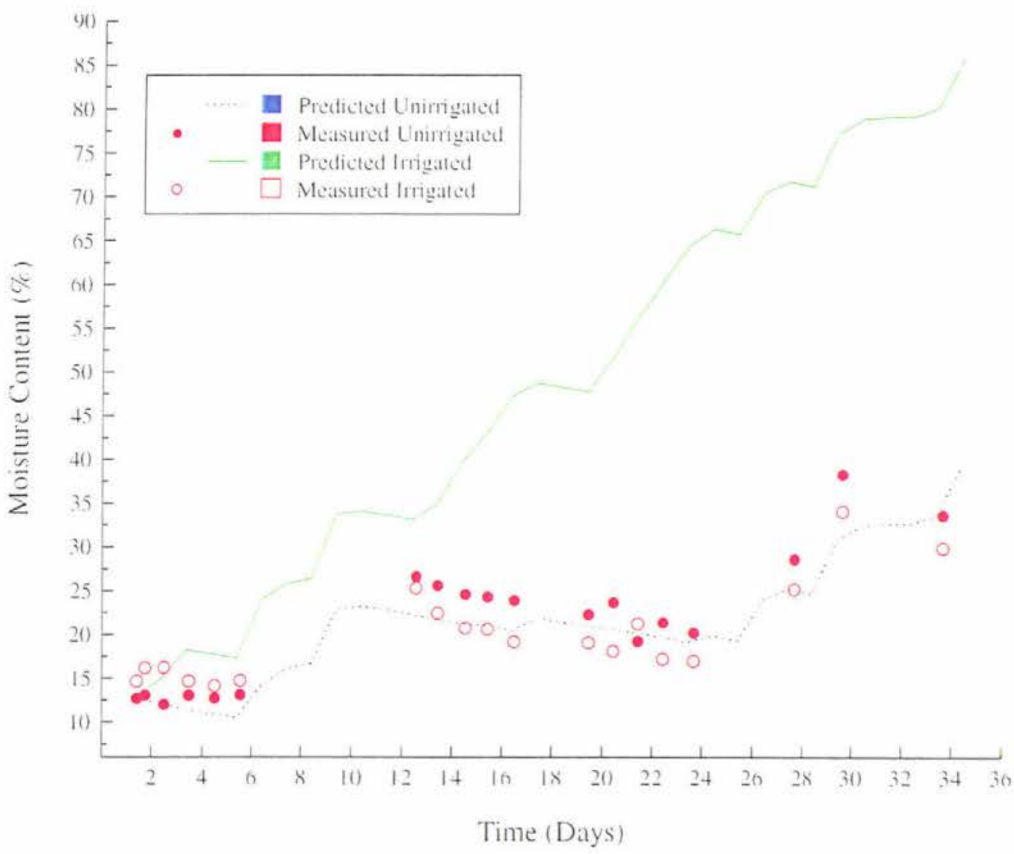

Fig 1. Theoretical Daily Water Balance for the Irrigated and Control (Unirrigated) Plots.

Figure-3.4: A graph showing the theoretical daily water balance for the irrigated and control (unirrigated) plots.

3.6 Discussion

It was observed that the soil below and around the lateral was wet but around the moles was still dry. This is shown in figure (3.5). Although the soil moisture content of the irrigated plot increased during the experiment, there was no appreciable difference between the irrigated plot and the control area. Thus any change in soil moisture was attributed to net rainfall but not irrigation.

This result was supported by the theoretical daily water balance for the irrigated plot and unirrigated (control) plot. Had the irrigation been successful, then the soil moisture measured in the irrigated block would have been expected to follow that predicted by the water balance with irrigation. In reality the soil moisture followed the measured, and predicted, soil moisture for the unirrigated control, which is clear from the figure (3.4).

Figure-3.5: A photograph showing that water did not reach to the mole level, but around the lateral it was quite wet.

3.7 Conclusions

The experiment showed that, in this pilot scale study, subirrigation was not successful. The major impediment appeared to be at the backfill trench. Although water had moved from the sump, into the lateral and out into the backfill, sufficient water did not move upto the level of the moles. Reasons for this may include:

(a) Not enough water was applied, to rewet the soil around the lateral sufficiently to raise the water level in the backfill trench upto the mole level.

(b) Not enough pressure head was available to force water from the drainage lateral to the moles.

(c) The hydraulic conductivity of backfill was too low.

At this point it was decided to proceed with stage II of the study and conduct a laboratory experiment designed to examine the hydraulic connection between the lateral and a mole in the backfill trench. This is reported in chapter in 4.

Chapter 4

LABORATORY EXPERIMENT

This chapter describes the construction and setting up of the laboratory model, how the laboratory experiment was conducted, and how the bin measurements were performed (see section 4.1.3). Saturated hydraulic conductivity measurements are described in section 4.2. Bulk density, particle density, porosity measurements, and particle size measurements were taken and are described in appendices and A2.

4.1 Head Flow Measurements in Laboratory Model

4.1.1 Objectives

The main objectives of the laboratory experiment were to evaluate the:

1) Effect of backfill material on the rate of flow through the system at different mole positions.
2) Effect of pressure head on the rate of flow through the system at different mole positions.
3) Effect of geometry of components on the rate of flow through the system.

4.1.2 Equipment

4.1.2.1 The Bin

A galvanised sheet steel bin, 2330mm long by 1200mm high by 300mm wide, was constructed in the laboratory. Eight manometer tubes were connected along the bottom of the bin to measure static water head.

4.1.2.2 Lateral

A length of Novaflow perforated plastic drainage pipe, 110mm in diameter, was laid down in the bottom of the bin. The distance from the centre-line of the lateral to the bottom of the bin was 150mm.

4.1.2.3 Mole

A slotted stainless steel pipe, 50mm in diameter, was used to form a permanent mole in the system. The total area of slots was 5280mm^2. This configuration was chosen to minimise hydraulic resistance at this point. A manometer tube was connected to the outlet of the mole to determine the head loss across the mole itself. Two sets of holes, 50mm in diameter, were made in the bin 250mm and 450mm above the centre line of the lateral to allow the mole to be fitted at two positions labelled bottom and top positions respectively. The mole was fixed at right angles to the lateral (see figure 4.1).

4.1.2.4 Constant head system

A constant head system was connected with the bin at the inlet side of the lateral, as shown in the figure 4.2. A number of holes were drilled in the upright pipe to allow different head pressures to be applied to the inlet side of the lateral. Rubber bungs were placed in all holes but one hole for each measurement. Water was continuously added to the constant head system from the mains, and excess water run to waste with a short length of hose inserted into the appropriate hole. A manometer tube was connected at the bottom of the header tank to allow accurate determination of the water level in the constant head system.

Figure-4.1: A photo showing the setting of the mole and lateral in the bin.

4.1.2.5 Flow meter

A Kent Veriflux Electromagnetic Flowmeter VTC, with a calibrated bore of 25mm, connected at the mole outlet, was used to measure the flow rate coming out of the system. The flow meter produced an analogue voltage output proportional to the flow. The flow meter was adjusted to achieve an output of 2000mV per litre/second, with a maximum output of 1 litres/sec. The accuracy of the flow meter was ± 0.5% of actual flow at 100% to 50% full flow rate (1l/s - 0.5l/s) and no more than ± 1% at 50% to 10% full flow rate (0.5l/s - 0.1l/s). A JJ Instrument chart recorder was connected to the flow meter. This gave a visual indication of when steady state flow condition had been achieved. The output of the flow meter was read with a Fluke volt meter with a resolution of 0.1 mV or 0.00005 litres/sec.

Figure-4.2: Bin model laboratory experiment.

4.1.2.6 Backfill Treatments

Experimental measurements were conducted with three backfill materials;

1) No backfill
2) Gravel backfill
3) Tokomaru silt loam soil (T.S.L.) backfill

Physical and hydraulic properties of the gravel and Tokomaru silt loam were determined and are given in section 4.2 and in appendices A1 and A2.

4.1.3 Method

Flow measurements using the bin apparatus were made for five situations.

4.1.3.1 No backfill with bottom mole position

Firstly, the laboratory experiment bin model was run with no backfill material in it with the mole at the bottom position. The purpose of this experiment was to measure the head and friction losses in the system due to lateral, mole, flow meter, and bin itself.

Subirrigation was carried out by running water into the constant head system from the mains. Three sets of measurements were made with water level in the constant head system set at seven different levels making 21 measurements in total (see table 4.1). Flow rate measurements were taken at each head setting using the digital volt meter and flow meter. The outlet from the flow meter was adjusted to be at the same elevation at the mole, to prevent any syphoning effects or introducing any extra static head requirements.

4.1.3.2 Gravel backfill with bottom mole position

In the second experiment, the bin was filled up with gravel to the marked ground surface (i.e.) 1050mm from the bottom of the bin as shown in the figure (4.3). Before taking the actual measurements, subirrigation was carried out by adding water to the constant head tank to saturate the gravel and then draining to let the backfill material settle. Four sets of flow rate measurements were made at seven different heads making 28 measurements in total (see table 4.2). Measurements of head were taken from the manometer tubes connected to the constant head tank, across the bin, and at the mole outlet.

Figure-4.3: Gravel backfill with bottom mole position.

4.1.3.3 Gravel backfill with top mole position

In the third experiment, the mole was shifted from bottom to top position (figure 4.4). Subirrigation was carried out by adding water to the constant head tank to saturate and then draining to let the backfill material settle. Three sets of flow rate measurements were made at five different heads making 15 measurements in total (see table 4.3). Measurements of head were taken from the manometer tubes connected to the constant head tank, across the bin, and at the mole outlet.

Figure-4.4: Gravel backfill with top mole position.

4.1.3.4 Tokomaru silt loam soil backfill with top mole position

In the fourth experiment, a mixture of T.S.L. top and subsoil was taken from the Massey University No 4 dairy Farm, where the field experiment was carried out. Before putting the soil sample in the bin, raking of the wet and clogged soil sample was done to break it into small pieces as shown in the figure (4.5).

Figure-4.5: A figure showing the raking of the tokomaru silt loam soil sample.

Gravel was placed around the lateral, and upto 40-50 mm above the lateral to act as a filter material. The bin was then filled up with the Tokomaru silt loam soil (T.S.L.) to the marked ground surface (i.e.) 1050mm from the bottom of the bin. Before taking the actual measurements, subirrigation was carried out by adding water into the constant head tank to saturate the soil and then draining to let the backfill material settle. Three sets of flow rate measurements were made at six different heads making 18 measurements in total (see table 4.4). Measurements of head were taken from the manometer tubes connected to the constant head tank, across the bin, and at the mole outlet.

4.1.3.5 Tokomaru silt loam soil backfill with bottom mole position

The mole was shifted from top to bottom position and the bin was filled up again with the Tokomaru silt loam soil. The gravel filter around the lateral was left undisturbed. Three sets of flow rate measurements were made at six different heads making 18 measurements in total (see table 4.5). Measurements of water head were taken from the manometer tubes connected to the constant head tank, across the bin, and at the mole outlet.

4.1.4 Results

4.1.4.1 No backfill

Head losses across the lateral, the mole, and the flow meter were determined from the first experiment. The head loss across the mole was calculated by taking the difference between the piezometric head measured at the mole outlet and the piezometric head measured at the bottom of the bin closest to the mole. In reality this also included any head loss due to friction at the bin walls but this was not expected to be significant due to the low streamline velocities. The average head loss across the lateral was determined by taking the average difference between the piezometric head measured at each of the eight tapping along the bottom of the bin and the constant head level. The head loss across the flow meter was calculated by taking the difference between the piezometric head measured at the mole outlet and the elevation of the flow meter outlet. Results are given in table (4.1). The head losses in the mole, lateral, and flow meter are plotted against the flow rate in figure (4.6).

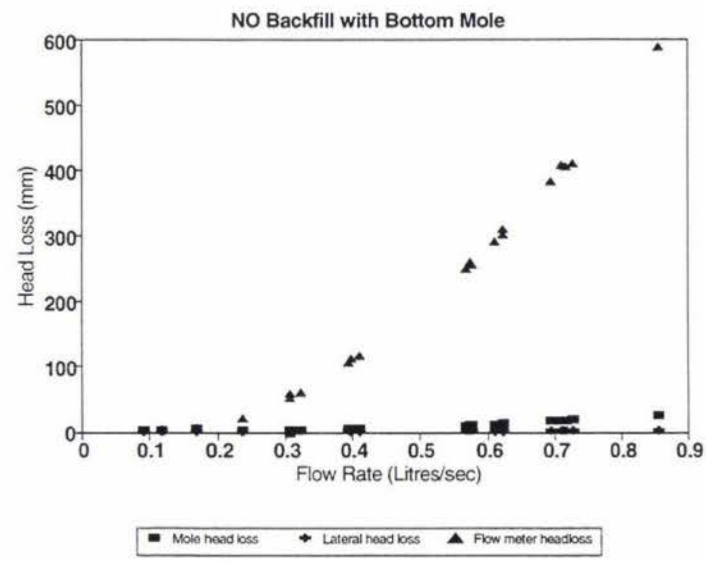

Figure-4.6: A graph showing the head losses in the mole, lateral, and flow meter plotted against the flow rate for no backfill treatment.

4.1.4.2 Results with Backfill materials

For each backfill treatment and mole setting the head losses across the lateral, the combined backfill and mole, and the flow meter were calculated in a similar manner to that described for the no backfill treatment. Results for each backfill treatment and mole setting are given in tables (4.2, 4.3, 4.4, and 4.5) and are plotted in figures (from 4.7 to 4.10).

