ASSESSMENT OF HORIZONTAL MIGRATION BEHAVIOR OF LIGHT NON-AQUEOUS PHASE LIQUID (LNAPL) AT CAPILLARY FRINGE DUE TO FLUCTUATING GROUNDWATER TABLE AND PRECIPITATION

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SCHOOL OF CIVIL ENGINEERING
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By

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I hereby declare that all corrections and comments made by the supervisor(s)and examiner have been taken into consideration and rectified accordingly.

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ABSTRAK

Pencemaran air bawah tanah akibat tumpahan minyak berlaku di seluruh dunia dan telah menjadi isu serius kerana bekalan utama dan sumber air minuman adalah di bawah tanah. Tumpahan minyak boleh berlaku semasa pengangkutan minyak, penyimpanan dan kebocoran tangki simpanan bawah tanah (UST). Air bawah tanah yang tercemar akan memberi kesan kepada alam sekitar. Oleh itu, kerja-kerja pembaikan untuk membersihkan tanah dan air bawah tanah yang tercemar diperlukan untuk mengelakkan penyebaran dan tahap pencemaran berlaku di bawah tanah. Apabila LNAPL sampai ke bawah permukaan persekitaran yang berbeza, adalah sangat kompleks untuk menentukan tingkah laku migrasi LNAPL. Oleh itu, untuk mempunyai pemahaman yang jelas dan kecekapan pemulihan yang lebih baik, eksperimen tangki 2D telah dijalankan untuk mengkaji dan memerhatikan migrasi sisi dan mendatar LNAPL dengan kesan turun naik air bawah tanah dan intensiti kerpasan. Kaedah Analisis Imej Mudah (SIAM) telah diguna pakai dalam kajian ini untuk menentukan taburan tepu LNAPL dan air dalam tangki 2D dengan pelbagai jenis turun naik air bawah tanah, isipadu LNAPL tetap dan intensiti kerpasan.

ABSTRACT

When the LNAPL reach to the subsurface of different environment, it is very complex to determine the migration behavior of LNAPL. Therefore, to have a clear understanding and better remediation efficiency, 2D tank experiments were conducted to study the lateral and horizontal migration of LNAPL with the effect of groundwater fluctuation and precipitation intensity. Simplified Image Analysis Method (SIAM) was adopted in this study to determine the saturation distribution of LNAPL and water in the 2D tank with different types of groundwater fluctuation, fixed LNAPL volume and the precipitation intensity. In saturation of water under high groundwater tables fluctuation with the effect of precipitation, the water saturation increased with the effect of precipitation while during the drainage stage, the water saturation experience significant decreased. When LNAPL migration behaviour under high groundwater tables, it can be observed that the LNAPL saturation at 40 cm increased to around 22%, while at water table, it dropped to 12%. The LNAPL at 40 cm only fall about 7% and this condition can be described by the entrapped diesel within the soil pores. For the vertical migration behaviour of LNAPL, it can be observed that the LNAPL saturation increased to 6% and increased more during the next hour of precipitation stage. Other than that, the saturation of diesel increased in the capillary fringe zone because the diesel tends to migrate deeper with the help of gravitational force. For the lateral migration, it can be observed that the LNAPL saturation increased at 28 cm, 31 cm and 38 cm around 11%, 6% and 4% respectively. After the precipitation stage, it can be observed that the LNAPL saturation increased back for all the 3 different elevation mentioned above. The LNAPL saturation remained higher after the drainage to 28 cm because the risen of the water table pushed up the accumulated diesel at 28 cm elevation to float along new capillary fringe.

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LIST OF SYMBOLS

C_u	Coefficient of uniformity
C_c	Coefficient of curvature or gradation
G_s	Specific Gravity
k	Coefficient of permeability
m	Mass
S_o	Degree of saturation of oil
S_w	Degree of saturation of water
γ_d	Dry density

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BS	British Standard
BTEX	Benzene, Toluene, Ethyl benzene and Xylene
DNAPL	Dense Non-Aqueous Phase Liquid
DSLR	Digital Single Lens Reflex
LNAPL	Light Non-Aqueous Phase Liquid
MATLAB	Matrix Laboratory
NAPL	Non-Aqueous Phase Liquid
NEF	Nikon Electronic Format
PCE	Tetracholoethylene
SIAM	Simplified Image Analysis Method
TCE	Trichloroetyhlene
TIFF	Tag Image File Format
U.S. EPA	United States Environmental Protection Agency
USCS	Unified Soil Classification System
USTs	Underground Storage Tanks

CHAPTER 1

INTRODUCTION

1.1 Background

Contamination of groundwater has become a huge global issue, especially for humans whose primary supply of drinking water is underground. Numerous examples of groundwater pollution, such as petroleum product leakage from USTs and pipelines and hydrocarbon spills, have been documented during the last few decades (Alazaiza *et al.,* 2020a). The groundwater can be contaminated by a variety of pollutants, most of it are the result from human activity. These pollutants can have a negative impact on human health and the environment when they reach the groundwater. Non-Aqueous Phase Liquids (NAPLs) are one of the contaminants. When it comes to non-aqueous phase liquids, there are two basic types: Light Non-Aqueous Phase Liquids (LNAPLs) and Dense Non-Aqueous Phase Liquids (DNAPLs). LNAPLs have a density less than or equal to water, whereas DNAPLs are denser than water. LNAPLs is defined as an immiscible organic liquid and it presents in the form of benzene, toluene and xylene (BTEX) or any other example of petroleum products. Other than that, the examples of DNAPLs are chlorinated solvents and halogenated hydrocarbons. When the LNAPL is released into a subsurface, it will migrate vertically downward through the unsaturated zone and move through the pores in the soil with the help of gravitational force and capillary forces until it reached the capillary fringe zone and starts to migrate horizontally and continue their downward migration in the saturated zone until it reached stable condition. During the migration of LNAPL through the soil pores, the liquid will leaves behind ganglia trapped and immobilized in the pores as non-drainable residual LNAPL (Wipfler *et al.,* 2004a).

