MIGRATION BEHAVIOR OF LIGHT NON-AQUEOUS PHASE LIQUID (LNAPL) AT UNSATURATED ZONE DUE TO PRECIPITATION AND FLUCTUATING GROUNDWATER TABLE

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SCHOOL OF CIVIL ENGINEERING
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ABSTRAK

Tumpahan minyak daripada produk petroleum di bawah tanah boleh menjadi sangat bermasalah. Pada mulanya, LNAPL dilepaskan dalam bentuk petrol, bahan api diesel, minyak pelincir dan produk petroleum lain. LNAPL menyebabkan pencemaran kepada tanah. Akibatnya, kerja pemulihan perlu dilakukan untuk mendapatkan semula tumpahan minyak supaya dapat membersihkan tanah dan air bawah tanah yang tercemar. Oleh itu, corak tumpahan minyak perlu diramalkan. Tujuan kajian adalah untuk menjalankan model eksperimen untuk mengetahui kesan hujan dan turun naik aras air bawah tanah terhadap corak migrasi LNAPL. SIAM telah diguna pakai untuk menilai corak pengaliran LNAPL dan air dalam tangki air 2D. Hujan telah disimulasikan oleh injap dan pam peristaltik untuk memberikan kadar hujan pada 8mm/jam sepanjang satu jam yang ditetapkan. Hasil eksperiment telah dianalisis dan dinilai dengan menggunakan MATLAB dan Microsoft Excel untuk mendapatkan pemahaman yang lebih lanjut tentang data yang dikumpul. Sebagai konklusinya, telah didapati bahawa ke ketepuan tanah akan meningkat secara puratanya sebanyak 36.9% selepas satu jam hujan pada kadar 8mm/jam. Kehadiran hujan selepas LNAPL telah distabilkan di paras air akan menyebabkan LNAPL berhijrah lebih dalam ke dalam lapisan tanah. Apabila aras air meningkat daripada 28cm kepada 38cm, LNAPL akan ditolak ke atas, menyebabkan peningkatan tepu LNAPL dalam zon tak tepu. Kemudian, apabila paras air kembali ke paras biasa, kebanyakan ketepuan LNAPL akan berkurangan di zon tidak tepu. Walau bagaimanapun, sebahagian daripada LNAPL kekal dalam zon tak tepu menyebabkan zon coreng. Kesimpulannya, SIAM menunjukkan tingkah laku migrasi LNAPL dan air dalam tangki dua dimensi dengan berkesan.

ABSTRACT

Oil spill from petroleum products in the underground can be very problematic. Initially, it is released as LNAPL in the form of gasoline, diesel fuel, lube oils and other petroleum products. It causes contamination to the soil. As a result, remedial work has to be done to retrieve the oil spill to clear the contaminated soil and groundwater. Thus, the oil spill pattern has to be predicted. The purpose of the study was to conduct an experimental model to find out the effect of precipitation and fluctuating groundwater table towards the migration behaviour of LNAPL. SIAM was adopted to access the saturation distribution of LNAPL and water in the 2D water tank. The precipitation was simulated by a valve and peristaltic pump to provide a constant rainfall rate of 8mm/hr throughout the one hour of stipulated time. The result was then analysed and assessed by using MATLAB and Microsoft Excel to get a more thorough understanding about the data collected. From the experiment, it can be concluded that the saturation of soil will increase an average of 36.9% after one hour of 8mm/hr precipitation. The presence rainfall after the LNAPL has been stabilised at the water table will cause the LNAPL to migrate deeper into the soil layer. When the water table increases from 28cm to 38cm, the LNAPL will be pushed upwards, causes an increase of LNAPL saturation in the unsaturated zone. Then, when the water table returns to normal, most of the LNAPL saturation will decrease. However, part of the LNAPL pool remains in the unsaturated zone causes a smear zone. In conclusion, SIAM shows the migration behaviour of LNAPL and water in a two-dimensional tank effectively.

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LIST OF ABBREVIATIONS

NAPL	Non-Aqueous Phase liquid
LNAPL	Light Non-Aqueous Phase liquid
DNAPL	Dense Non-Aqueous Phase liquid
BTEX	Benzene, Toluene, Ethylbenzene and Xylene
ASTM	American Society for Testing and Materials
SIAM	Simplified Image Analysis Method
BS	British Standard
USCS	Unified Soil Classification System
AASHTO	American Association of State Highway and Transportation Officials

CHAPTER 1

INTRODUCTION

1.1 Background

Water underground provides for drinking, irrigation and for use in different human activities. However, groundwater is often polluted with petroleum products from the underground storage tank, pipelines and spills of hydrocarbons.(Alazaiza *et al.*, 2019). In the previous history of environmental engineering, the issue of groundwater pollution due to entrapment of LNAPL and other petroleum products was not quantified due to factors such as difficulty in quantifying the LNAPL entrapment underground, the common belief that volume entrapped was insignificant and the lack of technology to retrieve entrapped LNAPL. (Dunford *et al.*, n.d.)This causes serious implication to the quality of groundwater. Even worse, due to the nature of groundwater in the hydrology cycle, groundwater contamination caused by LNAPL tends to have a long-term and localized effect and the self-purification of an aquifer might require decades or even centuries after the source of contaminants are removed. (Flores *et al.*, 2011).