Flow rate (l/s)	Heads relative to the centre line of the mole: Constant Head (mm)	Tappings across the bottom of bin: h1 (mm)	h2 (mm)	h3 (mm)	h4 (mm)	h5 (mm)	h6 (mm)	h7 (mm)	h8 (mm)	Mole outlet (mm)	Head losses: Across the lateral: h1 (mm)	h2 (mm)	h3 (mm)	h4 (mm)	h5 (mm)	h6 (mm)	h7 (mm)	h8 (mm)	Bin & mole (mm)	Flow meter (mm)
0.308	66	62	62	62	61	61	61	62	63	61	4	4	4	5	5	5	4	3	0	61
0.398	122	119	120	120	120	120	120	120	120	114	3	2	2	2	2	2	2	2	6	114
0.575	276	272	274	274	273	273	273	273	273	262	4	2	2	3	3	3	3	3	11	262
0.624	328	324	325	325	324	324	324	325	325	310	4	3	3	4	4	4	3	3	14	310
0.711	431	428	428	428	427	428	428	428	427	409	3	3	3	4	3	3	3	4	18	409
0.727	434	431	431	432	431	431	431	431	431	412	3	3	2	3	3	3	3	3	19	412
0.118	12	10	10	10	10	11	11	11	10	7	2	2	2	2	1	1	1	2	3	7
0.236	27	25	25	26	26	26	26	27	25	22	2	2	1	1	1	1	0	2	4	22
0.322	69	66	66	66	67	67	67	67	67	63	3	3	3	2	2	2	2	2	4	63
0.395	116	113	113	113	113	113	113	113	113	108	3	3	3	3	3	3	3	3	5	108
0.576	271	268	269	268	267	268	268	268	267	256	3	2	3	4	3	3	3	4	11	256
0.624	320	318	319	318	317	318	317	318	318	304	2	1	2	3	2	3	2	2	13	304
0.695	405	402	403	403	402	402	401	402	401	384	3	2	2	3	3	4	3	4	18	384
0.855	621	616	617	617	616	617	617	617	617	590	5	4	4	5	4	4	4	4	26	590
0.091	8	7	7	7	7	7	8	8	7	4	1	1	1	1	1	0	0	1	3	4
0.168	15	14	13	14	14	13	14	15	14	9	1	2	1	1	2	1	0	1	5	9
0.308	60	58	58	58	58	58	57	58	57	54	2	2	2	2	2	3	2	3	4	54
0.410	125	123	123	123	123	123	122	123	123	118	2	2	2	2	2	3	2	2	5	118
0.570	264	262	262	261	261	262	261	262	261	251	2	2	3	3	2	3	2	3	10	251
0.611	307	305	305	305	304	304	305	305	305	292	2	2	2	3	3	2	2	2	12	292
0.717	430	427	427	427	426	426	427	427	426	408	3	3	3	4	4	3	3	4	18	408

Table 4.1: Head loss measurements for no backfill treatment with mole at bottom position.

Flow rate (l/s)	Heads relative to the centre line of the mole: Constant Head (mm)	Tappings across the bottom of bin: h1 (mm)	h2 (mm)	h3 (mm)	h4 (mm)	h5 (mm)	h6 (mm)	h7 (mm)	h8 (mm)	Mole outlet (mm)	Head losses: Across the lateral: h1 (mm)	h2 (mm)	h3 (mm)	h4 (mm)	h5 (mm)	h6 (mm)	h7 (mm)	h8 (mm)	Bin & mole (mm)	Flow meter (mm)
0.187	16	16	16	16	15	15	16	16	14	11	0	0	0	1	1	0	0	2	4	11
0.315	66	65	64	65	65	65	64	65	63	60	1	2	1	1	1	2	1	3	5	60
0.382	108	105	106	106	105	107	104	106	105	100	3	2	2	3	1	4	2	3	5	100
0.576	271	268	269	268	267	268	268	269	267	256	3	2	3	4	3	3	2	4	11	256
0.630	328	326	327	326	325	325	326	325	325	315	2	1	2	3	3	2	3	3	10	315
0.710	422	419	419	419	417	418	419	418	418	397	3	3	3	5	4	3	4	4	20	397
0.860	623	623	623	622	623	623	,623	623	623	596	0	0	1	0	0	0	0	0	27	596
0.169	13	13	13	13	13	13	13	13	13	10	0	0	0	0	0	0	0	0	3	10
0.304	59	59	59	59	59	59	58	59	58	55	0	0	0	0	0	1	0	1	4	55
0.387	110	110	110	110	110	110	108	110	108	104	0	0	0	0	0	2	0	2	6	104
0.558	251	251	251	251	250	250	249	249	249	239	0	0	0	1	1	2	2	2	11	239
0.613	309	309	308	308	307	307	306	307	307	293	0	1	1	2	2	3	2	2	14	293
0.713	425	425	425	425	422	423	423	423	422	404	0	0	0	3	2	2	2	3	18	404
0.862	632	630	629	628	627	627	627	628	626	600	2	3	4	5	5	5	4	6	27	600
0.218	21	21	21	21	20	21	21	21	20	17	0	0	0	1	0	0	0	1	3	17
0.320	68	68	68	68	68	68	68	68	68	66	0	0	0	0	0	0	0	0	2	66
0.401	123	123	123	122	120	123	122	122	121	115	0	0	1	3	0	1	1	2	5	115
0.578	272	272	272	272	270	272	271	271	270	258	0	0	0	2	0	1	1	2	12	258
0.622	320	320	320	320	320	320	320	320	319	305	0	0	0	0	0	0	0	1	15	305
0.712	428	427	427	427	425	426	426	426	424	406	1	1	1	3	2	2	2	4	19	406
0.862	632	630	629	628	627	627	627	628	626	600	2	3	4	5	5	5	4	6	27	600
0.161	13	13	13	13	13	13	13	13	12	10	0	0	0	0	0	0	0	1	3	10
0.31	60	60	60	60	60	60	60	60	59	56	0	0	0	0	0	0	0	1	4	56
0.404	123	123	122	123	122	122	122	122	120	115	0	1	0	1	1	1	1	3	7	115
0.569	265	265	264	263	263	263	263	263	262	251	0	1	2	2	2	2	2	3	12	251
0.625	324	323	323	322	322	321	321	321	321	307	1	1	2	2	3	3	3	3	15	307
0.71	428	427	427	426	24	425	426	425	424	405	1	1	2	4	3	2	3	4	19	405
0.858	631	629	630	630	629	629	629	630	629	607	2	1	1	2	2	2	1	2	22	607

Table 4.2: Head loss measurements for gravel backfill treatment with mole at bottom position.

Flow rate (l/s)	Heads relative to the top of the mole: Constant Head (mm)	Tappings across the bottom of bin: h1 (mm)	h2 (mm)	h3 (mm)	h4 (mm)	h5 (mm)	h6 (mm)	h7 (mm)	h8 (mm)	Mole outlet (mm)	Head losses: Across the lateral: h1 (mm)	h2 (mm)	h3 (mm)	h4 (mm)	h5 (mm)	h6 (mm)	h7 (mm)	h8 (mm)	Bin & mole (mm)	Flow meter (mm)
0.155	19	19	19	19	19	19	19	19	18	17	0	0	0	0	0	0	0	1	2	17
0.261	59	59	59	59	59	59	59	59	58	57	0	0	0	0	0	0	0	1	2	57
0.345	105	105	105	105	105	105	105	105	104	101	0	0	0	0	0	0	0	1	4	101
0.497	222	222	222	222	222	222	220	220	219	211	0	0	0	0	0	2	2	3	11	211
0.692	425	425	424	425	425	425	424	424	422	407	0	1	0	0	0	1	1	3	18	407
0.214	40	40	40	40	40	40	39	40	39	38	0	0	0	0	0	1	0	1	2	38
0.276	68	68	68	68	68	68	68	68	67	64	0	0	0	0	0	0	0	1	4	64
0.352	111	111	111	111	111	111	111	111	111	106	0	0	0	0	0	0	0	0	5	106
0.502	228	228	228	228	227	227	226	225	224	217	0	0	0	1	1	2	3	4	10	217
0.692	425	425	424	425	425	425	424	424	422	407	0	1	0	0	0	1	1	3	18	407
0.214	40	40	40	40	40	40	39	40	39	38	0	0	0	0	0	1	0	1	2	38
0.281	71	71	71	71	71	71	70	71	70	31	0	0	0	0	0	1	0	1	4	67
0.370	122	122	122	122	122	122	122	122	121	117	0	0	0	0	0	0	0	1	5	117
0.505	228	228	228	228	228	228	227	227	226	219	0	0	0	0	0	1	1	2	9	219
0.683	414	414	413	414	413	413	413	413	411	393	0	1	0	1	1	1	1	3	20	393

Table 4.3: Head loss measurements for gravel backfill treatment with mole at top position.

Flow rate (l/s)	Constant Head (mm)	Heads relative to the centre line of mole: Tappings across the bottom of bin h1 (mm)	h2 (mm)	h3 (mm)	h4 (mm)	h5 (mm)	h6 (mm)	h7 (mm)	h8 (mm)	Mole outlet (mm)	Head losses: Across the lateral h1 (mm)	h2 (mm)	h3 (mm)	h4 (mm)	h5 (mm)	h6 (mm)	h7 (mm)	h8 (mm)	Bin & mole (mm)	Flow meter (mm)
0.015	72	72	72	71	70	70	71	69	68	54	0	0	1	2	2	1	3	4	16	54
0.033	114	114	114	114	113	113	113	114	113	72	0	0	0	1	1	1	0	1	41	72
0.069	209	209	209	209	209	209	209	208	207	55	0	0	0	0	0	0	1	2	154	55
0.099	263	263	263	263	263	263	263	262	261	123	0	0	0	0	0	0	1	2	140	123
0.113	360	360	360	360	359	359	358	358	357	137	0	0	0	1	1	2	2	3	222	137
0.122	410	410	410	410	410	410	410	409	408	139	0	0	0	0	0	0	1	2	271	139
0.019	70	70	70	70	70	70	70	68	67	45	0	0	0	0	0	0	2	3	25	45
0.038	120	120	120	120	120	120	120	119	118	61	0	0	0	0	0	0	1	2	59	61
0.065	218	218	218	218	218	218	218	217	216	85	0	0	0	0	0	0	1	2	133	85
0.077	267	267	267	267	266	266	266	265	264	96	0	0	0	1	1	1	2	3	170	96
0.090	313	313	313	312	312	312	311	311	309	108	0	0	1	1	1	2	2	4	204	108
0.122	410	410	410	410	410	410	410	409	408	139	0	0	0	0	0	0	1	2	271	139
0.019	70	70	70	70	70	70	70	68	67	45	0	0	0	0	0	0	2	3	25	45
0.040	119	119	119	119	119	119	119	107	106	63	0	0	0	0	0	0	12	13	56	63
0.068	217	217	217	217	217	217	217	215	214	86	0	0	0	0	0	0	2	3	131	86
0.080	268	268	268	268	268	268	266	266	265	94	0	0	0	0	0	2	2	3	174	94
0.084	315	315	315	315	315	315	315	313	312	99	0	0	0	0	0	0	2	3	216	99
0.116	411	411	411	411	411	411	408	409	407	114	0	0	0	0	0	3	2	4	297	114

Table 4.4: Head loss measurements for Tokomaru silt loam soil backfill treatment with mole at top position.

Flow rate (l/s)	Constant Head (mm)	Heads relative to the centre line of mole: Tappings across the bottom of bin h1 (mm)	h2 (mm)	h3 (mm)	h4 (mm)	h5 (mm)	h6 (mm)	h7 (mm)	h8 (mm)	Mole outlet (mm)	Head losses: Across the lateral h1 (mm)	h2 (mm)	h3 (mm)	h4 (mm)	h5 (mm)	h6 (mm)	h7 (mm)	h8 (mm)	Bin & mole (mm)	Flow meter (mm)
0.007	275	275	275	274	274	272	274	272	271	61	0	0	1	1	3	1	3	4	213	61
0.008	325	324	325	324	324	323	321	322	320	62	1	0	1	1	2	4	3	5	262	62
0.010	426	425	426	425	425	425	423	423	422	66	1	0	1	1	1	3	3	4	359	66
0.011	524	523	524	524	524	522	521	521	519	38	1	0	0	0	2	3	3	5	486	38
0.012	578	577	578	577	577	573	573	572	569	38	1	0	1	1	5	5	6	9	539	38
0.012	627	626	627	624	624	624	623	623	622	64	1	0	3	3	3	4	4	5	560	64
0.002	73	73	73	73	72	73	73	71	70	29	0	0	0	1	0	0	2	3	43	29
0.004	124	124	124	123	122	122	122	121	120	29	0	0	1	2	2	2	3	4	93	29
0.008	275	274	274	275	272	272	272	271	270	31	1	1	0	3	3	3	4	5	241	31
0.009	327	326	327	325	325	324	323	323	323	32	1	0	2	2	3	4	4	4	293	32
0.011	427	427	427	425	425	424	424	423	423	34	0	0	2	2	3	3	4	4	391	34
0.012	524	524	524	523	522	522	522	521	520	46	0	0	1	2	2	2	3	4	476	46
0.013	579	579	579	578	578	577	576	576	574	48	0	0	1	1	2	3	3	5	530	48
0.012	627	626	627	624	624	624	623	623	622	64	1	0	3	3	3	4	4	5	560	64
0.002	73	73	73	73	72	73	73	71	70	29	0	0	0	1	0	0	2	3	43	29
0.003	124	124	124	124	124	124	123	123	121	30	0	0	0	0	0	1	1	3	94	30
0.008	275	274	275	274	273	273	273	272	271	32	1	0	1	2	2	2	3	4	241	32
0.011	427	427	427	426	426	424	424	423	422	33	0	0	1	1	3	3	4	5	393	33
0.012	524	523	524	524	524	521	520	520	519	33	1	0	0	0	3	4	4	5	491	33
0.012	625	625	624	624	623	623	623	623	621	34	0	1	1	2	2	2	2	4	589	34

Table 4.5: Head loss measurements for Tokomaru silt loam soil backfill treatment with mole at bottom position.

4.1.5 Discussion

For the case of no backfill and the gravel backfill it was observed that most of the head loss occurred in the flow meter, see figures (from 4.6 to 4.8). This shows that in the field, where gravel is used as a backfill, the major restriction to subirrigation is likely to be friction in the mole channel itself. Although the equivalent length of pipe mole between the mole outlet and the discharge from the flow meter was shorter than a real mole. In the field, the head loss in this system would be indicative of the head loss a real mole with decreasing flow along its length.

In the case of Tokomaru silt loam soil as a backfill it was observed that the backfill itself now represented the major head loss in the system (figures 4.9 and 4.10). Contribution to head requirement from the lateral and flow meter was small at these low flow rates. This is also obvious from figure (4.6) when there was no backfill. More scatter in data was found. Probably this was due to great inaccuracy of flow measurements at low flows particularly for the bottom mole setting, and compaction of the soil while shifting the mole from top to bottom position.

For each set of experiments, the head at mole outlet should be same as the head loss in flow meter because the flow meter outlet was adjusted to the same elevation as the mole, which is clear from the results given in tables (from 4.1 to 4.5).

With the Tokomaru silt loam soil, the flow rate was greater at top mole position than at the bottom mole for the same relative head (see figures 4.9 and 4.10). This change in flow rate most likely occurred due to increased soil settlement and compaction in the bin after shifting the mole from top to bottom mole position. This conclusion was supported by measuring the bulk density, particle density, porosity, and saturated hydraulic conductivity (K_{sat}) of the gravels and tokomaru silt loam soil. (*Note: The backfill head loss in figures 4.7, 4.8, 4.9 and 4.10 includes the minor head loss due to mole).