The movement of LNAPL will be affected by the effect of groundwater changes and precipitation intensity. Groundwater changes can cause LNAPL to be vertically displaced and redistributed within the saturated and unsaturated zones (Flores *et al.,* 2016). The further the LNAPL migrates downward to the saturated zone, the more intense the precipitation. This is because the large amount of intruding water created a strong wetting front propagation force that pushed any LNAPL downward. This mechanism facilitated LNAPL migration into the saturated zone (RAMLI, 2014)

The simplified image analysis method has been employed for more precise characterization of subsurface processes and the behaviour of multiphase systems. SIAM is a nonintrusive and invasive technology that can be used to detect fluid saturations in porous media. SIAM requires little equipment, has the lowest cost, and has no harmful radiation impacts (FLORES, INUI, and KATSUMI, 2010).

1.2 Problem Statement

When petroleum products and pipelines, as well as hydrocarbon products, leak on the ground and underground, they can contaminate and pollute the groundwater table. The LNAPL will then migrate through the soil pores, moving vertically and horizontally under the influence of gravity force at the unsaturated zone, then horizontally at the capillary fringe zone, and finally downward through the saturated zone. The migration of LNAPL will be influenced by groundwater fluctuation and precipitation intensity. To repair LNAPL-contaminated areas efficiently and cost-effectively, a thorough understanding of the contaminant's behaviour is required. The movement of LNAPL in the unsaturated, capillary fringe, and saturated zones can be influenced by groundwater fluctuation and precipitation. To address this issue, accurate experimental models will be developed.

1.3 Objectives

The objectives of this study are stated below:

1) To determine the horizontal migration behavior of LNAPL at capillary fringe zone due to precipitation.
2) To determine the horizontal migration behavior of LNAPL at capillary fringe zone due to fluctuating groundwater table.
3) To assess the LNAPL migration behavior of LNAPL at capillary fringe zone due to precipitation and fluctuating groundwater table.

1.4 Scope of Work

The diesel LNAPL was employed in this study. Diesel is utilised because it is the most commercially available oil and is not volatile, making it easier to regulate the experiment's quality. Sand will be employed as the porous media because it has a higher permeability and can decrease the experiment period. Soil geotechnical properties tests will be performed on the gathered soil samples. The porous medium are chosen depending on the results of the testing. The two-dimensional water tank and soil sample were employed with varying groundwater levels and precipitation intensity impacts, which were then submitted to image analysis (SIAM) to examine the LNAPL migration behavior at the capillary fringe zone.

1.5 Expected Outcome

The expected outcome of this experimental work is to comprehend the migrating behaviour of LNAPL in soil, as well as the effect of precipitation at the capillary fringe zone. Understanding LNAPL migration behaviour will aid in understanding the cause of water contamination and how to prevent it.

1.6 Dissertation Outline

This dissertation consists of five chapters. Chapter 1 is an introduction that includes the background of the study, problem statements, objectives, scope of works and expected outcome. Chapter 2 is literature, in which author's articles are used to explain more about the research. Chapter 3 is a research methodology, which discusses the procedures carried out in the study to achieve the objectives and the flow chart was developed to make it more understandable. Chapter 4 is the results and discussion. This chapter contain the findings of the study, discussion and suggestions on the study. Finally in Chapter 5, the study will be concluded and summarize all the things discussed in the previous chapter and draw conclusions on the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Hydrocarbons classified as NAPLs (Non-Aqueous Phase Liquids) separate and immiscible when exposed to water or air. As a result, the two liquids will form a physical barrier that prohibits them from mixing, owing to their differing physical and chemical qualities (Charles J. Newell et al.). There will be a downward migration and contamination of the soil until the water table is reached if NAPL (LNAPL or DNAPL) are released at ground level. Once it reaches the water table, it will continue to travel downward into the saturated zone, increasing the contaminated plume's intensity.

LNAPL migration is also influenced by precipitation intensity and groundwater table rise, which reduces residual LNAPL saturation at the upper capillary interface as a result of precipitation's effect on the groundwater table (Rui Zuo et al. 2021). The further down the LNAPL migration into the saturated zone LNAPL, the more intense the precipitation is. Thus, any LNAPL inside its path was forced down by an extremely high wetting front propagation force given by the large infiltrating water volume. The LNAPL was used in this research because the movement of LNAPL is the fastest compared to the others.

Migration of LNAPL is caused by a number of variables, including density, viscosity, interfacial tension, wettability, capillary pressure, saturation, and relative permeability. Therefore, it is essential to know and comprehend the elements that influenced the migrating behaviour of LNAPL and to establish the types of remediation measures that may be implemented to prevent groundwater pollution. Various remediation techniques, including physical chemical treatment, thermal remediation, biological remediation, and phytoremediation, can be employed to heal the soil. (U.S EPA,2006).