1.2 Problem Statement

The oil spill issue could be caused by oil spill, exploitation of petroleum, wastewater from oil extraction, stacking of oily slag and sludge, automobiles exhaust emission and other sources of pollutants in the soil. The leakage and spillage of different petroleum hydrocarbon causes large area of soil contamination. Petroleum hydrocarbons such as diesel, gasoline is commonly used Light Non-aqueous Phase Liquid (LNAPL) that pollutes the environment (Tomlinson *et al.*, 2017) . The complex behaviour of LNAPL spreading in the soil underground make it difficult to have a complete picture in the case of contamination. The oil spill exerts a different characteristic in the unsaturated zone, capillary fringe, as well as the saturated zone.

Preferably, the oil spill shall be carried out before the contaminants reached the water table to prevent the contamination of groundwater which will further complicate the remediation work. However, the pattern of LNAPL migration could be easily affected by factors such as the fluctuating groundwater table and volume of LNAPL underground making it hard to predict the area of influence. Furthermore, the pattern of infiltration of LNAPL into the subsurface layer can be altered in the present of rain of different intensity. The presence of rainwater will divert the migration of oil in the soil. During raining, the groundwater level will fluctuate and the rise of groundwater level will cause the vertical displacement and redistribution of LNAPL within the saturated and unsaturated zone. Hence, the migration of LNAPL become uneven.

The purpose of the study is to determine the depth and width of contamination through physical experiment by using two-dimensional (2D) tank analysis. The oil is released into the tank to observe the migration pattern of LNAPL under the influence of capillary and gravitational force. The area and time taken by the LNAPL to travel into the groundwater table is also a concern for investigation. This is to pinpoint the exact area of influence of oil spill contamination for remediation purpose.

1.3 Objectives

The objectives of this experimental study are:

1. To analyse changes of LNAPL infiltration rate due to precipitation
2. To analyse LNAPL migration behaviour in the unsaturated zone due to precipitation

and fluctuating groundwater table

3. To assess the LNAPL migration behaviour at the unsaturated zone due to precipitation and fluctuating groundwater table

1.4 Scope of Work

The experimental study is started by determining the geotechnical properties of soil. Sieve analysis test, constant head test, standard proctor test and the specific gravity test are conducted to establish suitable parameters for the porous media. Then, a two-dimensional water tank is used to simulate the subsurface environment. The Simplified Image Analysis Method (SIAM) is used to record and analyse the distribution of water and LNAPL saturation in porous media. A rainfall simulator is used to simulate the precipitation process. The LNAPL migration behaviour is studied under the effect of precipitation with different rainfall intensity. In addition to that, how fluctuation of the groundwater table affects the migration behaviour of LNAPL is analysed by using MATLAB and Microsoft Excel.

1.5 Expected Outcome

The migration behaviour of LNAPL under the soil can bring serious environmental effects especially towards the groundwater. This experimental study allows us to gain insights on the pattern of contamination and migration behaviour of LNAPL underground. Precipitation or rainfall also would affect the migration behaviour of LNAPL underground. Thus, the relationship between the precipitation and groundwater fluctuation with the migration behaviour of the LNAPL in the unsaturated zone will be established. The influence of different rates of precipitation or rainfall intensity towards the flow pattern of LNAPL will also be shown. All the data collected can be useful for further research on the remediation and containment of the soil contaminated by LNAPL and how the rain or precipitation might disrupt the progress of remediation.

1.6 Dissertation Outline

The dissertation is made up of 5 chapters, from introducing the topic of research, objectives, problem statements and scope of work in chapter 1 to conclude the result of research in chapter 5. In Chapter 2, literature review which summarises the concept, previous finding and other academic writing relating to the knowledge placed in context. Meanwhile, Chapter 3 discuss the methodology, which is the method and procedures used to achieve the research's objectives. On the other hand, Chapter 4 discuss about the results and discussion obtained from the experimental study. All the result obtained would be tabulated and explained. For discussion part, the result would be analysed and justified. Lastly, in Chapter 5, the conclusion summarized the outcomes of the research project and provides recommendations in line with the outcome of the research.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Non-aqueous phase liquids (NAPLs) are organic liquids that will exists as a separate phase in water. There are two types of NAPLs, namely Dense Non-aqueous liquids (DNAPLs) and Light Non-aqueous Phase Liquids (LNAPLs).

LNAPL is a groundwater contaminant that is originates from petroleum oil, liquid petrol or diesel fuel. It is less dense than water and will normally stop near the water table. This could be problematic to the quality of groundwater as it could be brought over a long distance once it presents in the soil.

The migration behaviour of LNAPL underground is largely influenced by the local soil profile. For example, in the area of beach sand where the media is rather homogeneous and high permeability, the LNAPL will migrates downward under the force of gravity with minimal lateral expansion. However, the LNAPL footprint will be influenced by the action of capillary forces, interfacial tension, saturation and the density and viscosity of the LNAPL.