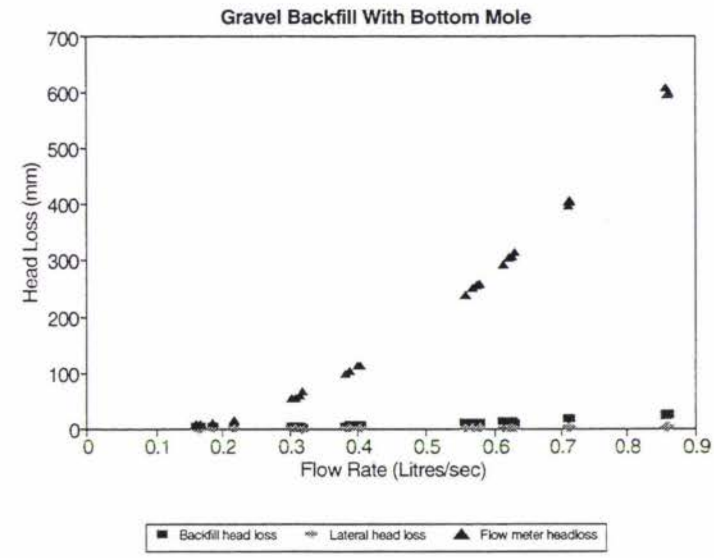

Figure-4.7: A graph showing the head losses in the mole, lateral, and flow meter plotted against the flow rate for gravel backfill with bottom mole position.

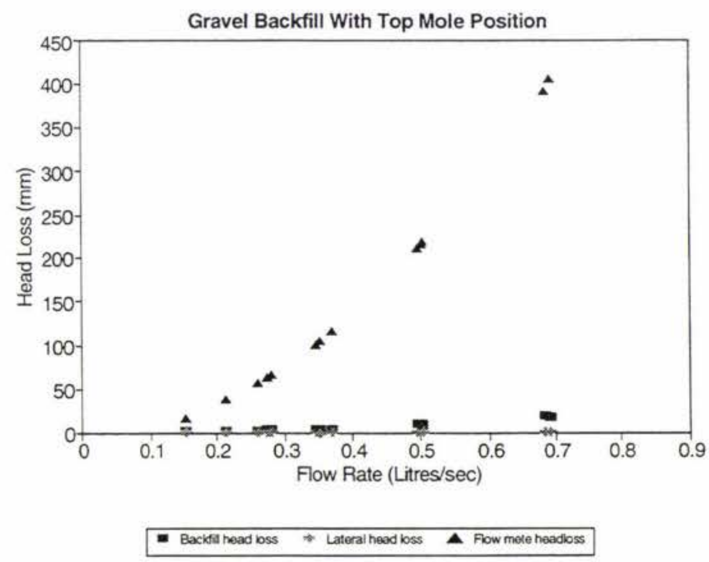

Figure-4.8: A graph showing the head losses in the mole, lateral, and flow meter plotted against the flow rate for gravel backfill with top mole position.

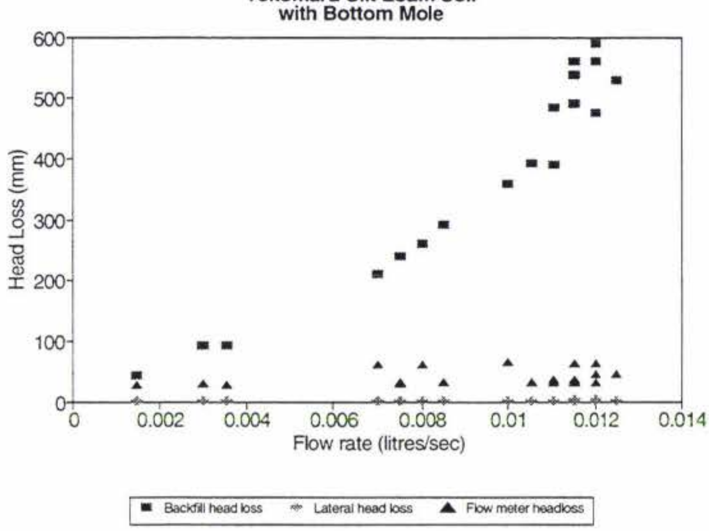

Figure-4.9: A graph showing the head losses in the mole, lateral, and flow meter plotted against the flow rate for Tokomaru silt loam backfill with bottom mole position.

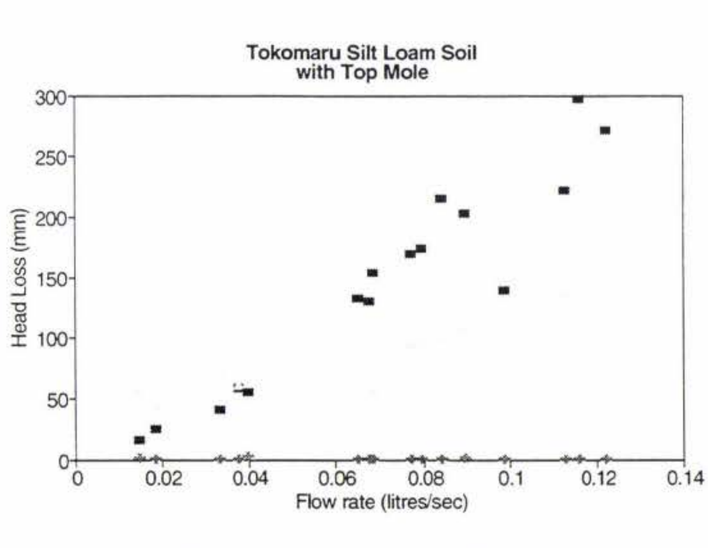

Figure-4.10: A graph showing the head losses in the mole, lateral, and flow meter plotted against the flow rate for Tokomaru silt loam soil backfill with top mole position.

4.1.6 Development of a Simple Model

In order to progress the results it was decided to further analyses the results by developing a simple mathematical model to describe the rate of flow expected in the system as a function of the head available. The total head relative to the mole, and hence the final discharge point, was used as this represented the total head loss that would be experienced in a field situation. This included head losses due to flow from the sump or constant head supply, through the lateral, through the backfill material into the mole, and along the mole itself.

Plots were made of the flow rate through the system versus the head available to the centre line of the mole for each treatment (figures 4.11, 4.13, 4.15, 4.17, and 4.19). These show clearly that flow through the system increases as head relative to the mole increases. The curvatures of these plots suggested that the flow and head were related by power law relationship. This was supported by developing log-log plots which were all fairly linear (figures 4.12, 4.14, 4.16, 4.18, and 4.20). Thus it was decided to fit a relationship of the form of equation (4.1).

$$Q = aH^b \tag{4.1}$$

where

Q = Flow rate (litres/sec)

H = Total head relative to mole

a,b = Constants

Estimation of the constant parameters *(a)* and *(b)* was carried out using a non linear regression (NLR) program on a programmed calculator. The results are given in table (4.6).

Treatment	***a***	***b***	**Correlation(%)**
No backfill with bottom mole	0.0412	0.473	99.26%
Gravel backfill with bottom mole	0.056	0.417	99.8%
Gravel backfill with top mole	0.035	0.489	99.96%
T.S.L soil backfill with bottom mole	$0.0309 x 10^{-3}$	0.948	99.8%
T.S.L soil backfill with top mole	$0.0192 x 10^{-2}$	1.079	99.8%

Table 4.6: A table showing the constants *(a, b)* and correlation coefficient (%) between the predicted and measured flow rate for each backfill treatment and mole setting.

It can be seen from table (4.6) that the correlation parameters are all better than 99% indicating that the form of the model chosen adequately fits the data. No physical significance can be attributed to the values of the fitted parameters *(a)* and *(b)* except that in general *(a)* is lower for the Tokomaru silt loam soil than that for the gravel backfill.

To test the model, plots of predicted versus measured flow rate were made (figures from 4.21 to 4.25). These plots show very good fit for the gravel backfill cases. For the T.S.L data there is more scatter. However, this is most likely due to inaccuracy in the original flow measurements.

Experimental linear and log-log graphs

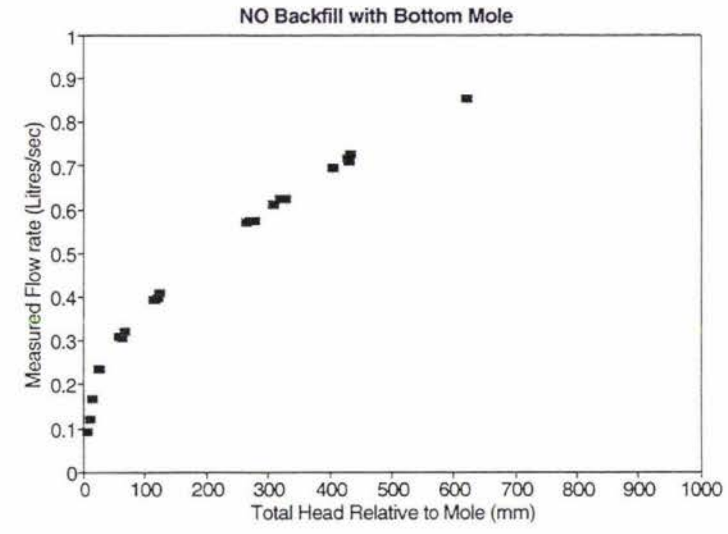

Figure-4.11 A linear graph between measured flow rate and head relative to the bottom mole position with no backfill material.

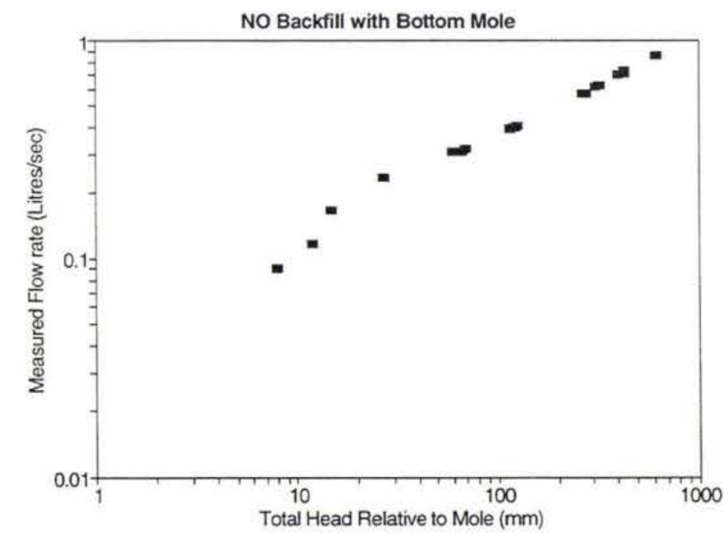

Figure-4.12: A log-log graph between the measured flow rate and head relative to the bottom mole position with no backfill.

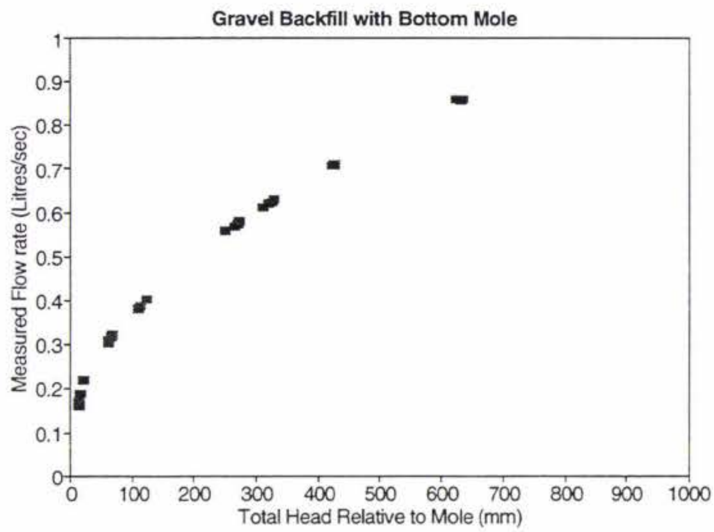

Figure-4.13: A linear graph between the measured flow rate and head relative to the bottom mole position with gravel backfill.

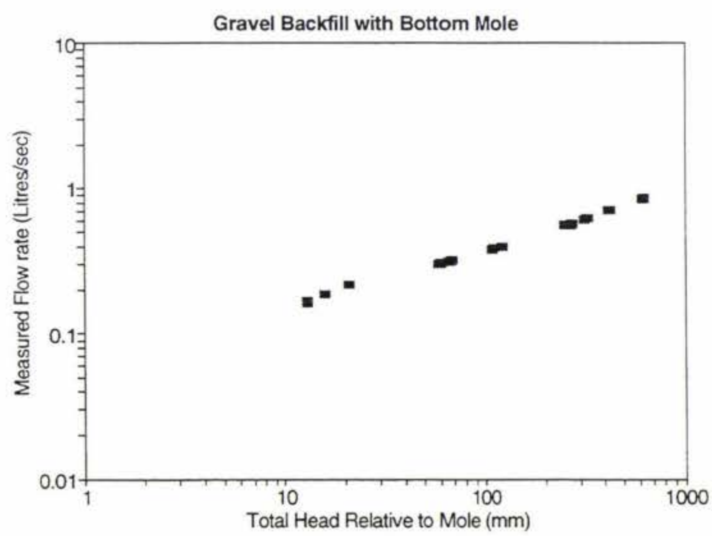

Figure-4.14: A log-log graph between the measured flow rate and head relative to the bottom mole position with gravel backfill.

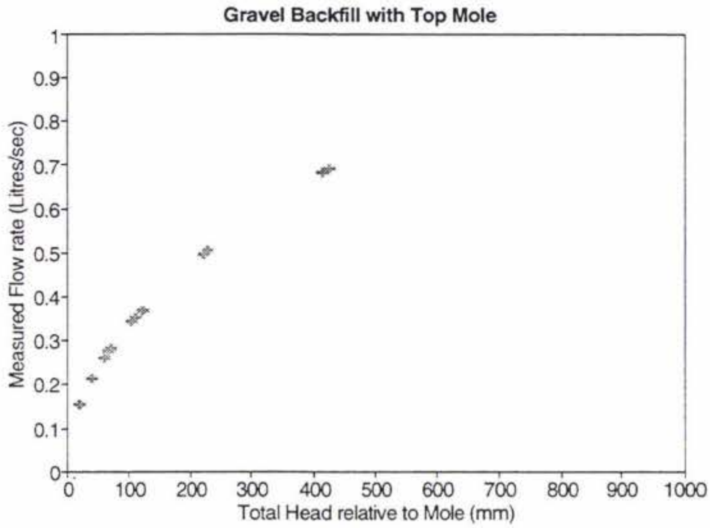

Figure-4.15: A linear graph between the measured flow rate and head relative to the top mole position with gravel backfill.