2.2 Non-Aqueous Phase Liquid (NAPL)

NAPL consists of hydrocarbons that are incompatible with water and air. NAPL migration is a complex process regulated by gravity, buoyancy, capillary forces, and soil texture. NAPLs are insoluble in water and therefore, they have the ability to persist for a number of years and contaminate vast areas of groundwater. (Alazaiza et al., 2021). Mobile Phase NAPL and Residual Phase NAPL are two types of NAPL phase properties. Mobile Phase NAPL is a continuous mass of NAPL that flows under a hydraulic gradient, whereas Residual Phase NAPL is lodged between soil particles and cannot be easily moved hydraulically. When NAPLs are subsequently released into the subsurface, they will move downward until they reach the vadose zone. Temperature, soil and fluid compressibility, soil heterogeneity, amount of spilled NAPL, and geometry of the spill source will also be the main factors contributing to the migration of NAPLs (KAMON *et al.,* 2007).

2.2.1 Light Non-Aqueous Phase Liquid (LNAPL)

LNAPLs are a type of pollutant with a lower density than water. They are characterised as an immiscible organic liquid and can take the form of gasoline, diesel fuel, lubricants, or other petroleum products. LNAPLs include numerous hydrocarbon fuel constituents, including toluene, benzene, xylene, and ethyl benzene (BTEX) (Newell et al. 1995). When LNAPLs are released to the subsurface as a result of a leak or spill, they migrate downward and form free lenses that exist above the water table or become stuck in the subsurface pores. A portion of it will evaporate into the air (volatilization), adhere to the surface of soil particles (sorption), and dissolve into the groundwater (dissolved plume) (KAMON *et al.,* 2007).

2.2.2 Dense Non-Aqueous Phase Liquid (DNAPL)

DNAPLs are difficult to detect and it is expected to be a major limiting factor in site rehabilitation (Huling and Weaver, 1991). To limit the possibility of increasing DNAPL mobility, remediation approaches should be carefully examined. The remediation procedures consist of groundwater pumping, soil flushing, and biodegradation to remediate the immobile and various phases of DNAPL components (Huling and Weaver, 1991). The types of DNAPLs included chlorinated solvents such as tetrachloroethylene (PCE) and trichloroethylene (TCE) (Newell et al. 1995). DNAPL that may be present in the subsurface will exist in distinct physical states, or phase. Gaseous, solid, liquid, and immiscible are the example of the phases that existed. As vapours, pollutants may be present in the air phase. In solid phase, pollutants may adsorb or partition onto soil or aquifer material. In water phase, contaminants may dissolve in water according to their solubility and lastly in immiscible phase, the contaminants may be present as dense non-aqueous phase liquids.

2.3 Oil Spillage and Contamination of Soil

More than once a year, there are incidents of oil spills or contamination of soil by hydrocarbons caused by oil products being transported on the ground and pipelines ruptures or leaking underground. Mechanical failure, exterior corrosion, operational dysfunction, and accidental damage all played a role in these mishaps (R. Vanloocke et. Al., 1975). Because of the oil spill's impact on the soil, which it has already penetrated, the groundwater table has been contaminated to the point where it is no longer clean and may even be unfit for many industrial uses (R. Vanloocke et. Al., 1975).

2.3.1 Effects Of LNAPL Contamination At Subsurface

The groundwater can be contaminated by a variety of pollutants, most of it are the result of human activity. These pollutants can have a negative impact on human health and the environment when they reach the groundwater. Non-Aqueous Phase Liquids (NAPLs) are one of the contaminants. When it comes to non-aqueous phase liquids, there are two basic types: (LNAPLs) and dense (DNAPLs). Light Non-Aqueous Phase Liquids (LNAPLs) have a density less than or equal to water, whereas Dense Non-Aqueous Phase Liquids (DNAPLs) are denser than water. Hydrocarbon fuel components including toluene, benzene, xylene, and ethyl benzene (BTEX) are good examples of LNAPL (Newell et al. 1995). TCE is one of the example of DNAPLs, whereas PCE is one of the example of chlorinated solvents (Newell et al. 1995). After being discharged into the subsurface, LNAPLs will descend through the unsaturated zone until they reach the capillary fringe zone due to gravity (Das and Mirzaei 2012). It will contaminate the subsurface, affecting the quality of the groundwater as a result. Ganglia are caught and fixed in pores during the migration of LNAPL, leaving behind non-drainable residual LNAPL (Wipfler and van der Zee 2001). LNAPL will move further downward and accumulate at the groundwater table if its volume is considerable. LNAPL that has been spilled in considerable quantities may reach the capillary fringe and create a floating and moving lens that floats and moves with the prevailing hydraulic gradient (Harris Ramli, 2013). At some point, residual LNAPL saturation may cause the floating LNAPL lens to become immovable. Flowing water will be contaminated as it passes over this area of immobile water (Bear and Cheng 2010). Figure 2.1 illustrates the example of spill in subsurface.