The natural precipitation process would impact the depth and area of influence of LNAPL. Typically, the precipitation intensity will show a contrary different with the period of precipitation. In the case where there is a heavy rain, it will normally last for a short period of time. Conversely, in the case where there is a drizzle, it could rain for a long period of time (Harris, 2014).

2.2 Non-aqueous Phase Liquid (NAPL)

Non-aqueous phase liquids (NAPLs) are organic liquids or wastes that are sufficiently immiscible with water such that they may persist as a separate phase in the subsurface for many years (Murphy and Ramsey, 2007). They might exist in the soil layer in two forms, either they may sorb to or be present in pores between sediments. In the first case, the NAPL may travel on the sediment, ready to desorb once it reaches a less concentrated aqueous environment.

On the other case, if the sediment is disrupted, the NAPL will become free to move with water again, or in the case of DNAPLs travels down dip. NAPL can be held in the soil layer by capillary forces or a microphase pool (Loop, 2019). NAPL usually is categorized as either Light non-aqueous phase liquid (LNAPL) or Dense non-aqueous phase liquid (DNAPL). The primary difference between the two is their density. LNAPL is less dense than water while DNAPL is denser than water. They might have quite different scenarios in terms of geophysical detection because of how they distribute themselves within the soil layers. DNAPLs are usually situated below the water table as compared to LNAPL pools which are normally located near the water table, at the interface between the unsaturated and saturated zones (Redman, 2009).

2.3 Light Non-aqueous Phase Liquid (LNAPL)

Light Non-aqueous phase liquid generally refers to petroleum hydrocarbon liquid that are lighter than water (Lu, 2015). The Light Non-aqueous phase Liquid (LNAPL) causes varying degree of affect towards ground water quality across the country (Newell et. al., 1995). However, since it is less dense than water, LNAPL will normally stop near to the depth of water table and brought over a long distance once it seeps through the soil. The typical sources of LNAPL contamination comes from petroleum products (Newell et. al., 1995). The products are usually organic mixtures with multiple components with different water solubility.

Examples of highly soluble additives are methyl tertiary-butyl ether and alcohols are highly soluble. The presence of MTBE underground low level made water undrinkable because of turpentine-like odor and taste of chemical compounds. At high doses, it is considered to be carcinogenic to human (Kuffner, 2022). Other examples of LNAPL such as benzene, toluene, xylene, and ethyl benzene (BTEX) are slightly soluble in water. Acute exposure of BTEX can cause sensory and skin irritation, while long term exposure can cause serious problem to the internal organs especially to the kidney, liver and the blood system (Mitra and Roy, 2011). Diesel is also a common LNAPL contaminant. Breakdown of diesel compounds releases volatile, dissolved and highly carcinogenic polyaromatic hydrocarbons (PAHs). It may cause sub hazardous fumes, surface water pollution, soil contaminations and other serious environmental issues (Lipko, 2002).

The occurrence of LNAPL and migration behaviour is governed by the type of soil in which LNAPL, water, and air share pore spaces under various hydrological settings. The hydrogeological settings of a LNAPL exist in three phases, which are unconfined, confined, and perched. The soil capillary pressure and LNAPL saturation and mobility are an also important factor that influences the migration behaviour of LNAPL (Lu, 2015).

There are three major forces that control the behaviour of the LNAPL layer, namely, capillary forces, viscous forces and gravity or buoyancy forces. Capillary force comes from the interplay of cohesive forces within each liquid phase and the adhesive forces within each fluid phase and the adhesive forces between the solid phase and each of the fluids. Viscous force directly proportional to the permeability and to the pressure gradient, while buoyancy forces are proportional to the density difference between the fluid (Conrad et al., 1992).

2.4 Dense Non-aqueous Phase Liquid (DNAPL)

The two main common characteristics of DNAPL are they have density greater than water and are only slightly soluble in water (Cohen and Mercer, 1993). Examples of DNAPL include chlorinated solvents such as chlorobenzenes, chloromethanes, tetrachloroethylene (PCE) and trichloroethylene (TCE) (Alazaiza *et al.*, 2019). The difference in both physical and chemical properties causes the formation of separate physical interface which prevents the liquid from mixing. However, it is difficult to monitor the DNAPL migration behaviour underground as it can pass through the unsaturated zone until it reaches the bottom of the aquifer. Moreover, some DNAPLs have the ability to dissolve in water and be transported into the groundwater as a solute. The transport process involves the transport of DNAPL components and associated dissolved solutes in the aqueous and gas phase (Pan *et al.*, 2020)

2.5 Unsaturated Zone (Vadose Zone)

Unsaturated zone is located at the interface between the atmosphere, vegetation and the land surface. It plays an important role in the hydrological cycle as it involves in many processes controlling the complicated relationships between precipitation, infiltration, surface runoff, evapotranspiration and groundwater recharge. The level of water table and capillary fringe may vary over time due to seasonal variations, recharge due to irrigation, and groundwater withdrawal (Zhang *et al.*, 1998). Variations in water table may also occur over shorter periods of time due to changes of water levels in nearby rivers, lakes, and ocean tides (Williams and Oostrom, 2000). There exist three possible underground soil conditions, namely unsaturated zone, capillary fringe and saturated zone.