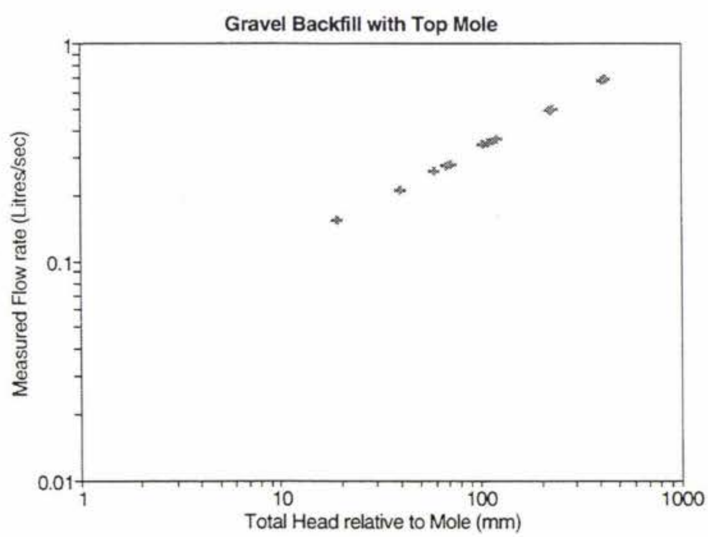

Figure-4.16: A log-log graph between the measured flow rate and head relative to the top mole position with gravel backfill.

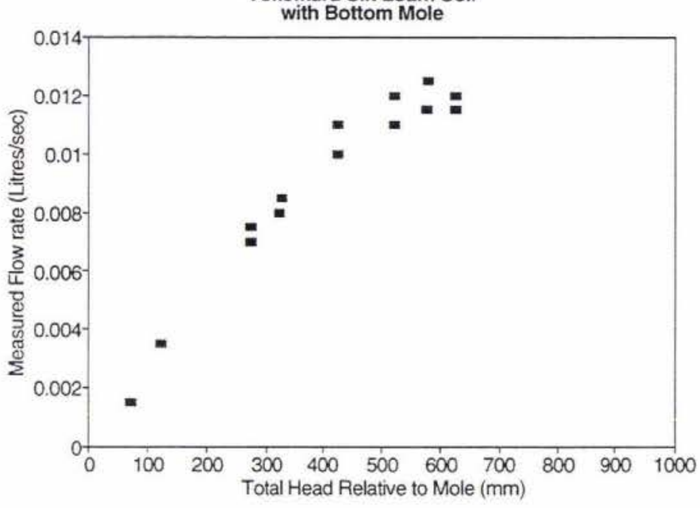

Figure-4.17: A linear graph between the measured flow rate and head relative to the bottom mole position with tokomaru silt loam soil backfill.

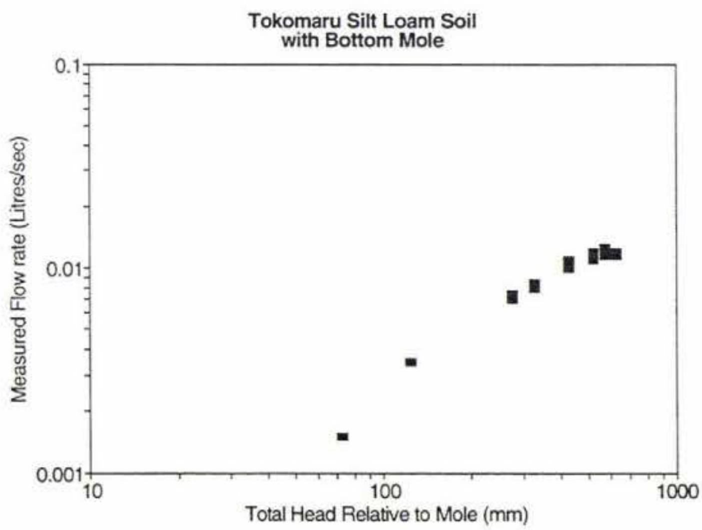

Figure-4.18: A log-log graph between the measured flow rate and head relative to the bottom mole position with tokomaru silt loam soil backfill.

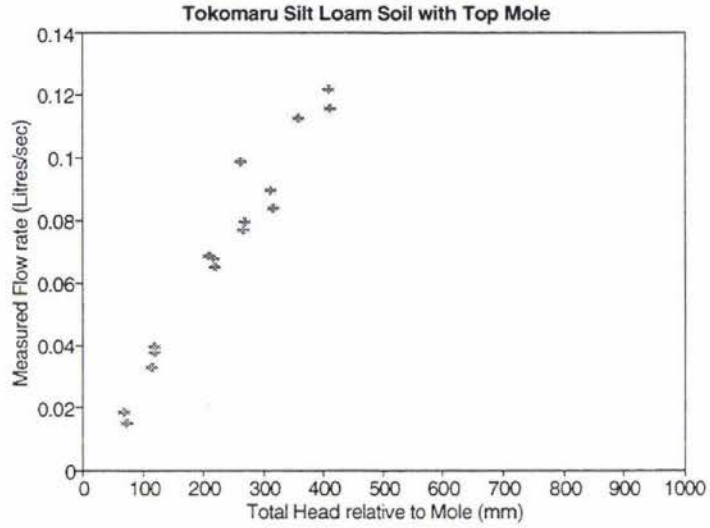

Figure-4.19: A linear graph between the measured flow rate and head relative to the top mole position with tokomaru silt loam soil backfill.

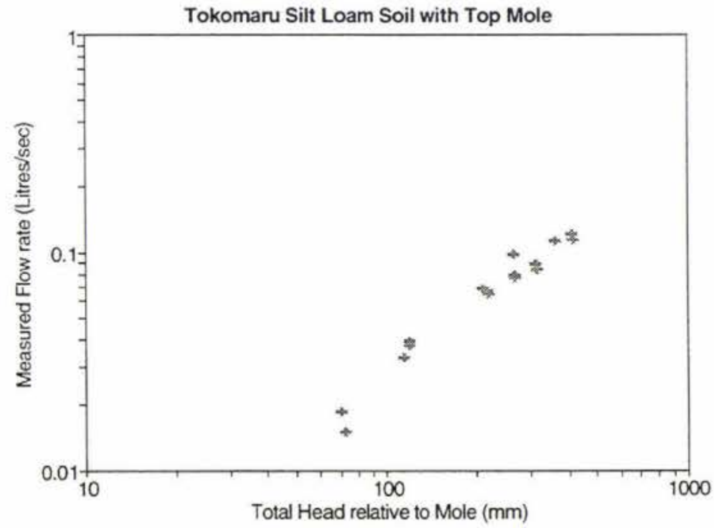

Figure-4.20: A log-log graph between the measured flow rate and head relative to the top mole position with tokomaru silt loam soil backfill.

Non linear regression analysis graphs

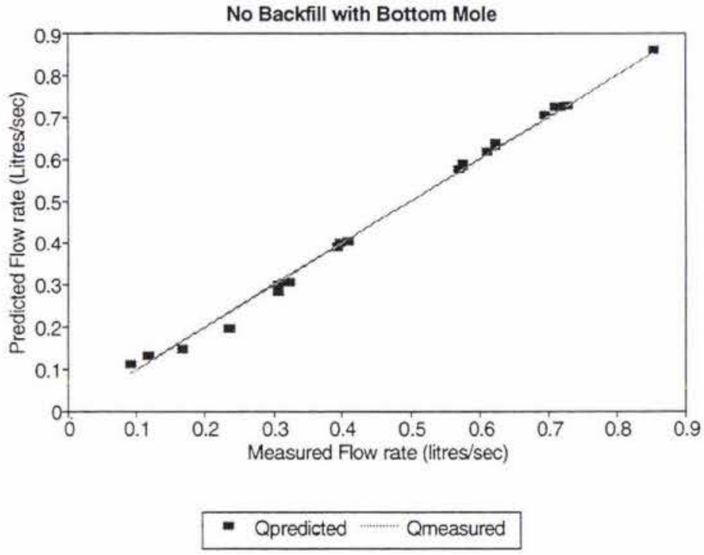

Figure-4.21: A graph showing the correlation between the predicted and measured flow rates for no backfill with bottom mole position.

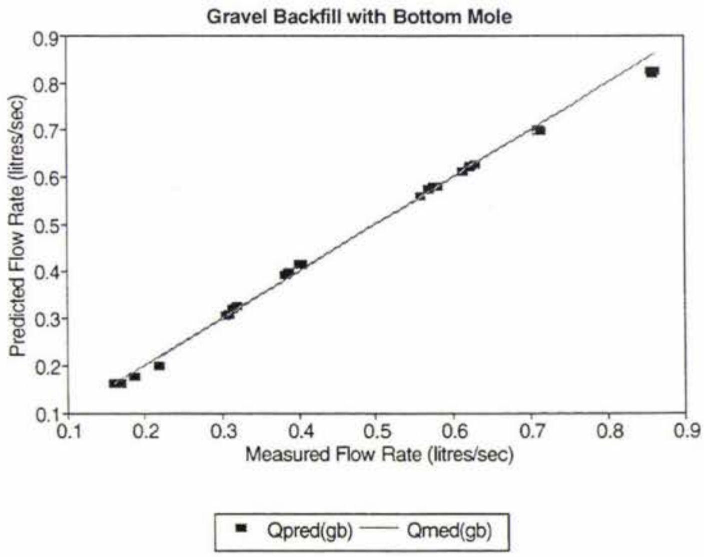

Figure-4.22: A graph showing the correlation between the predicted and measured flow rates for gravel backfill with bottom mole position.

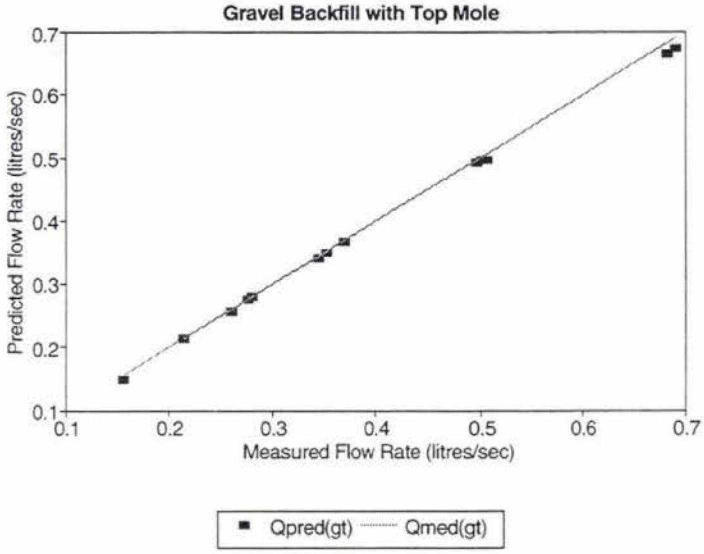

Figure-4.23: A graph showing the correlation between the predicted and measured flow rates for gravel backfill with top mole position.

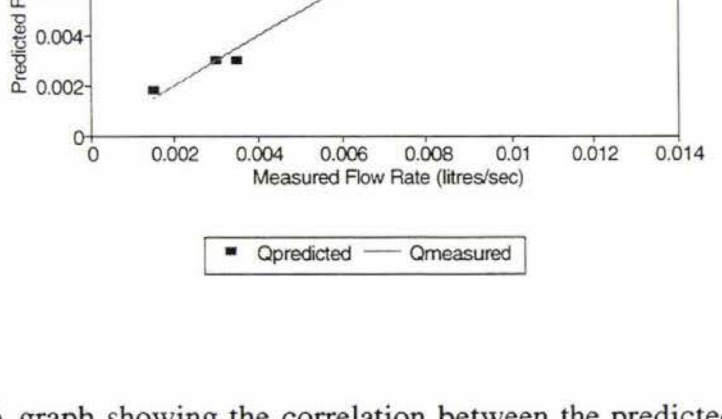

Figure-4.24: A graph showing the correlation between the predicted and measured flow rates for T.S.L. soil backfill with bottom mole position.

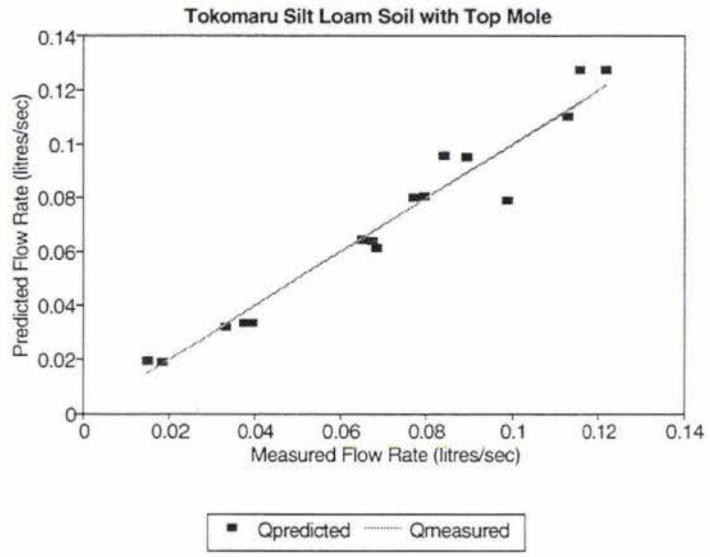

Figure-4.25: A graph showing the correlation between the predicted and measured flow rates for T.S.L. soil backfill with top mole position.

The predicted flow rate values in (l/s) for the various treatments versus the head (H) values relative to the mole position using the model equation are shown in figure (4.26). It is clear that there is little difference in predicted flow rate between the case of no backfill at bottom mole position and gravel backfill at bottom and top mole positions. The three curves overlap each other. This is most likely due to experimental error and the fit of the non linear regression analysis.

The results show that the geometry of the system had little effect on the flow characteristics of the bin. Furthermore the gravel backfill posed little resistance to flow compared to the flow meter. There was a significant reduction in flow rate for the same head when Tokomaru silt loam was used as a backfill compared to the gravel. Although the position of the mole apparently caused a significant difference in the flow rate this result is most likely due to compaction of the material between experiments. This point will be discussed further in section 4.2.5.