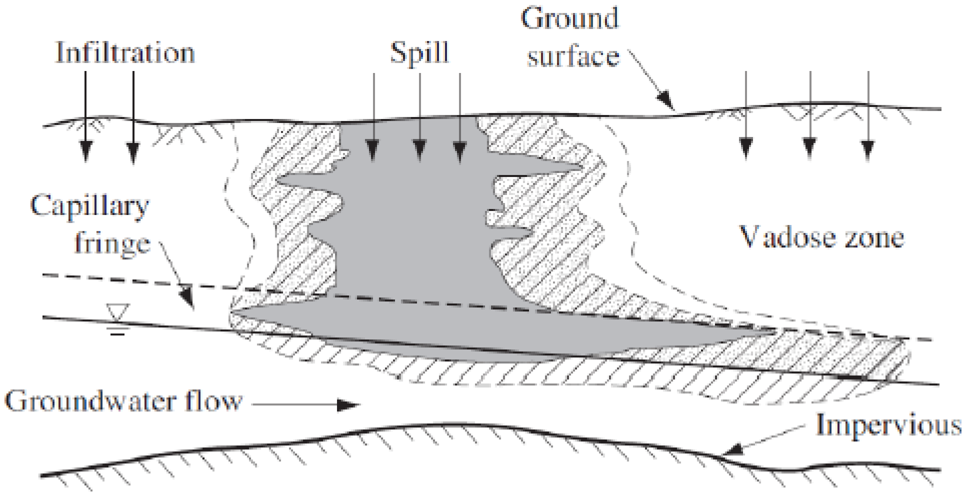


Figure 2.1: Spill in subsurface (Bear and Cheng 2010)

2.4 LNAPL Movement in Porous Media

When LNAPL was spilled in porous media, most of it was able to percolate into the unsaturated region, but some remained in the soil pores as residual saturation (Kerr Environmental et al., n.d.). When it moves down to the unsaturated zone, capillary forces keep a portion as residual phase in the soil pores until movement ceases (S. Yimsiri et. Al., 2016). Due to retentive capillary forces, a small volume of LNAPL could be trapped in a zone that is partially saturated (Tomlinson et al., 2014). As fine-grained soil has a relatively poor infiltration capacity, LNAPL may also build on the surface and flow as runoff. In addition to LNAPL contamination, other harmful fluid components may evaporate or undergo biodegradation (Broje and Keller 2007; Revill et al. 2007, cited in Amro et al., 2013). LNAPL will begin to displace groundwater if it has generated sufficient head to penetrate water-filled pore spaces while also spreading laterally in a predominantly radial way (Los Angeles LNAPL Working Group, 2011). According to the article, the water table changes caused the LNAPL contained in the porous material to be pushed further downward (Motasem Y.D. Alazaiza et. Al., 2021). The fluctuation of the groundwater table will complicate the migration of LNAPL by causing the LNAPL to be redistributed over the zone of fluctuation as a result of capillary force (S. Yimsiri et. Al., 2016).

2.4.1 LNAPL Movement at Vadose Zone

Subsurface is separated into three zones which are unsaturated zone (vadose zone), capillary fringe zone and saturated zone. Once LNAPL is released at subsurface, it will be penetrated at vadose zone till residual saturation condition is attained. At this stage, LNAPL will become discontinuous and stationary (S. Sudsaeng et. Al., 2012). (S. Sudsaeng et. Al., 2012). There will be two forces that act on the fluid which are gravity and capillary pressure. Gravity will be the dominating force when free-phase LNAPL flows down toward the water table. The LNAPL will extend laterally along the top of capillary fringe and draining of the upper regions of the vadose zone will the diminish the total head at the interface between the LNAPL and the groundwater, which then allow the water table to rebound slightly.

2.4.2 LNAPL Movement at Capillary Fringe Zone

Capillary fringe zone is a zone in which the moisture-saturated zone is immediately above the water table and below the saturation barrier. The capillary fringe zone is situated in the vadose zone, where its height varies according to the soil type and quality. The LNAPL will extend laterally along the capillary fringe's uppermost edge. LNAPLs will migrate lower with the running water as the water table and capillary fringe fall, leaving a residual proportion in the saturated zone (Lenhard et al. 2004; Kechavarzi et al. 2005). Aside from this, it is believed that the presence of imprisoned LNAPL beneath the water table causes the mobile, free-phase LNAPL inside the capillary fringe to decrease (Kechavarzi et al. 2005). Due to this tendency, the polluted zone may encompass the entire water table including capillary fluctuation zones (Fetter, 1999).

2.5 Effects of Precipitation Intensity

Precipitation is the liquid or solid water that falls from clouds or forms on the earth's surface and ground objects as a result of the condensation of water vapour in the air. There are various types of precipitation, including rain, sleet, and snow. It comprises the bulk of the global water cycle. Precipitation can take liquid, solid, or mixed forms. Rain and drizzle are examples of liquid precipitation, which can also take the form of dew or a liquid coating. In contrast, solid precipitation can take on a greater variety of forms, such as snow, hail, ice pellets, ice needles, and ice crystals. When water vapour condenses into larger and larger droplets of water, precipitation forms in the clouds, and when the clouds get heavy enough, the precipitation falls to the ground as rain. The size of smaller raindrops is roughly 1 millimetre, the size of larger raindrops is between 2 and 3 millimetres, and the size of really huge raindrops is greater than 4.5 millimetres. Small raindrops have a nearly spherical shape, while larger ones are flattened throughout their descent, particularly in the cloud's lowest regions. In addition, the terminal velocity of rain drops range from two to ten metres per second for the smallest and largest, respectively. Raindrops are significantly larger during heavy rain than during moderate rain. Larger-than-six-millimeter-diameter drops only form during intense rainfall, particularly at the beginning of a storm. Intensity and duration will also affect whether precipitation is absorbed or becomes surface runoff. Therefore, the greater the rainfall intensity, the larger the raindrops will be. High precipitation intensity can move soil particles and may exceed the soil's capacity to absorb rainfall at the same rate, resulting in infiltration-excess runoff.