The unsaturated zone immediately located below the land surface and contains, water and air in the open spaces or pores. It is a multiphase system containing dissolved and undissolved solids (organomineral complexes and biomass), liquids (water and non-aqueous phase liquid pollutants and gases (soil gases). Open system in the vadose zone is dynamics which means that water, gases and solutes are continuously being redistributed (Holden and Fierer, 2005). Thus, the structure of the unsaturated zone will affect the rate and migration pattern), where the capillary barrier exists at the fine-coarse interface.

2.6 Saturated Zone (Phreatic Zone)

Saturated zone is the area that lies directly beneath the saturated zone where the pores, fractures, and cavities are filled with water and located under the aquifer, below the groundwater table (Dublyansky, 2013). The soil is typified in many structures and therefore is not typically homogenous (Zuo et al., 2021). As the top of the saturated zone rises towards the surface, it will reach a level of equilibrium with the overlying unsaturated zone. The boundary between the saturated zone and unsaturated zone are not a fixed and distinct one as the water table will rise and fall depending on the precipitation rate (Pepper and Gentry, 2015).

2.7 Capillary Fringe

Capillary fringe is defined to include the tension saturated zone and upward limit of water transport by the matric potential of the sediment (Whitford and Duval, 2020). In this area the area it is expected where a sharp change in θ occurs. The capillary fringe is held 100% by capillary tension and there is no θ change in soil at the water table measured in a well. In the capillary fringe, it can be observed that the water level changes in the tank resulted in residual soil moisture redistribution within the soil (Slater and Comas, 2009). The pollution that penetrates the capillary will be influenced by wetting-front movement or groundwater table fluctuations (Rubin, 2005).

2.8 Transport of Oil Spill Contamination in Vadose Zone

The migration behaviour of LNAPL in the vadose zone is under the influence of gravitational hydrodyanamic and capillary forces (Zuo *et al.*, 2021). The factors that influence the mechanism includes permeability, porosity, pore size distribution and the surface properties of porous media.

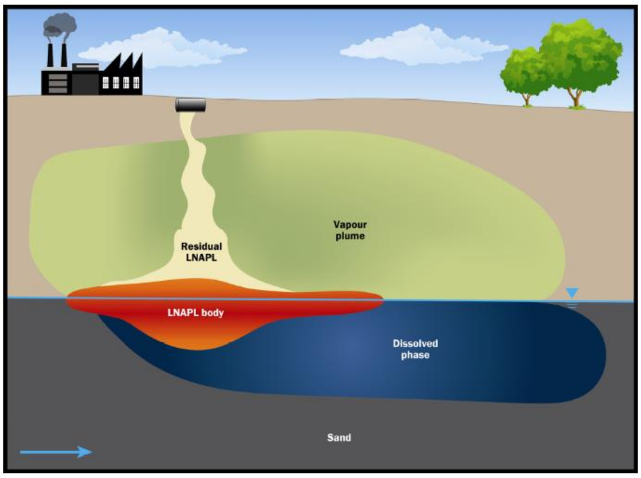

Figure 2. 1 LNAPL release into beach sands (Source: Brown et al., 2017)

After the initial release of LNAPL at the ground surface, it will migrate downwards in the unsaturated zone with limited lateral expansion. During the downward migration, the NAPL plume is subjected to partial entrapment and the release of some vapours of volatile compounds into the gaseous phase of the vadose zone. If the volume of LNAPL released is limited and in small quantity, then the LNAPL contaminant might completely entrapped in the vadose zone. (Rubin, 2005)This is due to retentive capillary forces.

If a larger volume of LNAPL is released, then the LNAPL will continue to migrate downwards towards the underlying water table. Once in contact with the saturated zone, the vertical migration of the LNAPL continues until buoyancy and increasing water content impede vertical migration. LNAPL begins to spread laterally at the capillary fringe unless sufficient LNAPL elevation head (potential energy exists) for it to displace water and penetrate below the water table (Tomlinson *et al.*, 2014). In such cases, the vertical LNAPL penetration will continue until the pressure head is balanced by the upward forces of buoyancy and water displacement pressure. The resulting LNAPL body will continue to migrate laterally following the water table down hydraulic gradient and horizontally due to LNAPL mounding above the water table, creating a LNAPL head gradient in response to the resisting forces.

When a LNAPL was released in a large volume in a short period of time, the LNAPL elevation head will dissipate quickly, thus resulting in a larger lateral spread and less penetration below the ground water table. Meanwhile, in the case where there is a longer-term release with a constant LNAPL elevation head, it will continue to overcome the resistance of buoyancy and capillary pressure below the water table, thus it will cause a smaller lateral spread with deeper penetration into the ground water table for a similar volume of LNAPL released.