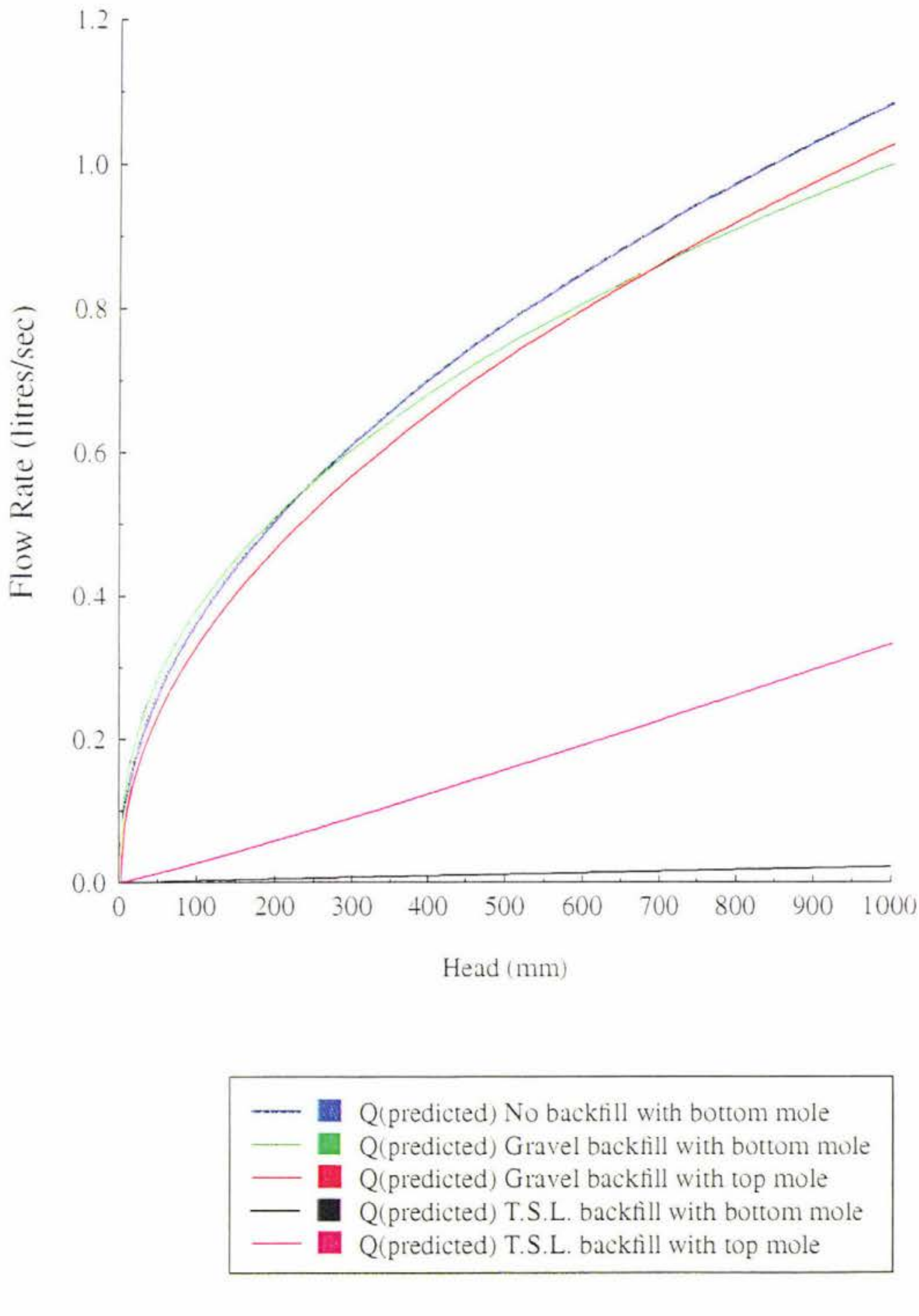

Figure-4.26: A graph between the predicted flow rate and the head relative to mole position for different backfill treatments with bottom and top mole positions.

4.2 Determination of Saturated Hydraulic Conductivity (K_{sat})

The saturated hydraulic conductivity of the gravel, and Tokomaru silt loam soil was determined in the laboratory using the constant head and falling head permeameter techniques described by Jumikis (1972). In addition the saturated hydraulic conductivity of two recycled high density polyethylene materials in chip form was tested.

4.2.1 Theory

Saturated hydraulic conductivity (K_{sat}) can be determined under steady state and unsteady state conditions. Under steady state conditions, the constant head permeameter is more suited for gravel, sand, and coarse and medium sand. Under unsteady state conditions, the falling head permeameter is most suited for fine sands, silts, and clays (Jumikis, 1972).

4.2.1.1 Constant head determination K_{sat}

A constant head permeameter consists of a vertical cylinder containing the soil sample for which the saturated hydraulic conductivity is to be determine (figure 4.27). The soil sample can be in a disturbed state, or in an undisturbed state. Two piezometric tubes are attached to the permeameter cylinder spaced a distance (L) apart. The horizontal cross-sectional area of the cylinder, and hence the soil sample, perpendicular to the direction of flow of water through the soil sample is (A). Water pressure is applied and water enters the permeameter from its top giving a downward flow. The applied head is kept constant by allowing water to overflow at the top of the cylinder or through a suitably positioned port. The amount of water flowing during a certain time is collected in a graduated cylinder. The pressure difference $(h = h_1 - h_2)$ is the head loss required to overcome the resistance to flow over the reference length. According to Darcy's Law, the rate of flow of water through a porous material is given by equation (4.2) in a steady state situation.

$$Q = A\ K_{sat} i \tag{4.2}$$

where

Q = Flow rate (ml/sec)

A = Cross sectional area of flow (mm^2)

i = Hydraulic gradient (mm/mm)

K_{sat} = Saturated hydraulic conductivity of the material (mm/sec)

The hydraulic gradient *(i)* can be calculated from equation (4.3).

$$i = h/L \tag{4.3}$$

The apparent velocity of flow through the porous media *(v)* can be calculated from equation (4.4).

$$v = K_{sat} i \tag{4.4}$$

Rearrangement of equation (4.2) enables the determination of the saturated hydraulic conductivity using equation (4.5).

$$K_{sat} = v/i = Q/Ai \tag{4.5}$$

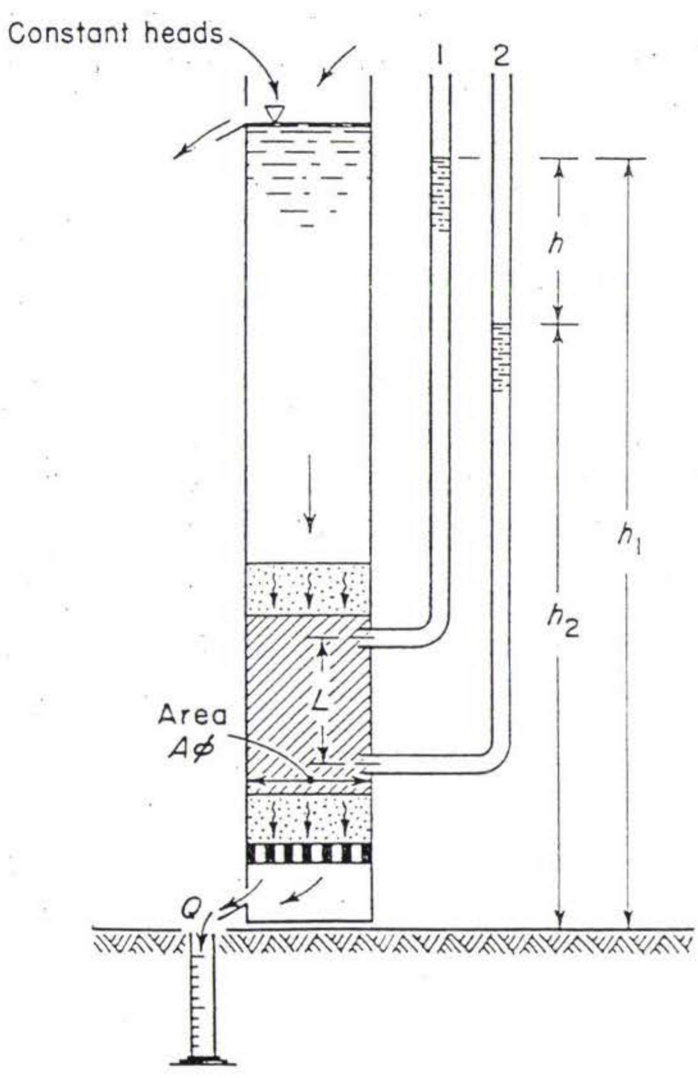

Figure-4.27: Constant head permeameter.

4.2.1.2 Falling head determination of K_{sat}

A falling head or variable head permeameter consists of a vertical test cylinder of cross-sectional area *(A)* containing the soil sample to be tested for permeability. To the top of the test cylinder is attached a vertical, transparent tube of constant cross-sectional area *(a)* (figure 4.28). The sample is first allowed to saturate then the standpipe filled to a certain height with water. The time (t_2-t_1) for the water level to drop from height (h_1) to (h_2) in the standpipe is recorded using a stop watch.

For this apparatus the saturated hydraulic conductivity can be determined from equation (4.6) (Jumikis, 1972).

$$K_{sat} = (a/A)\ L\ ln(h_1/h_2)/(t_2-t_1) \quad (4.6)$$

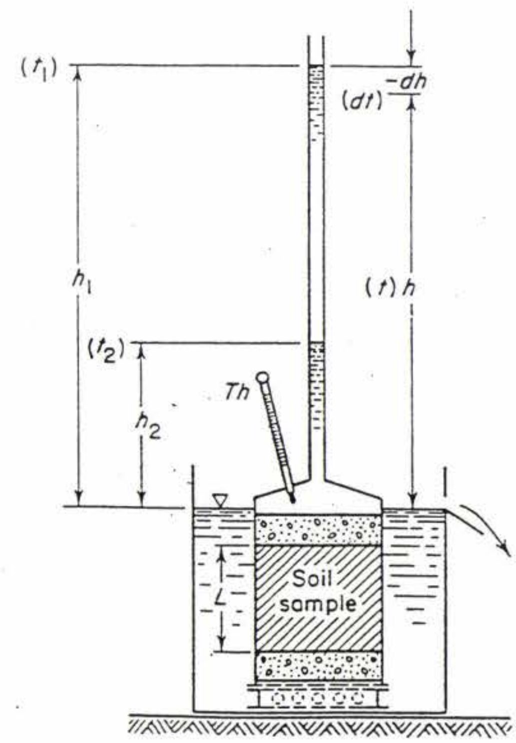

Figure-4.28: Falling head permeameter.

4.2.2 Equipment

A constant head permeameter was constructed in the laboratory (figure 4.29 and 4.30). It consisted of a 2m long clear perplex cylinder with an aluminium base plate and a removable top. The base and top were secured with three stainless steel rods running between them external to the cylinder. The cross-sectional area of the tube was 5037 mm^2. Water was added to the top of the cylinder through a tapping on the top plate. Water discharged from the base plate through a filter layer resting on a coarse screen. Twenty tappings were installed in the cylinder at 100mm centres to allow variation of the manometer tapping points and the overflow port. A steel ruler was attached to the outside of the cylinder to allow the head in the manometer tubes to be determined. The flow rate could be controlled by opening and closing a valve at the outlet from the base plate.

The constant head permeameter was also used as a falling head permeameter.

4.2.3 Method

4.2.3.1 Saturated hydraulic conductivity of gravel

Flow rate and head difference measurements of the sample were taken 22 times using the constant head permeameter. The constant head was maintained by using the top tapping point on the cylinder for all runs. A gravel sample of length 1000mm was placed in the permeameter cylinder (figure 4.29). The amount of water flowing through the sample was collected in a graduated cylinder over a known time. At each setting three measurements of flow rate were made and the average was recorded. The pressure head difference was determined from the manometers readings. The saturated hydraulic conductivity of the material was determined 22 times using equation (4.5).

Figure-4.29: The determination of *(K_{sat})* of gravel using the constant head permeameter.

4.2.3.2 Saturated hydraulic conductivity of H.D.P.E (milk bottle plastic chips)

Flow rate and head difference measurements of the sample were taken 10 times using the constant head permeameter using the technique described for the gravel (section 4.2.3.1). A sample of length 900mm was taken in the permeameter cylinder. A small amount of gravel was put on the top of the sample to stop chips floating in the permeameter (figure 4.30).

4.2.3.3 Saturated hydraulic conductivity of H.D.P.E (commodity bottle plastic chips)

Flow rate and head difference measurements of the sample were taken 10 times using the constant head permeameter, using the technique described for the gravel (section 4.2.3.1). A sample of length 800mm was used in the permeameter cylinder. A small amount of gravel was put on the top of the sample to stop chips floating in the permeameter (figure 4.31).

4.2.3.4 Saturated hydraulic conductivity of Tokomaru silt loam soil

The constant head vertical permeameter was used as a falling head permeameter. A soil sample of length 175 mm, taken from the bin around the top mole position, was put into the permeameter cylinder. The cylinder was filled up with water and the sample was allowed to saturate. The time for the water level to fall 100mm, from 1000mm to 900mm above the sample surface, was measured with a stop watch. (K_{sat}) values were determined 5 times using equation (4.6). Saturated hydraulic conductivity was also determined for another soil sample, taken from the bin around the bottom mole position after the mole had been moved to this new position. The sample was packed into the permeameter to achieve a bulk density of 1180kg/m^3 similar to that measured for samples taken from around the bottom mole position (see appendix

A1). Measurements were repeated five times for this sample.

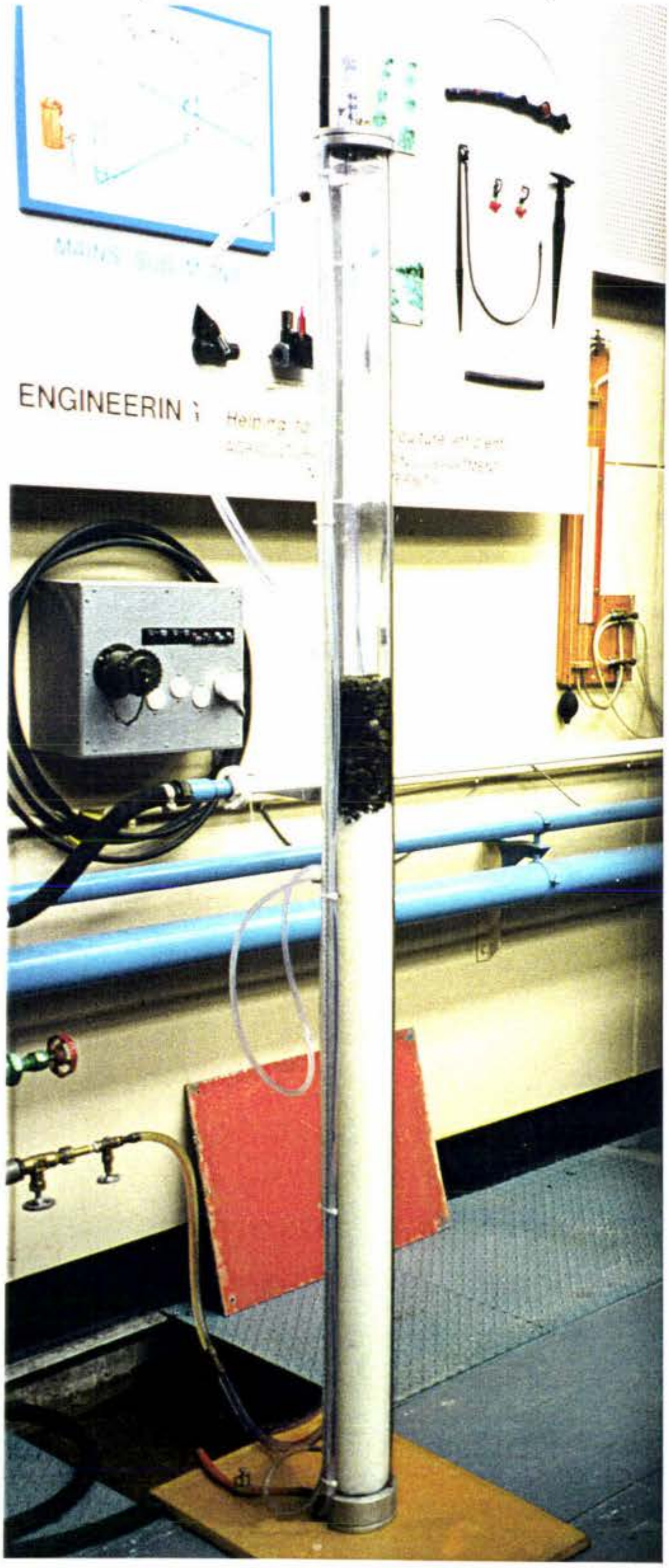

Figure-4.30: The determination of (K_{sat}) of milk bottle plastic chips using the constant head permeameter.