2.6 Properties of LNAPL

The characteristics of the LNAPL will have an impact on the pore size as well as the transport on a field scale. At the pore scale, migration and dispersion of LNAPL are controlled by variables related to transport. On the other hand, it is difficult to forecast LNAPL migration at the field scale due to the complicated release history and the underlying heterogeneity. The following examination of pore scale principles is necessary, therefore, in order to construct conceptual models that incorporate field scale observations (Charles J. Newell et. Al). LNAPL transport parameters include density, viscosity, interfacial tension, wettability, capillary pressure, saturation, and relative permeability. Density is the most important LNAPL transport parameter.

2.6.1 Density

The density of a substance is the ratio of its mass to volume. The density of a fluid can be measured using its specific gravity (S.G.), which is defined as the mass of a certain volume of a material at a specified temperature divided by the mass of the same volume of water at the same temperature. It is less dense than water, but because its specific gravity is less than 1, LNAPL tends to float on water, whereas water's is greater (DNAPL). The temperature of a fluid will rise as its density decreases. The density of fluids considered to be DNAPLs under typical subsurface conditions may drop as a result of remedial activities that add heat to the ground (Johnson and Leuschner, 1992). LNAPL is formed when the density of DNAPLs near water is reduced enough to briefly convert DNAPL to LNAPL. The buoyancy and subsurface flow of a liquid are both affected by its density. The density and viscosity of a liquid will be affected by the porous material's hydraulic conductivity. The hydraulic conductivity of a liquid rises in direct proportion to its density (Charles J. Newell et. Al., 1995).

2.6.2 Viscosity

Viscosity is defined as the fluid's resistance to flow. In terms of dynamic or absolute viscosity, mass per unit length per unit time is the unit of measure. This resistance is supposed to be dependent on temperature. This is because the viscosity of the majority of fluids decreases with increasing temperature, and the lower the viscosity, the less energy is required for a fluid to flow through a porous material. Additionally, the hydraulic conductivity will increase as fluid viscosity lowers (Charles J. Newell et. Al., 1995).

2.6.3 Interfacial Tension

A physical interface is formed when two immiscible liquids come into contact due to the interaction of their interfacial energy. The difference in molecular attraction forces between the fluids and the interface causes interfacial tension, which is defined as the surface energy at the interface (Bear, 1972). The unit of measurement is kcal/m2. Interfacial tension is a measure of how stable a liquid-liquid contact is (Charles J. Newell et. Al., 1995). Interfacial tension is affected by a variety of factors, including temperature (Davis and Lien, 1993), pH, surfactants, and dissolved gases. It is an important factor in determining the wetness of a surface (Mercer and Cohen, 1990).

2.6.4 Wettability

With an immiscible fluid present, the tendency of one fluid to spread or adhere to a solid surface can be characterised as wettability. If you have a multiphase system, a wetting fluid coats the solid surfaces and tends to fill smaller pore spaces, whereas a non-wetting fluid is confined to the biggest linked areas. Solid surfaces in the vadose zone, where LNAPL, air, and water are present, will be wetted by liquids, such as water.

Mineral surfaces are coated with LNAPL and pore gaps are evacuated when just LNAPL and air are present. The wetting fluid in a saturated zone is water, which displaces LNAPL from the pore spaces because only water and LNAPL are available. Surface tension, surface tension distribution, and surface tension history of the porous media are all factors that influence wettability (Mercer and Cohen, 1990).

Many factors influence the wettability of subsurface media, and some researchers have found that the wetting of subsurface media by NAPL may be variable (Anderson, 1986). It is important to understand the overall behaviour of NAPLs in multiphase systems, and wettability is a helpful qualitative indication for this purpose (Anderson, 1986). On solid surfaces, NAPL wettability data are frequently given for flat, homogenous material, which does not accurately reflect the varied aquifer and soil materials seen in the field. General consensus is that refined petroleum products, such as those found at Superfund sites, can be regarded of as both a wetting and a nonwetting fluid in LNAPL systems..

2.6.5 Capillary Pressure

Pressure differences across the interface between the wetting and non-wetting phases are referred to as capillary pressures, which are also expressed in terms of a column of water. Pore size can also be determined using this technique. Additionally, it's an indicator of how well liquid molecules adhere to one another and to a solid surface (cohesion) (adhesion). Wetting fluid is drawn to porous medium by capillary pressure, while non-wetting fluid is rejected (Bear, 1972). It is necessary for a non-wetting fluid to overcome capillary pressure in order to penetrate porous media. As the capillary pressure increases, the pore size decreases in conjunction with the decrease in initial moisture content and increase in interfacial tension. It is the condition of the capillaries that is important. In order to better understand the relationship between capillary pressure and NAPL movement in hydrostatic and hydrodynamic settings, Mercer and Cohen compiled a number of formulas (1990).

The capillary forces that hold NAPL in place are considerable, but they can be slightly overcome by the viscous forces involved in groundwater flow. It is impossible to mobilise all of the remaining hydrocarbons in most aquifers simply by altering the hydraulic gradient (Wilson and Conrad, 1984).

2.6.6 Saturation and Residual Saturation

Saturation is the proportion of a porous medium's total pore space that contains a certain fluid in a typical volume. Residual saturation is the saturation level at which a continuous LNAPL becomes discontinuous and is immobilised by capillary forces. Remaining LNAPL saturation is a possible source of continued ground-water contamination since it is strongly maintained in the pore spaces and cannot be easily removed with existing remediation technologies. Several parameters, including pore-size distribution, wetting qualities of the fluids and soil particles, interfacial tension, hydraulic gradients, ratios of fluid viscosities and densities, gravity, buoyancy forces, and flow rates, influence the extent of residual saturation (Mercer and Cohen, 1990; Demond and Roberts, 1991). Several factors contribute to the potential for greater retention of NAPLs within pores in the saturated zone relative to the unsaturated zone, including: 1) the potential existence of the NAPL as the wetting fluid relative to air in the unsaturated zone, resulting in NAPL spreading to adjacent pores with residual retained in small pore spaces; 2) the potential existence of the NAPL as the non-wetting fluid in the saturated zone, resulting in NAPL present as blobs; and 3) the potential existence of the NAPL (Anderson, 1988).