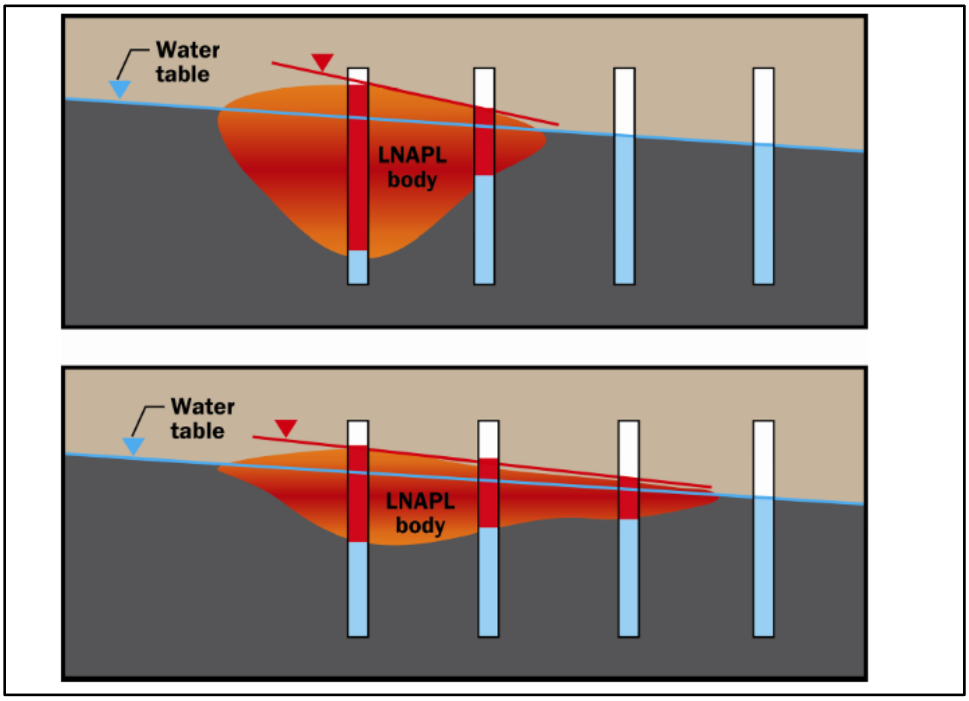

Figure 2. 2 The downward LNAPL migration through the unsaturated zone and penetrate the water table will eventually stabilize with time (Rivett *et al.*, 2014)

LNAPL passage leaves a trail of residual LNAPL in the form of disconnected ganglia and droplets. Residual, immobile, saturations of LNAPL form due to hydrodynamic instabilities at the pore scale and represent the maximum amount of LNAPL that can be held in place by capillary forces that arise from the tensional states at LNAPL-water and LNAPL-air interfaces. Residual saturation values depend upon the geological media properties.

2.9 Factors that influence the LNAPL migration

The properties of LNAPL will influence the speed of LNAPL migration and the migration behaviour of LNAPL. Besides that, the properties of porous media will also influence the footprint area as well as the entrapment and other conditions.

2.9.1 Capillary forces

The capillary pressure is the pressure difference across the interface between the wetting and non-wetting phase. It is commonly used to measure how a liquid molecule attached to each other and to a solid surface. The molecules would be held in the place by capillary forces from the pressure drop across the curved interface between two immiscible fluids. When LNAPL are encountered in porous media soil, the molecules are normally present in the form of droplets held in pores or as contiguous bodies of liquid 'ganglia' joined through two or more pores. (Brown *et al.*, 2017)

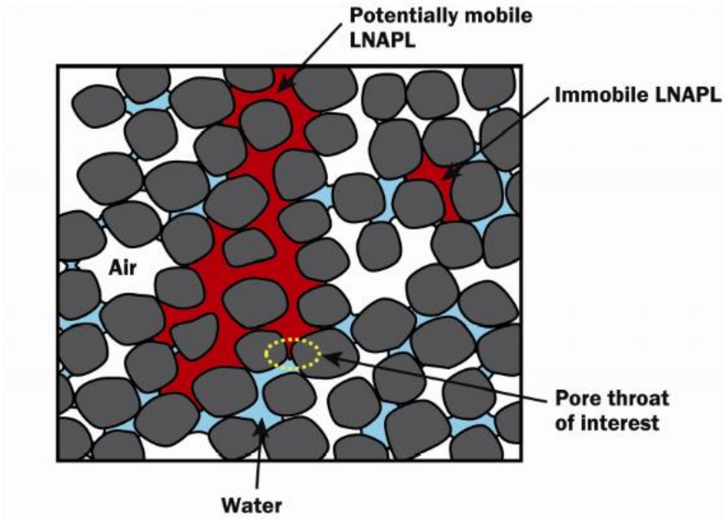

Figure 2. 3 The fluid distribution in the unsaturated zone. The LNAPL body is prevented from entering the identified pore throat by the large entry pressure due to the pore throat's small aperture. (Brown *et al.*, 2017)

The curvature of the interface indicates that the pressure in the LNAPL (concave) side of the interface (PL) is greater than the pressure immediately adjacent in the water phase (Pw). The pressure drop is defined as the capillary pressure with the threshold capillary pressure (or entry pressure) for a non-wetting fluid (typically LNAPL) to enter a wetting fluid (typically water) given by:

$$P_L - P_w = \frac{2\sigma_{LW}\cos\theta}{r}$$

(2.1)

Where,

$\sigma_{LW} =$ interfacial tension;

$\theta =$ contact angle;

r =pore throat radius

2.9.2 Density

Soil density is the relation between the mass and the volume of a dry soil sample. One way to express the density of a fluid is to use the specific gravity (S.G.), which is the mass ratio of a volume of material at constant temperature to the mass of a volume of water at the same temperature. (Tat and van Gerpen, 2000)

A NAPL is less dense than water (LNAPL) and will float on the water if its S.G. value is less than 1.0. If its S.G. is higher than water, often greater than 1.0, it is denser than water. Most fluids lose density as the temperature rises. (Cavelan *et al.*, 2022). Therefore, the thickness fluids considered to be DNAPLs under normal subsurface conditions will drop during remedial actions that add heat to the subsurface.