Figure-4.31: The determination of (K_{sat}) of commodity bottle plastic chips using the constant head permeameter.

4.2.4 Results

Results of the determination of the saturated hydraulic conductivity for gravel, H.D.P.E material, and Tokomaru silt loam soil backfills are presented in tabular form in tables (4.7, 4.8, 4.9, and 4.10). It was noted that for the constant head permeameter the largest variation in measured flow rate at any one setting was ±2% of the average and most were within ±0.5%.

No. of Obs.	Q (Avg.) (ml/sec)	h (mm)	v (mm/sec)	i (mm/mm)	Ksat (mm/sec)
1	14.3	4	2.8	0.004	710
2	28.5	9	5.7	0.009	629
3	60.4	30	12.0	0.030	400
4	100.3	77	19.9	0.077	259
5	144.2	138	28.6	0.138	207
6	10.3	2	2.1	0.002	1025
7	29.2	8	5.8	0.008	725
8	48.0	21	9.5	0.021	454
9	69.8	37	13.9	0.037	374
10	139.6	117	27.7	0.117	237
11	31.9	11	6.3	0.011	575
12	50.7	21	10.1	0.021	479
13	76.0	41	15.1	0.041	368
14	104.0	68	20.7	0.068	304
15	151.3	139	30.0	0.139	216
16	5.2	1	1.0	0.001	1032
17	15.1	4	3.0	0.004	747
18	22.7	7	4.5	0.007	643
19	30.7	11	6.1	0.011	553
20	51.3	22	10.2	0.022	463
21	79.5	42	15.8	0.042	376
22	113.0	86	22.4	0.086	261

Table 4.7: A table showing the (K_{sat}) measurements for gravels.

No. of Obs.	Q (Avg.) (ml/sec)	h (mm)	v (mm/sec)	i (mm/mm)	Ksat (mm/sec)
1	5.6	26	1.1	0.028	40
2	18.0	109	3.6	0.120	30
3	23.3	160	4.6	0.170	27
4	28.0	200	5.6	0.220	25
5	57.9	521	11.5	0.580	20
6	17.9	113	3.6	0.125	28
7	24.0	167	4.8	0.185	26
8	33.3	248	6.6	0.275	24
9	45.9	387	9.1	0.430	21
10	55.9	505	11.1	0.560	20

Table 4.8: A table showing the *(K_{sat})* measurements for milk bottle plastic chips.

No. of Obs.	Q (Avg.) (ml/sec)	h (mm)	v (mm/sec)	i (mm/mm)	Ksat (mm/sec)
1	7.9	18	1.6	0.023	70
2	13.3	36	2.6	0.045	59
3	22.5	68	4.5	0.085	53
4	25.2	80	5.0	0.100	50
5	72.3	375	14.4	0.470	31
6	22.3	67	4.4	0.084	53
7	34.5	125	6.9	0.156	44
8	47.5	190	9.4	0.238	40
9	69.2	314	13.7	0.393	35
10	82.8	460	16.4	0.575	29

Table 4.9: A table showing the *(K_{sat})* measurements for commodity bottle plastic chips.

Time (sec)	K_{sat} (mm/sec)
407	0.045
405	0.045
408	0.045
406	0.045
407	0.045

Note: L = 175mm, h_1 = 1000mm, h_2 = 900mm, and (a/A) =1.

Table 4.10: A table showing the (K_{sat}) measurements for Tokomaru silt loam soil.

4.2.5 Discussion

For the gravel backfill, (K_{sat}) varied widely from 200 to 1000 mm/sec (Table 4.7). Similarly for the H.D.P.E chips considerable variation was observed (Table 4.8). As it was suspected that (K_{sat}) might be effected by turbulence in the coarse material. It was decided to investigate the relationship between (K_{sat}) and apparent velocity of flow. Plots of (K_{sat}) versus flow velocity for the gravel and H.D.P.E chips are shown in figures 4.32, 4.33, and 4.34. These plots show clearly that K_{sat} decreases as velocity and hence turbulence increases. This phenomena has also been reported by Jumikis (1972).

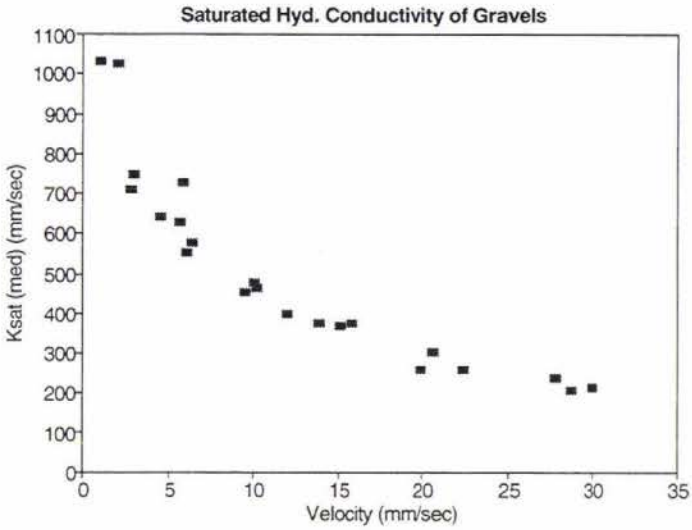

Figure-4.32: A linear graph between the measured (K_{sat}) and the velocity of flow of water through the gravel.

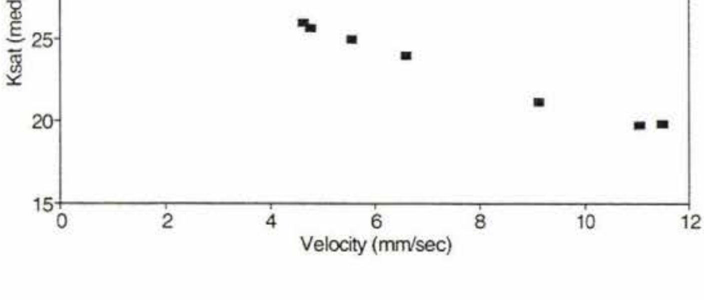

Figure-4.33: A linear graph between the measured (K_{sat}) and the velocity of flow of water through the milk bottle plastic chips.

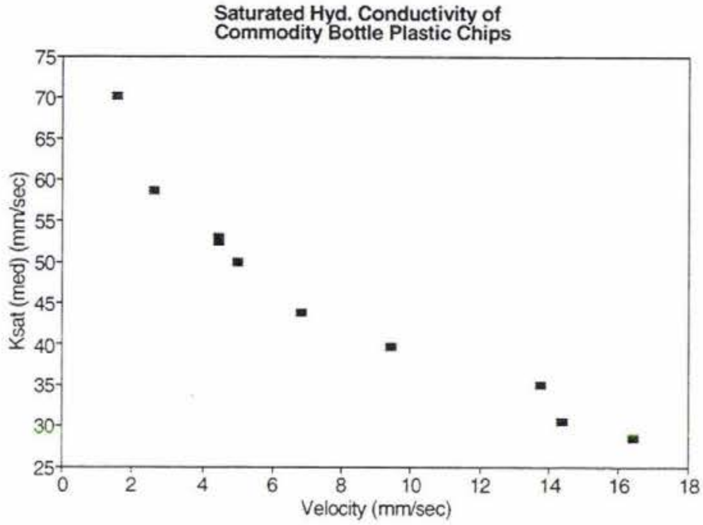

Figure-4.34: A linear graph between the measured (K_{sat}) and the velocity of flow of water through the commodity bottle plastic chips.

Semi-log plots as shown in figures 4.35, 4.36, and 4.37 of the same data tend to be linear suggesting a mathematical relationship of the form of equation 4.7.

$$K_{sat} = a - b \ln(v) \tag{4.7}$$

Non linear regression was used to fit the constants *(a)* and *(b)* for the gravel and H.D.P.E materials. These results are given in table 4.11 along with the correlation coefficients.

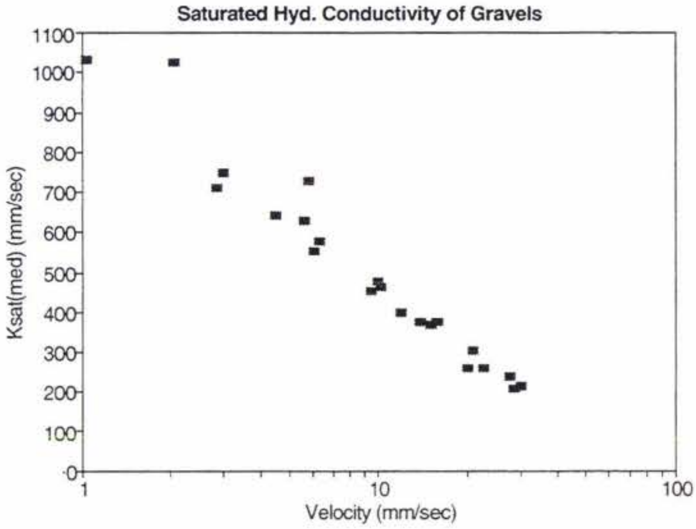

Figure-4.35: A semi-log graph between the measured *(K_{sat})* and the velocity of flow of water through the gravel.

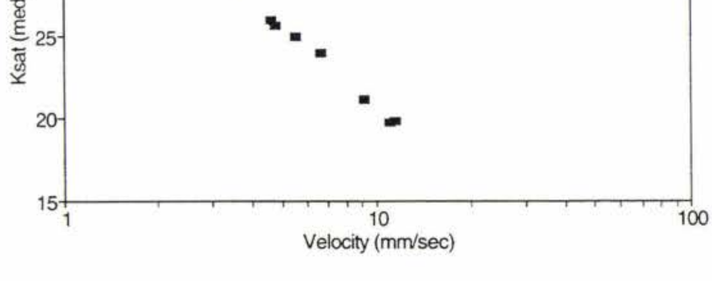

Figure-4.36: A semi-log graph between the measured *(K_{sat})* and the velocity of flow of water through the milk bottle plastic chips.

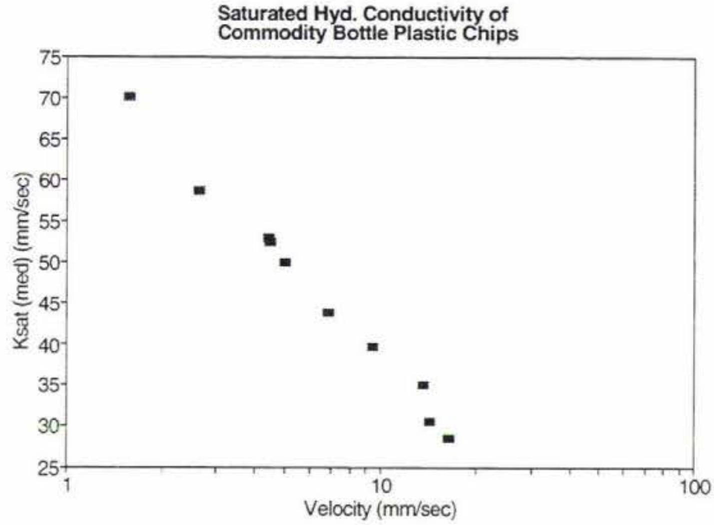

Figure-4.37: A semi-log graph between the measured (K_{sat}) and the velocity of flow of water through the commodity bottle plastic chips.

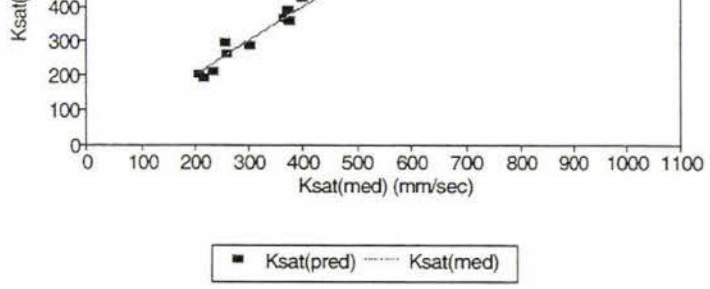

Figure-4.38 A graph showing the correlation between the predicted and measured (K_{sat}) values for the gravel.

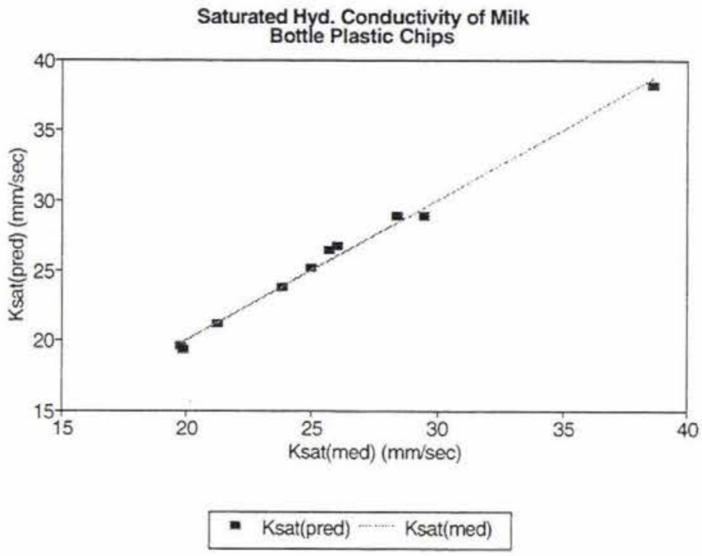

Figure-4.39 A graph showing the correlation between the predicted and measured (K_{sat}) values for the milk bottle plastic chips.