2.6.7 Relative Permeability

According to this definition, relative permeability is the ratio of the effective permeability of a medium to fluid at a specific saturation level to the medium's permeability to fluid at 100 percent saturation level. The relative permeability scale goes from 0 to 1. An LNAPL/water system's relative permeability diagram is shown in the picture below, which depicts how two fluids interfere with each other to restrict mobility.

From the relative permeability curves above, it can be used to describe different types of multiphase flow regimes, all of which may exist may exist at any particular site (Williams and Wilder, 1971);

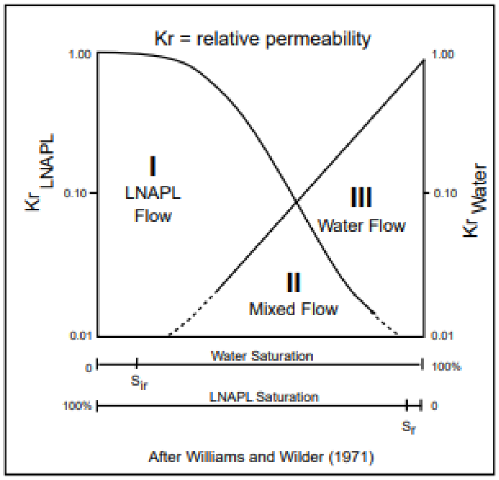


Figure 2.2: Hypothetical relative permeability curves for water and an LNAPL in a porous medium

On the basis of Figure 2.2, saturation is high in Zone I: LNAPL, where it occurs as a possibly mobile, continuous phase. Small pores are the only places where water can pass through. Water has a low permeability ratio. Conditions like this can be seen in big mobile product accumulations. ZONE II: While LNAPL and water are both present in continuous phases, they do not share pore spaces. Because of this, the permeability of each fluid is considerably reduced. These characteristics may be indicative of water table zones with lesser accumulations of mobile products. Discontinuous and confined in isolated pores, the LNAPL is found in Zone III. LNAPL, not water flow, is nearly entirely what is meant by the term "flow." Zones with residual LNAPL maintained below the water table are examples of such circumstances.

2.7 Behaviour of LNAPL Migration in Fluctuating Water Table and Effects of Precipitation

Groundwater fluctuation are mostly occurs due to the recharge from rainfall and is also one of the contaminant migration agents (Flores et al. 2011). The rainfall indirectly affects the vertical displacement of LNAPL through the fluctuating groundwater level. When considering the effect of groundwater fluctuations and precipitation intensity, it will effects the migration of LNAPL. Groundwater fluctuations can cause vertical displacement and redistribution of LNAPL within the saturated and unsaturated zone (Flores et al. 2011). The higher the precipitation intensity, the deeper the LNAPL will migrate downward to the saturated zone. This is because the high amount of infiltrating water provided a high wetting front propagation force that pushed down any LNAPL within its flow path. This mechanism helped LNAPL migrate easily into the saturated zone. (Harris Ramli, 2013).

2.8 Simplified Image Analysis Method (SIAM)

The method that has been used to for the image analysis for more accurate characterization of subsurface processes and the behavior of multiphase systems is the simplified image analysis (SIAM). SIAM is considered as unintrusive and intrusive technique that can be used to measure the saturations of fluid in a porous media. SIAM requires minimal equipment, incurs by far the lowest cost, and does not have hazardous radiation effects (Flores et al. 2011). SIAM will be used to generate detailed time-dependent saturation maps for water and LNAPL for a range of experimental conditions (Motasem Y.D. Alazaiza et. Al, 2019). SIAM method provides a rapid and cost-effective tool for the interpretation of laboratory experiments and for quantifying the dynamic changes in fluid saturation which is difficult to capture using conventional methods. Researchers will be able to benefit from the findings of these studies as they acquire a better knowledge of the influence of upward and downward water table variation on LNAPL behaviour in porous media. In addition, they can provide well-controlled experimental data that can be used to validate numerical models, which is a valuable resource.

2.9 LNAPL Remediation Technique

The remediation of LNAPL at contaminated areas should be done to reduce the degree of contamination at the contaminated sites. The LNAPL recovery and mitigation approaches may include bioremediation, physical barriers, ground water pump and treat system.

2.9.1 Bioremediation

Bioremediation of immiscible hydrocarbon is limited due to the NAPLs present a highly hostile environment to the survival of most soil microbes, the basic requirements for microbial proliferation (nutrients, terminal electron acceptor, pH, moisture, osmotic potential, etc.) are difficult if not impossible to deliver or maintain in the NAPL (Huling and Weaver, 1991). Therefore, bioremediation may be restricted to the periphery of the NAPL zone in both saturated and unsaturated media, depending on the circumstances. It has been postulated that biologically-produced surfactants resulting from microbial activity near a NAPL have increased the rate of NAPL solubilization (Wilson and Brown, 1989). This, on the other hand, has not been proven. Microbes have the potential to boost contaminant mass transfer rates from the NAPL by degrading the solubilized elements and so establishing steeper concentration gradients than would be achieved by solubilization alone.