2.9.3 Viscosity

A fluid's natural property called viscosity has an impact on how quickly it moves through a porous media. The viscosity of LNAPL will increase over time due to subsurface weathering. It could be characterized as internal friction within a vapour phase that results in flow resistance. The harder it is to flow, the higher the viscosity. The higher the viscosity, the longer it takes to move through subsurface and will show apparent delayed responses to aqueous phase pressure changes. This resistance is also impacted by temperature. Most fluids become less viscous as temperature rises. The hydraulic conductivity rises as the fluid's viscosity decreases. The viscosity of LNAPL is considerably higher than that of water with reported kinematic viscosities of more than 0.4Pa s for heavy fuel oil and even higher for used fuel oil. (Oostrom *et al.*, 2006)

2.9.4 Interfacial Tension

Interfacial tension is the force acting on the interface between two phases per unit area. Interfacial tension is the energy required to dissolve the cohesive intermolecular interactions between the two phases, which could be fluids or solids. The contact between the liquids is generally more stable the higher the interfacial tension. Interfacial tension is influenced by temperature, pH variations, surfactant concentrations, and the presence of dissolved gases. Interfacial tension is influenced by the phase's wettability. (Moeini *et al.*, 2014)

2.9.5 Wettability

Wettability is defined as a fluid's general propensity to spread over or adhere to a solid surface in the presence of other fluids with which it is immiscible. This concept has been applied to relate to fluid dispersion at the pore scale. In a multiphase system, the wetting fluid preferentially coats solid surfaces and has a tendency to occupy smaller pore volumes. The wetting phase of two-phase fluids prefers to cover the solid phase over the fluid phase, for example, and this is frequently assessed using contact angle. In the vadose zone, where air, water, and LNAPL are present, liquids, primarily water, preferentially saturate solid surfaces. LNAPL will cover mineral surfaces preferentially and place air from pore spaces when there is air and LNAPL. LNAPL will be forced out of pore spaces by water acting as a wetting fluid when only water and LNAPL are present in the saturated zone. The NAPL and aqueous-phase composition, the presence of organic matter, mineralogy, surfactants, and the saturation history of the porous medium are factors that affect wettability (Cheng *et al.*, 2016).

2.9.6 Saturation

In a sample volume of a porous medium containing a certain fluid, saturation is the proportion of the total pore volume. The mobility of an LNAPL and its saturation in the medium are related, according to the relative permeability function. The migration of LNAPL inside the vadose zone resembles that of a discharge of a dense non-aqueous phase liquid (DNAPL). (Kueper et al., 2003) Due to retentive capillary pressures immobilising material within soil pores, migration will cease within the vadose zone if only a tiny amount of LNAPL is released. For bigger independent leases, LNAPL will spread due to the lithology of the overburden or bedrock geology and drain under the gravitational effect. Due to both increasing water content and related buoyant pressures resulting from the contrast in density between LNAPL and water fluid, as opposed to DNAPLs, which sink as they contact the water table, the saturated aquifer will delay but not completely block LNAPL migration deeper. The LNAPL head gradient, which is initially greater than the water table gradient due to the LNAPL release, is what primarily controls the lateral spread of LNAPL near the water table inside the capillary fringe. The driving forces of an LNAPL discharge will penetrate below the water table.

2.10 Natural Hydrological Process

The natural hydrological process is the total of all processes in which water moves from the land and ocean surface to the atmosphere and back in the form of precipitation (Chakravarty and Kumar, 2019). Water evaporates from sea, lakes and rivers due to solar radiation. As the water vapor reached the atmosphere, it is being cooled and condensed, thus returning to the land and sea as precipitation. Some of the water precipitating penetrates the ground and moves downward through incisions forming aquifers. Finally, a part of underground water leads to the sea. This forms the natural hydrological process of the earth (Inglezakis et al., 2016).