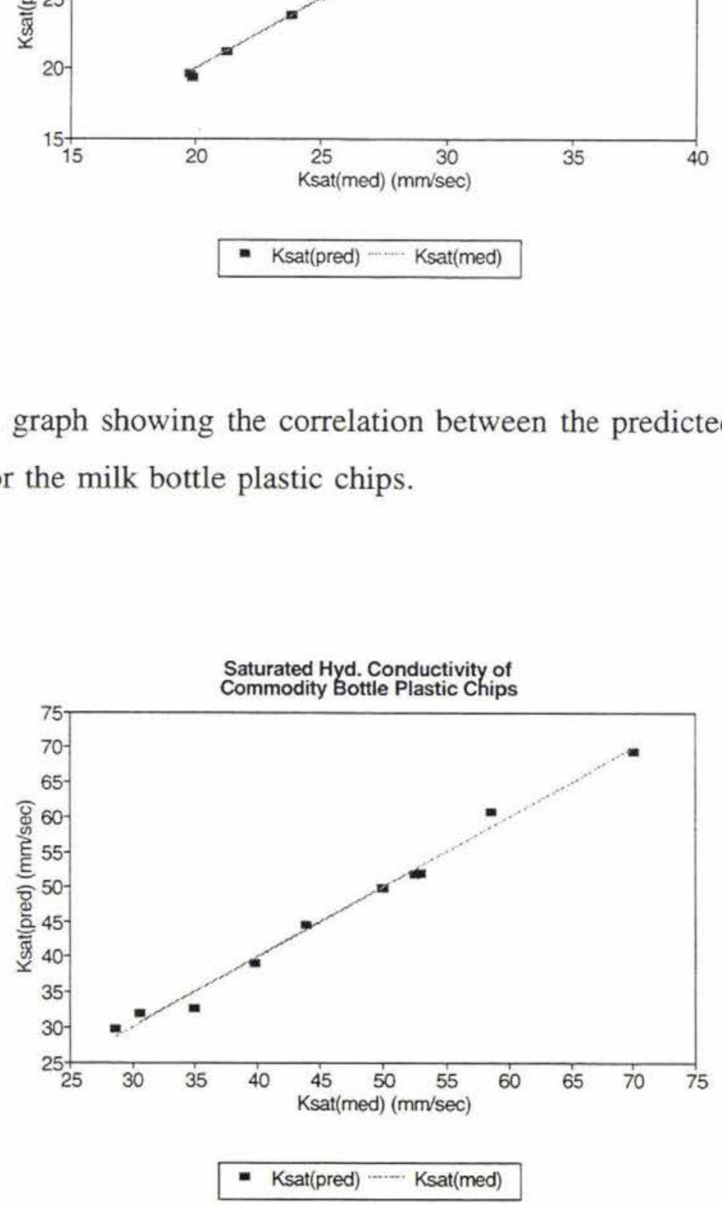

Figure-4.40 A graph showing the correlation between the predicted and measured (K_{sat}) values for the commodity bottle plastic chips.

Material type	*a*	*b*	Correlation(%)
Gravel	1063	-256	97.83%
Milk bottle chips (H.D.P.E)	39	-8	99.57%
Commodity bottle chips (H.D.P.E).	77	-17	99.50%

Table 4.11: A table showing the correlation coefficients, and *(a)* and *(b)* constants for different materials.

It can be seen from table 4.11 that reasonable fits were obtained between the predicted and measured K_{sat} values, which is also clear from figures 4.38, 4.39, and 4.40. The implication of these results is that as velocity increases a minimum value of saturated hydraulic conductivity is approached. This implies that the relationship between flow and hydraulic gradient in Darcy's equation is not necessarily linear. Increasing the pressure head available will not necessarily cause a linear increase in flow. Therefore, in a field situation, raising the head in the sump may not necessarily provide any beneficial increase in water flow.

In the first experiment, no control of bulk density was considered for the T.S.L sample. and the measured K_{sat} value obtained was 0.045 mm/sec (see table 4.11). For the second experiment, a bulk density of 1180 kg/m^3 was achieved similar to that measured for samples taken from around the bottom mole position (see appendix A1). It was noted that there was no flow through the sample and no (K_{sat}) value was obtained. This may help explain why the bin results were so different for top and bottom mole positions.

Chapter 5

GENERAL DISCUSSION

In chapter 4 the head flow characteristics of an ideal lateral to mole connection system where determined and related to the physical and hydraulic properties of the backfill material. The laboratory experiment was ideal in the sense that the hydraulic connection between the lateral and the mole was 100% efficient, that is the flow rate of water into the bin through the lateral equalled the flow rate out of the bin through the mole.

However, in the field this ideal connection would not be expected due to lateral and downward vertical water movement from the lateral into the surroundings soil. An efficiency of hydraulic connection between the lateral and the mole can be defined as

$$\eta = \text{Flow rate into mole/Flow rate out of lateral section}$$

By considering the evapotranspiration rate from an area of land supplied by one mole it is possible to determine the flow rate required into that mole and hence the efficiency of hydraulic connection required.

In order to determine the peak effective subirrigation requirements in the field it is assumed that the spacing between laterals and hence effective length of a mole channel is 50 m, and the spacing between the mole channels is 2 m. These are typical dimensions for systems installed on flat land in New Zealand. Furthermore it is assumed that the peak evapotranspiration rate is 10mm/day. This will be a maximum under most New Zealand conditions and allows for deep percolation losses downward and laterally in the field.

The area fed by each mole-lateral combination will therefore be 100 m^2. The maximum amount of irrigation (Q) required per mole per day can be calculated from equation (5.1).

$$Q = ET\ A \tag{5.1}$$

For the system outlined above Q will be 100 litre/day/mole or 0.0116 l/sec/mole on average if irrigation is applied 24 hours per day or 0.0232 l/sec/mole using a more realistic 12 hour irrigation cycle.

In the laboratory experiment with gravel backfill, the maximum flow rate was 0.862 l/sec per mole with 500mm head relative to the mole position. This would be a typical head if the water level in the sump is maintained just below ground level. This means the hydraulic connection efficiency between mole and lateral must only be 2.6% or greater for the system to work in the field with a 12 hour irrigation cycle (1.3% for continuous irrigation). Because the saturated hydraulic conductivity (K_{sat}) of the gravels is 10^6 times greater than the saturated hydraulic conductivity (K_{sat}) of the surrounding Tokomaru silt loam soil, water is more likely to move upward from lateral to mole than downward or laterally. Therefore the efficiency of hydraulic connection between lateral and mole is likely to be high. This means that with gravel backfill there is unlikely to be a problem in getting sufficient water from a lateral to a mole channel, irrespective of the mole position above the lateral.

However, with the Tokomaru silt loam soil the maximum flow rate was 0.12 l/sec against the head value 500mm relative to the mole position. This means that the hydraulic connection efficiency between mole and lateral must be at least 20 % to work in the field with a 12 hour irrigation cycle (10% for continuous irrigation). Because the saturated hydraulic conductivity *(K_{sat})* of the backfill in this case is more or less equal to the saturated hydraulic conductivity *(K_{sat})* of the surrounding material there is likely to be more downward and lateral movement than upward movement from lateral to mole. Therefore the efficiency of hydraulic connection is likely to be very low. This helps explains why the subsurface tile drainage system with mole channels used in the field experiment did not work as a subirrigation system.

If the sizing of system is reduced by reducing the lateral spacing and hence the effective mole length or reducing the mole spacing then the efficiency of hydraulic connection required will be reduced. For example 40m lateral spacing with 1m mole spacing gives a maximum irrigation requirement of 0.005 l/sec/mole. This means that the system requires just 1.2% hydraulic connection efficiency to work in the field with gravel backfill or ≥ 8% with tokomaru silt loam soil backfill and a 12 hour irrigation cycle. Under these circumstances soil backfill may work but the extra cost of laterals and mole spacing may be prohibitive.

Economically it may be worth while to consider using the milk bottles or commodity bottles plastic chips as a backfill material. They are light in weight and their saturated hydraulic conductivity lies between the K_{sat} values of gravel and tokomaru silt loam soil (see table 5.1).

Costs of gravel and H.D.P.E chips are given in table 5.2. It is clear that gravel is cheaper than milk and commodity bottle plastic chips, but their transportation cost is much higher than the H.D.P.E. material. Because the bulk density value of the milk and commodity bottle plastic chips is four times less than the bulk density of gravel, this means it requires less amount of material to get the same volume (see

Table 5.1). It is also obvious from table 5.2 that if gravel material is transported 2 or 3 kilometre then it will cost more than the commodity bottle plastic chips. A possible disadvantage of commodity bottle plastic chip is that it may not be perceived to be environmentally friendly. Although H.D.P.E is reportedly inert, use of plastic waste in this manner may not be desirable.

Material type	Bulk density (kg/m^3)	K_{sat} (mm/sec)
Gravel	1442	200 - 1000
Milk bottle plastic chips	313	20 - 40
Commodity bottle plastic chips	272	30 - 70
Tokomaru silt loam soil	1180	0.03 - 0.045

Table 5.1: A table showing the bulk density and K_{sat} values for different materials.

Material type	Cost ($dollar/m^3$)	Transportation ($dollar/km/m^3$)
Gravel	37.36	35
Milk bottle plastic chips	313.29	0.32
Commodity bottle plastic chips	108.67	0.32

*(All prices include GST).

Table 5.2: A table showing the difference in cost for gravel and H.D.P.E. material.

Chapter 6

CONCLUSIONS - RECOMMENDATIONS

6.1 Conclusions

According to the results obtained in the field experiment it was concluded that sufficient water did not move from the drainage lateral to the moles. Reasons behind this may include that enough water was not applied, enough pressure head was not available to force water to move from drainage lateral to moles, and the hydraulic conductivity of the backfill was too low, as discussed in chapter 3.

According to the results obtained from the bin model laboratory experiment, the following conclusions can be drawn:

1) With gravel and Tokomaru silt loam soil backfill, flow rate through the mole increased as the pressure head relative to mole position increased.
2) The flow rate through the system with gravel backfill was eight times more than the flow rate with Tokomaru silt loam soil. This means there is unlikely to be a problem with subirrigation with gravel backfill.
3) With gravel backfill, an hydraulic connection efficiency between the lateral and mole of around 2 to 3% is required.

4) With tokomaru silt loam soil backfill, the hydraulic connection efficiency between the lateral and the mole must be 10 to 20% to work in the field. Because the saturated hydraulic conductivity in the backfill trench is equal to the saturated hydraulic conductivity in the surrounding material. Therefore the efficiency of hydraulic connection is likely to be very low and that is why the system did not work in the field experiment.

5) With tokomaru silt loam soil backfill the flow rate was higher at the top mole position than bottom mole position but this was most likely due to compaction of the soil not due to the mole position.

6) Recycled plastic bottle chips may be useful as an alternative backfill material. Their low bulk density means that transportation costs would be lower leading to overall lower costs in most situations. However the environmental friendliness of the material is unknown at this stage.

6.2 Recommendations for future research

In light of the above Conclusions, it is recommended that the following topics merit further research:

1) Studies should be conducted to determine the potential of subirrigation systems in fine textured soils. with mole drains using gravel as a backfill material.

2) Laboratory experiments should be conducted to determine the head flow relationships for other alternative backfill materials. The effect of saturated hydraulic conductivity of these relationships could also be investigated in more detail. A mathematical model of the flow pattern in the backfill trench could be developed and tested for this purpose.

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APPENDICES

A1 Determination of Bulk density, Particle density, and Porosity

A1.1 Theory

Bulk density

The bulk density of a material (D_b) can be found by determining the mass of a dry sample (M_s) in a known volume (V_t) (equation A1.1).

$$D_b = M_s/V_t \tag{A1.1}$$

Particle Density

The particle density (D_s) can be found by displacment of air in a dry sample of known volume and determining the volume of water added by weighting the wet sample (equation A1.2).

$$D_s = M_s/(V_t-V_w) \tag{A1.2}$$

Porosity

The porosity of a sample *(n)* can be determined once the bulk density and particle density are known (equation A1.3).

$$n = (1 - D_b/D_s) \times 100\% \tag{A1.3}$$

A1.2 Equipment and Method

The bulk density, particle density, and porosity of gravel was determined using a cylindrical can 100mm in diameter and 120mm long (volume 800mm^3). The weight of the can was 90gm. The can was filled with the gravel sample, weighed, and then water was added into it very slowly in order to remove the air from it. Then it was weighed again (table A1.1). The procedure was repeated five times.

Similarly, the bulk density, particle density, and porosity of the H.D.P.E material (milk & commodity bottle plastic chips) was determined five times as shown in table (A1.2).

For the Tokomaru silt loam soil, the bulk density was measured by the core method (Jumikis, 1972) using cylindrical cores 50mm long and 50mm in diameter (volume 865mm^3). Five core soil samples were taken from the bin around the top mole position and five core soil sample were taken from the bin around the bottom mole position. All the core samples were weighed and then dried by putting them in the oven for 24 hours at 105 C^o. Then the dry mass of all the soil samples *(Ms)* in grams was determined. The bulk density and porosity of the tokomaru silt loam soil samples, taken from the bin around the top and bottom mole positions, were determined (table A1.3). The particle density of the tokomaru silt loam soil was taken to be 2600 kg/m^3 (Pollok, 1975).

A1.3 Results and Discussion

Results of the measurements are presented in tables A1.1, A1.2, and A1.3. From the bulk density measurements, it was found that the bulk density value for the soil sample taken from the bin around the top mole position was less (1132 kg/m^3) than for the soil sample taken from the bin around the bottom mole position (1180 kg/m^3) which suggests greater compaction of soil around the bottom mole. This may explain why the flow rates in the experiment with the mole in the bottom position were lower than those with the mole in the top position. In the process of digging out the soil to move the mole, from the top to bottom position, it was suspected that the soil layer immediately above the lateral, which was not disturbed, was compacted more than in the original case. Furthermore, there was more opportunity for clay particles to block the gravel filter layer around the lateral.

No of Obs.	Weight of empty can (gm)	Can + dry sample (gm)	Can + sample+ water (gm)	Weight of water poured (gm)	Vw (cm**3)	Ms (gm)	Vt-Vw (cm**3)	Bulk Density (kg/m**3)	Particle Density (kg/m**3)	Porosity (percent)
1	90	1435	1805	370	370	1345	490	1564	2745	43
2	90	1270	1645	375	375	1180	485	1372	2433	44
3	90	1265	1650	385	385	1175	475	1366	2474	45
4	90	1310	1705	395	440	1220	420	1415	2905	51
5	90	1370	1785	415	340	1280	520	1488	2462	40
Average								1441	2604	44

Table A1.1: A table showing the bulk density, particle density, and porosity measurements of gravels.