2.9.2 Physical Barriers

The example of low permeability barriers are grout curtains, slurry walls, sheet piling for the control of ground-water and LNAPL flow (Mitchell and van Court, 1992) may be applicable as components for remedial operations at many sites. Containment of groundwater and/or mobile LNAPL during remediation are examples of potential applications. However, several of the concerns cited regarding difficulties in DNAPL containment (Huling and Weaver, 1991) will exist for LNAPL containment. Permeable treatment walls (e.g., Brown et al., 1992; Gillham and Burris, 1992) are an emerging technology for passive control of aqueous-phase contaminant migration. Figure 3 shows the barriers used to channel ground water flow.

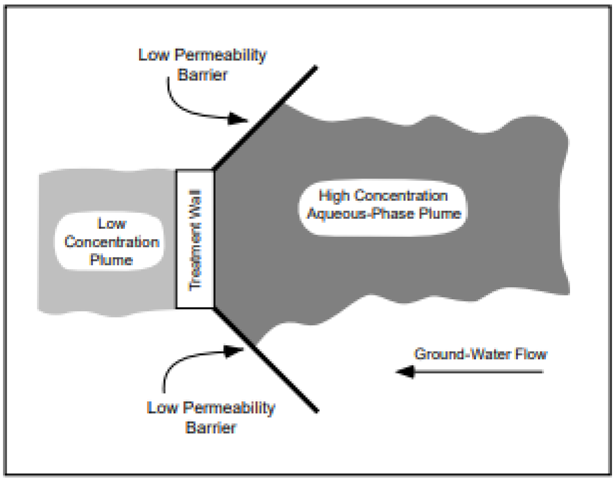


Figure 2.3: Map view of reactive treatment wall and low permeability barriers used to channel ground-water flow (Charles J. Newell, n.d)

2.9.3 Ground-Water Pump-and-Treat

Pump-and-treat systems, which have been in use for decades, extract contaminated ground water for above-ground treatment. These systems have primarily been developed for the recovery of aqueous-phase pollutants. Flushing of hundreds or thousands of pore volumes of ground water may be required to significantly diminish contaminant levels at some sites (Border and Kao, 1992; Geller and Hunt, 1993; Hunt et al., 1988a; Newell et. Al., 1990). Complete mobilization of LNAPL trapped below the water table using increased hydraulic gradients alone is not practical under conditions encountered in the field (Hunt et al., 1988a; Wilson and Conrad, 1984). Several of the more LNAPL components that are soluble may continue to dissolve in groundwater, resulting in contamination of the groundwater at unsafe levels, possibly necessitating containment operations. Depending on site conditions, time frames of many decades or centuries may be required to remove LNAPLs trapped in the saturated zone using dissolution alone.