2.10.1 Precipitation and percolation

Precipitation is the basic component of water cycle a key hydrologic variable in of water cycle for meteorology, climatology and hydrology (Liang and Wang, 2020). Precipitation intensity is determined as the average rainfall rate in mm/h or mm/min for a specific duration and a selected frequency (Ramke, 2018). Typically, if the precipitation takes place for a very long time, the intensity will be low. Inversely, if the precipitation only lasted for a short period of time, the rainfall intensity will be high. (Harris, 2014)

Percolation is a process where the precipitation moves through the soil layers and rocks with the help of capillary and gravity forces. Large rainfall event (>20mm) will play an important role to form deep percolation. (Liu *et al.*, 2016)

2.10.2 Imbibition

Imbibition is the process of absorption of one substance by another, in particular the uptake of water by a plant or seed (Oxford Languages). Imbibition can be defined as the spontaneous taking up of a liquid by a porous solid. It occurs when the fluid-filled solid is immersed or brought in contact with another fluid which preferentially wets the solid. The imbibing fluid displaces the non-wetting resident fluid. An example of this phenomenon is a reservoir rock soaking up water and expelling oil. In a study conducted by J.W. Graham et. al (1959), it stated the phenomenon of linear imbibition, where in a rock that is filled with oil and connate water (water trapped in pores of rocks), it can be observed that the presence of water on the imbibition face gives a flow of water into and a counterflow of oil from the matrix. This is caused by the nature of water that advances in one direction only (Graham *et al.*, 1959)

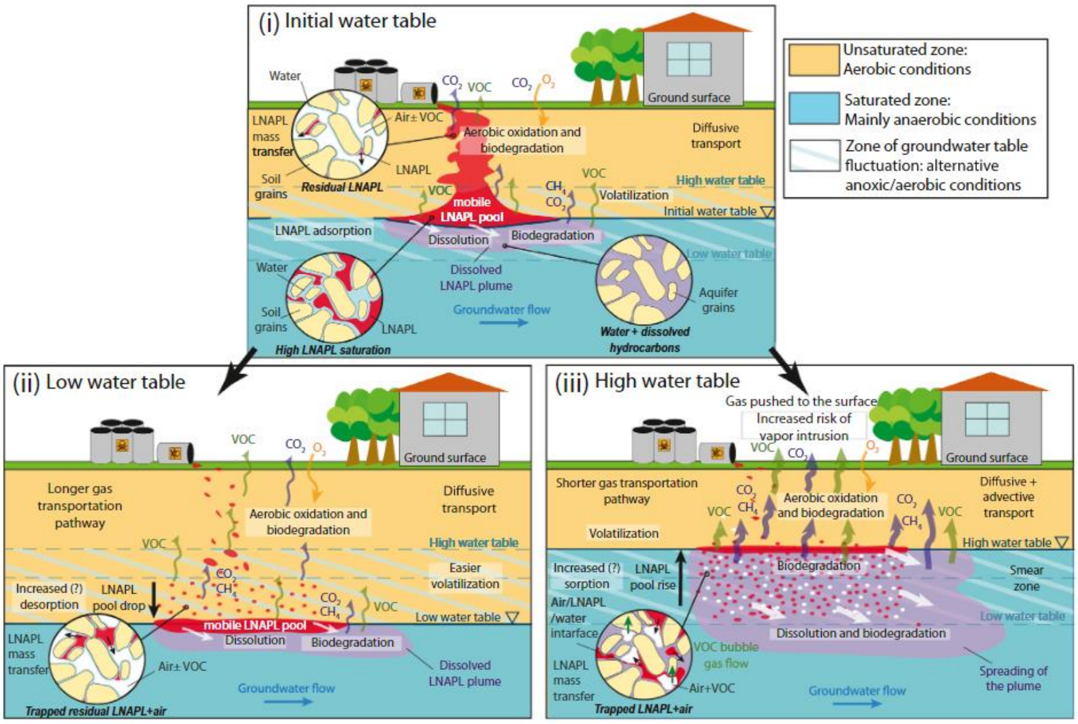

Figure 2. 4 Conceptual models showing the LNAPL mobilization during the water table fluctuations (Tomlinson *et al.*, 2014)

2.11 Simplified Image Analysis Method

Two DSLR cameras (Nikon 5300) were placed in front of the 2D water tank. Two camera lenses were attached with two different bandpass filters which have blue and red bandpass filters. The two bandpass filter have wavelength of 450nm and 640nm. 450nm bandpass filter only allow reflected blue light spectrum, while 640nm bandpass filter only allow for reflected red light spectrum.

2.12 Summary

It can be summarized that there are two types of NAPL, LNAPL and DNAPL. DNAPL have density greater than water and are only slightly soluble in water (Cohen and Mercer, 1993). On the other hand, LNAPL is Light Non-aqueous phase liquid generally refers to petroleum hydrocarbon liquid that are lighter than water (Lu, 2015). Since it is less dense than water, LNAPL will normally stop near to the depth of water table and brought over a long distance once it seeps through the soil. After the initial release of LNAPL at the ground surface, it will migrate downwards in the unsaturated zone with limited lateral expansion. The vertical migration of LNAPL will continue until buoyancy and increasing water content impede vertical migration. LNAPL begins to spread laterally at the capillary fringe unless sufficient LNAPL elevation head (potential energy exists) for it to displace water and penetrate below the water table (Tomlinson *et al.*, 2014). The factors that will influence the LNAPL migration including capillary force, density, viscosity, interfacial tension, wettability and saturation.

CHAPTER 3

METHODOLOGY

3.1 Overview

To identify the geotechnical properties of the sand, physical tests are carried out in the study. Standard proctor test, constant head permeability test, specific gravity test and sieve analysis were conducted. Design precipitation intensity should be close to the natural precipitation.