No of Observ.	Weight of empty can (gm)	Volume of can Vt (cm**3)	Can + moist sample from bin (gm)	Can + dry sample (gm)	Mw (gm)	Ms (gm)	Moisture content (%)	Bulk Density (kg/m**3)	Particle Density (kg/m**3)	Porosity (percent)
1	27.08	91	174.56	132.22	42.34	105.14	40	1155	2600	56
2	29.39	91	165.79	127.04	38.75	97.65	40	1073	2600	59
3	28.84	91	171.94	128.15	43.79	99.31	44	1091	2600	58
4	29.71	91	187.53	145.02	42.51	115.31	37	1267	2600	51
5	27.55	91	164.71	125.2	39.51	97.65	40	1073	2600	59
Average							40	1132	2600	56

Table A1.2: A table showing the bulk density, particle density, and porosity measurements of Tokomaru silt loam soil samples taken from the bin around the top mole positions..

No of Observ.	Weight of empty cane (gm)	Volume of cane Vt (cm**3)	Cane + moist sample from bin (gm)	Cane + dry sample (gm)	Mw (gm)	Ms (gm)	Moisture content (%)	Bulk Density (kg/m**3)	Particle Density (kg/m**3)	Porosity (percent)
1	27.33	91	174.84	137.85	36.99	110.52	33	1215	2600	53
2	29.44	91	170.41	135.01	35.4	105.57	34	1160	2600	55
3	27.85	91	178.89	132.96	45.93	105.11	44	1155	2600	56
4	29.46	91	181.28	138.21	43.07	108.75	40	1195	2600	54
5	27.53	91	179.64	134.41	45.23	106.88	42	1175	2600	55
Average							39	1180	2600	55

Table A1.3: A table showing the bulk density, particle density, and porosity measurements of Tokomaru silt loam soil samples taken from the bin around the bottom mole positions..

No of Obs.	Weight of empty can (gm)	Can + dry sample (gm)	Can + sample+ water (gm)	Weight of water poured (gm)	Vw (cm**3)	Ms (gm)	Vt-Vw (cm**3)	Bulk Density (kg/m**3)	Particle Density (kg/m**3)	Porosity (percent)
1	95	360	900	540	540	265	325	306	815	62
2	95	365	910	545	545	270	320	312	844	63
3	95	370	915	545	545	275	320	318	859	63
4	95	355	880	525	525	260	340	301	765	61
5	95	380	920	540	540	285	325	329	877	62
Average								313	832	62

Table A1.4: A table showing the bulk density, particle density, and porosity measurements of milk bottle plastic chips.

No of Observ.	Weight of empty cane (gm)	Cane + dry sample (gm)	Cane + sample+ water (gm)	Weight of water poured (gm)	Vw (cm**3)	Ms (gm)	Vt-Vw (cm**3)	Bulk Density (kg/m**3)	Particle Density (kg/m**3)	Porosity (percent)
1	95	320	860	540	540	225	325	260	692	62
2	95	325	865	540	540	230	325	266	708	62
3	95	340	875	535	535	245	330	283	742	62
4	95	350	890	540	540	255	325	295	785	62
5	95	315	860	545	545	220	320	254	688	63
Average								272	723	62

Table A1.5: A table showing the bulk density, particle density, and porosity measurements of milk bottle plastic chips.

A2 Particle Size Analysis of the Gravels, Milk Bottles Plastic Chips, Commodity Bottles Plastic Chips and Tokomaru Silt Loam Soil

A2.1 Equipment and Method

Sieve analysis was done five times to measure the particle size of the gravels, milk bottles plastic chips, and commodity bottles plastic chips samples. A known weight of the sample was taken in a recommended sets of sieve. This set of sieves was shaken for 3 minutes using the electric shaker. The amount of the sample retained on the each sieve was weighed and cumulative passing percentage was calculated for each material sample.

A2.2 Results

Results of the measurements are presented in tables A2.1, A2.2, and A2.3.

Sample number	1 Sieve Weight (gm)	2 Seive Openings (mm)	3 Total Weight Seived(G) (gm)	4 Retained + seive (gm)	5 Retained on seive (gm)	6 Retained on seive (%)	7 Cumulative retained (g)	8 Cumulative retained (%)	9 Cumulative passing (g)	10 Cumulative passing (%)
I		20		0.0	0.0	0.0	0.0	0	1289.7	100
	539.3	16	1289.7	684.9	145.6	11.3	145.6	11	1144.1	89
	544.4	11.2		1333.8	789.4	61.2	935.0	72	354.7	28
	515	8		861.9	346.9	26.9	1281.9	99	7.8	1
	506.1	5.6		513.9	7.8	0.6	1289.7	100	0.0	0
	405.7	Pan		405.7	0.0	0.0	1289.7	100	0.0	0
	Sum				1289.7	100.0				
II		20			0.0	0.0	0.0	0	1277.6	100
	539.3	16	1277.6	693.5	154.2	12.1	154.2	12	1123.4	88
	544.4	11.2		1269.2	724.8	56.7	879.0	69	398.6	31
	515	8		898.0	383.0	30.0	1262.0	99	15.6	1
	506.1	5.6		520.9	14.8	1.2	1276.8	100	0.8	0
	405.7	Pan		406.5	0.8	0.1	1277.6	100	0.0	0
	Sum				1277.6	100.0				
III		20			0.0	0.0	0.0	0	1354.1	100
	539.3	16	1354.1	714.4	175.1	12.9	175.1	13	1179.0	87
	544.4	11.2		1317.7	773.3	57.1	948.4	70	405.7	30
	515	8		905.8	390.8	28.9	1339.2	99	14.9	1
	506.1	5.6		517.8	11.7	0.9	1350.9	100	3.2	0
	405.7	Pan		408.9	3.2	0.2	1354.1	100	0.0	0
	Sum				1354.1					
IV		20			0.0	0.0	0.0	0	1303.3	100
	539.3	16	1303.3	679.0	139.7	10.7	139.7	11	1163.6	89
	544.4	11.2		1304.3	759.9	58.3	899.6	69	403.7	31
	515	8		891.9	376.9	28.9	1276.5	98	26.8	2
	506.1	5.6		529.7	23.6	1.8	1300.1	100	3.2	0
	405.7	Pan		408.9	3.2	0.2	1303.3	100	0.0	0
	Sum				1303.3					
V		20			0.0	0.0	0.0	0	1245.7	100
	539.3	16	1245.7	670.5	131.2	10.5	131.2	11	1114.5	89
	544.4	11.2		1259.0	714.6	57.4	845.8	68	399.9	32
	515	8		828.3	373.3	30.0	1219.1	96	26.6	2
	506.1	5.6		529.6	23.5	1.9	1242.6	100	3.1	0
	405.7	Pan		408.8	3.1	0.2	1245.7	100	0.0	0
	Sum				1245.7					

Table A2.1: A table showing the particle size analysis measurements of gravels.

Sample number	1 Sieve Weight (gm)	2 Seive Openings (mm)	3 Total Weight Seived(G) (gm)	4 Retained + seive (gm)	5 Retained on seive (gm)	6 Retained on seive (%)	7 Cumulative retained (g)	8 Cumulative retained (%)	9 Cumulative passing (g)	10 Cumulative passing (%)
I		16	521.1	0.0	0.0	0.0	0.0	0	521.1	100
	585	9.5		585.1	0.1	0.0	0.1	0	521.0	100
	569.5	4.75		888.8	319.3	61.3	319.4	61	201.7	39
	644.4	2.36		787.3	142.9	27.4	462.3	89	58.8	11
	533.3	1.18		584.8	51.5	9.9	513.8	99	7.3	1
	538.4	0.6		544.9	6.5	1.2	520.3	100	0.8	0
	500.4	0.3		501.2	0.8	0.2	521.1	100	0.0	0
	345	Pan		345.0	0.0	0.0	521.1	100	0.0	0
Sum					521.1	100.0				
II		16	334.0	0.0	0.0	0.0	0.0	0	334.0	100
	585	9.5		585.3	0.3	0.1	0.3	0	333.7	100
	569.5	4.75		713.3	143.8	43.1	144.1	43	189.9	57
	644.4	2.36		779.8	135.4	40.5	279.5	84	54.5	16
	533.3	1.18		580.2	46.9	14.0	326.4	98	7.6	2
	538.4	0.6		545.4	7.0	2.1	333.4	100	0.6	0
	500.4	0.3		501.0	0.6	0.2	334.0	100	0.0	0
	345	Pan		345.0	0.0	0.0	334.0	100	0.0	0
Sum					334.0	100.0				
III		16	327.8	0.0	0.0	0.0	0.0	0	327.8	100
	585	9.5		585.3	0.3	0.1	0.3	0	327.5	100
	569.5	4.75		703.1	133.6	40.8	133.9	41	193.9	59
	644.4	2.36		783.4	139.0	42.4	272.9	83	54.9	17
	533.3	1.18		581.4	48.1	14.7	321.0	98	6.8	2
	538.4	0.6		544.9	6.5	2.0	327.5	100	0.3	0
	500.4	0.3		500.7	0.3	0.1	327.8	100	0.0	0
	345	Pan		345.0	0.0	0.0	327.8	100	0.0	0
Sum					327.8	100.0				
IV		16	293.5	0.0	0.0	0.0	0.0	0	293.5	100
	585	9.5		585.3	0.3	0.1	0.3	0	293.2	100
	569.5	4.75		683.2	113.7	38.7	114.0	39	179.5	61
	644.4	2.36		775.4	131.0	44.6	245.0	83	48.5	17
	533.3	1.18		576.0	42.7	14.5	287.7	98	5.8	2
	538.4	0.6		544.0	5.6	1.9	293.3	100	0.2	0
	500.4	0.3		500.6	0.2	0.1	293.5	100	0.0	0
	345	Pan		345.0	0.0	0.0	293.5	100	0.0	0
Sum					293.5	100.0				
V		16	278.9	0.0	0.0	0.0	0.0	0	278.9	100
	585	9.5		585.3	0.3	0.1	0.3	0	278.6	100
	569.5	4.75		673.5	104.0	37.3	104.3	37	174.6	63
	644.4	2.36		769.5	125.1	44.9	229.4	82	49.5	18
	533.3	1.18		576.6	43.3	15.5	272.7	98	6.2	2
	538.4	0.6		544.3	5.9	2.1	278.6	100	0.3	0
	500.4	0.3		500.7	0.3	0.1	278.9	100	0.0	0
	345	Pan		345.0	0.0	0.0	278.9	100	0.0	0
Sum					278.9	100.0				

Table A2.2: A table showing the particle size analysis measurements of H.D.P.E material (milk bottle plastic chips).

Sample number	1 Sieve Weight (gm)	2 Seive Opening (mm)	3 Total Weight Seived(G) (gm)	4 Retained + seive (gm)	5 Retained on seive (gm)	6 Retained on seive (%)	7 Cumulative retained (g)	8 Cumulative retained (%)	9 Cumulative passing (g)	10 Cumulative passing (%)
I		16	322.7	0.0	0.0	0.0	0.0	0	322.7	100
	585	9.5		597.7	12.7	3.9	12.7	4	310.0	96
	569.5	4.75		812.7	243.2	75.4	255.9	79	66.8	21
	644.4	2.36		702.3	57.9	17.9	313.8	97	8.9	3
	533.3	1.18		540.4	7.1	2.2	320.9	99	1.8	1
	538.4	0.6		539.0	0.6	0.2	321.5	100	1.2	0
	500.4	0.3		500.6	0.2	0.1	321.7	100	0.0	0
	345	Pan		345.0	0.0	0.0	321.7	100	0.0	0
Sum					321.7	99.7				
II		16	341.4	0.0	0.0	0.0	0.0	0	341.4	100
	585	9.5		597.0	12.0	3.5	12.0	4	329.4	96
	569.5	4.75		817.5	248.0	72.6	260.0	76	81.4	24
	644.4	2.36		710.5	66.1	19.4	326.1	96	15.3	4
	533.3	1.18		547.3	14.0	4.1	340.1	100	1.3	0
	538.4	0.6		539.5	1.1	0.3	341.2	100	0.2	0
	500.4	0.3		500.6	0.2	0.1	341.4	100	0.0	0
	345	Pan		345.0	0.0	0.0	341.4	100	0.0	0
Sum					341.4	100.0				
III		16	324.4	0.0	0.0	0.0	0.0	0	324.4	100
	585	9.5		597.8	12.8	3.9	12.8	4	311.6	96
	569.5	4.75		806.0	236.5	72.9	249.3	77	75.1	23
	644.4	2.36		707.0	62.6	19.3	311.9	96	12.5	4
	533.3	1.18		545.0	11.7	3.6	323.6	100	0.8	0
	538.4	0.6		539.0	0.6	0.2	324.2	100	0.2	0
	500.4	0.3		500.6	0.2	0.1	324.4	100	0.0	0
	345	Pan		345.0	0.0	0.0	324.4	100	0.0	0
Sum					324.4	100.0				
IV		16	376.6	0.0	0.0	0.0	0.0	0	376.6	100
	585	9.5		598.0	13.0	3.5	13.0	3	363.6	97
	569.5	4.75		844.5	275.0	73.0	288.0	76	88.6	24
	644.4	2.36		716.2	71.8	19.1	359.8	96	16.8	4
	533.3	1.18		548.8	15.5	4.1	375.3	100	1.3	0
	538.4	0.6		539.5	1.1	0.3	376.4	100	0.2	0
	500.4	0.3		500.6	0.2	0.1	376.6	100	0.0	0
	345	Pan		345.0	0.0	0.0	376.6	100	0.0	0
Sum					376.6	100.0				
V		16	377.2	0.0	0.0	0.0	0.0	0	377.2	100
	585	9.5		600.2	15.2	4.0	15.2	4	362.0	96
	569.5	4.75		833.6	264.1	70.0	279.3	74	97.9	26
	644.4	2.36		721.1	76.7	20.3	356.0	94	21.2	6
	533.3	1.18		552.0	18.7	5.0	374.7	99	2.5	1
	538.4	0.6		540.6	2.2	0.6	376.9	100	0.3	0
	500.4	0.3		500.7	0.3	0.1	377.2	100	0.0	0
	345	Pan		345.0	0.0	0.0	377.2	100	0.0	0
Sum					377.2	100.0				

Table A2.3: A table showing the particle size analysis measurements of H.D.P.E material (commodity bottle plastic chips).