CHAPTER 3

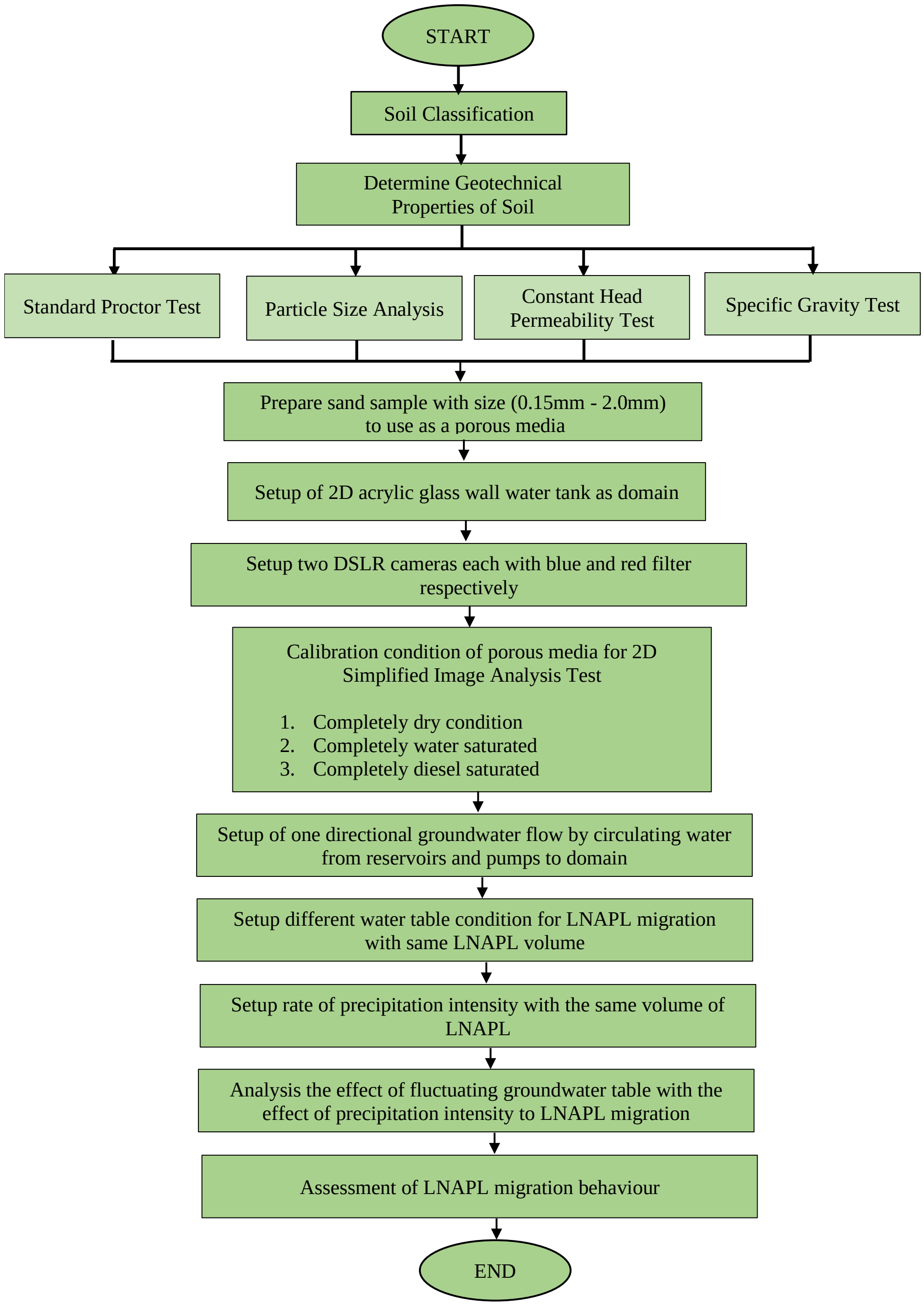
METHODOLOGY

3.1 Overview

The geotechnical qualities of the soil sample were assessed by conducting various tests to obtain the parameters required for analysis and compatibility of porous media. Tests undertaken include particle size analysis (sieve analysis), standard proctor test, constant head permeability test, and specific gravity test, among others. The sample is sieved many times to determine the particle size, which falls between 2.0 mm and 0.15 mm. The constant head permeability test was then conducted to determine the soil's permeability, followed by the proctor test to determine the soil's compaction properties with varying moisture content. A specific gravity test is conducted to determine the porosity and void content of the soil. Diesel is the type of LNAPL used in this experiment because it is a commercially available oil. Using a 2D acrylic glass water tank and the simplified image analysis method (SIAM), the migration and behaviour of LNAPL have been evaluated. Using SIAM, the migratory behaviour and saturation of water and LNAPL are measured. For this SIAM setup, two DSLR cameras with 450 and 656 nm bandpass filters are required. Red Sudan III dye was utilised for LNAPL and Brilliant Blue FCF dye was used for water in order to improve visual observation and light absorption. At each end of the water tank, pumps are attached to the reservoirs to mimic unidirectional groundwater flow. Then, a similar setup was undertaken with the precipitation intensity of 10 mm/hr and diesel was released to disclose the level of pollution. The photos obtained during the tests are then compared to three calibration photographs consisting of entirely dry medium, fully saturated with blue-dyed water, and fully saturated with red-dyed LNAPL. A proprietary MATLAB application was used to process the acquired images. This MATLAB image processing resulted in a more accurate depiction of LNAPL migration and allowed for additional analysis.

3.2 Flow Chart

The experimental works and procedure to assess the migration behaviour of LNAPL was conducted according to the flow chart.



3.3 Geotechnical Test on Porous Media

Before starting the experiment, a few geotechnical test has been done to the soil sample to determine the geotechnical properties of a soil and from the test, the suitable parameters is been chosen as a selection as a porous media.

3.3.1 Particle Size Analysis

In particle size analysis, the proportions by mass of the various particle sizes present in the soil are stated quantitatively. It has been undertaken to determine the distribution of soil, which is significant since the particle size distribution can influence the soil's qualities. Sieve analysis and sedimentation analysis are the two methods for determining the particle size analysis. Sieve analysis is used to determine the size of gravel and coarse sand using many layers of sieves with varying sized apertures and grains larger than 0.063 mm. For fine-grained silt and clay soils with a grain size of less than 0.063 mm, sedimentation analysis is conducted. British Standard (BS) and American Society for Testing and Materials (ASTM) are the two specifications that can be used to determine the particle size analysis (ASTM). The difference between these two requirements is the sieve's configuration and size. According to BS, sieve sizes of 14 mm, 10 mm, 6.3 mm, 5.0 mm, 3.35 mm, 2.0 mm, 1.18 mm, 0.600 mm, 0.425 mm, 0.212 mm, 0.150 mm, and 0.063 mm were used to classify soil. The ASTM sieve sizes for soil classification include 12.5 mm, 9.5 mm, 4.75 mm, 2.36 mm, 1.18 mm, 0.600 mm, 0.300 mm, 0.150 mm, 0.075 mm, and a pan. In this study, the ASTM and BS sieves are stacked together, and the range of sample sizes is between 2.0 mm and 0.150 mm. The sieves are organized from greatest to smallest mesh size. Then, a 2 kg sample is placed in the sieves and left to vibrate for approximately 10 minutes. After noting the weight of each sample maintained on each sieve, the percentage of material passing through each sieve can be computed. For the particle size analysis, the BS standard was implemented to determine the percentage passing. The percentage of passing against particle size and the particle size distribution curve have been plotted on a semi-log graph based on the collected data. The soil is then classified using the USCS criteria as references.

Figure 3.1: Sieve Analysis

3.3.2 Standard Proctor Test

The standard proctor test has been conducted to determine the compaction of a particular soil and the soil's characteristics with a change in moisture content. When the soil reaches the optimal moisture content, it will become more compact and attain its maximum dry density. This is due to the fact that during compaction, the soil particles are rearranged and the air volume within each particle is diminished. It is possible to determine the link between moisture content and dry density. The optimal moisture content can be determined from the graph of dry density versus the moisture content. The normal proctored examination procedure is as follows.