3.2 Particle Size Analysis

Figure 3. 1 Mechanical Sieve shaker

Sieve analysis was conducted to determine the particle size distribution of the sand. In the experiment, the sand size used were in between 150 um and 2 mm. The experiment has two procedure which are following American Society for Testing and Materials (ASTM) standard and British Standard Sieve analysis.

There were two types of particle size analysis which are sieve size analysis and sedimentation analysis. The British Standard has a sieve size of 14mm, 10mm, 6.3mm, 5.0mm, 3.35mm, 2.0mm, 1.18mm, 600um, 425µm, 212µm, 150µm, 63µm and pan while for ASTM, the sieve size was 12.5mm, 9.5mm, 4.75mm, 2.36mm, 1.18mm, 600µm, 300µm, 150µm, 75µm and pan to classify the soil. The sieve was arranged from the largest size to the smallest size for both standards.

The test was conducted by using a mechanical shaker as shown in Figure 3.1. The specimen was placed in the sieve and vibrates for 20 minutes to ensure the homogeneity of the soil particle sieved. After that, the time weight of the retained for each sieve was recorded, and the percentages passing through each sieve were recorded. The result was analysed by plotting the particle size distribution curve on a semi lot graph.

3.3 Standard Proctor Test

Dry density and moisture content for soil are related by given compact effort, established in the laboratory. The standard proctor is a laboratory method for determining the optimum moisture content at which the soil becomes most dense. The increase of dry density usually done by compacting the soil to make the particle more packed. The blows applied by the rammers should be done systematically. The method used was the standard hammer with a weight of 2.5kg as shown in Figure 3.2. The first two blows should be applied at the edge and diametrically opposite to each other; the next two halfway between and the fifth at the centre. The next four (numbered 6,7,8,9) are placed between those already applied. After that, the rammers are worked systematically around the mould and across the middle so that the whole area is uniformly compacted.

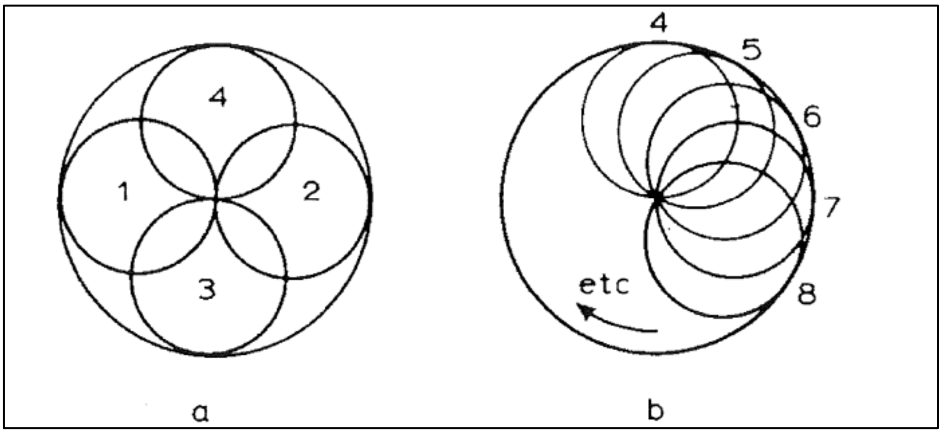

Figure 3. 2 Rammer pattern for compaction

The volume of water in the soil and the degree of compaction applied to determine the dry density can be achieved. Then the relationship between moisture content and dry density can be obtained. With the result, a graph of dry density against moisture content was plotted and the maximum dry density and optimum moisture content relationship were determined.

Figure 3. 3 Apparatus for Standard Proctor Test

3.4 Constant Head Permeability Test

Figure 3. 4 Setup for Standard Proctor Test

The objective of the test is to determine the permeability (hydraulic conductivity) of a sandy soil by the constant head permeability test. The experiment was set up as shown in Figure 3.4. The constant head test is suitable for permeable soils with permeability > 10^{-4}cm/s. The permeability refers to ability of soil to allow flow of water through it. The test is started by measuring the initial mass of the pan along with the dry sand (M1). The cap of the permeameter is removed and the inside diameter of the chambers is measured. The average inside diameter of the permeameter (D) is calculated. A piece of porous web is placed on the inner support ring to prevent the sand will flow into the inlets and outlets. Using a scoop, the sand is poured into the permeameter in a uniform manner. The cap is secured firmly with the cap nuts. The sample length is measured. The funnel is adjusted to allow the constant water level in it to remain a few inches above the top of the soil. The flexible tube is connected from the tail of the funnel to the bottom outlet of the permeameter and the valves on top of the permeameter is kept open.

3.5 Particle density test

The specific gravity is a measure of the average density of the solid particles at which make up the soil mass. The mass of sand has been determined by using the small pycnometer method. This method is suitable for soil with particles size less than 2mm. The sand is first passed through the sieve to remove sand bigger than 2mm before testing. The distilled water is used as the density bottle fluid.

The small pycnometer bottle as shown in Figure 3.5(a) used are first washed together with the stopper. The density bottles are then dried and weighed to the nearest