EFFECT OF SOIL GRAIN SIZE ON THE OIL MIGRATION IN THE CAPILLARY FRINGE ZONE

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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

Permintaan petroleum yang meluas pada hari ini teleh menyebabkan kemunculan masalah terhadap tangki simpanan bawah tanah dan saluran paip minyak. Lama-kelamaan, talian paip dan tangki ini boleh mempunyai terkakis dan menyebabkan kebocoran. LNAPL mempunyai parameter yang kompleks untuk membolehkan LNAPL bergerak melalui media berliang di bawash keadaan tepu, iaitu penekanan zon pinggir kapilari. Oleh itu, ketinggian kapilari atau kedalaman kapilari adalah sangat penting untuk menentukan kerana kedalamannya adalah kedalaman lokasi kerja-kerja pembersihan untuk menjalan. Objektif utama kajian ini adalah untuk menentukan penekanan zon pinggir kapilari apabila dihadapi dengan diesel dalam sampel pasir yang mempunyai bijiran yang berbeza saiz. Ujian Model Satu Dimensi telah dilaksanakan dengan Analisis Imej bagi menentukan zon pinggir kapilari. Dengan perbezaan keterangan warna air biru dan warna diesel merah, imej yang ditangkap kemudian diproses oleh Kod MATLAB untuk penskalaan atas keterangaan itu. Warna tergelap biru dan merah menentukan 100% penepuan air dan diesel dan sampel pasir. Dengan menentukan tahap tertinggi daripada 100% penepuan air, ketinggian kapilari boleh digambarkan keluar. Dalam kajian ini, keputusan menunjukkan bahawa nilai D_{10} terkecil mempunyai ketinggian kapilari yang tertinggi pasukan pelekat terbesar antara zarah-zarah pasir. Selain itu, diesel dituang ke dalam sampel pasir dan penekanan zon pinggir kapilari telah ditetapkan. Hasil kajian menunjukkan diesel boleh menekan lebih zon pinggir kapilari dalam bijirin kecil saiz sampel pasir. Berdasar kepada Teori Young-Laplace, daya kapilari yang bertindak arah sama seperti daya graviti telah ditolak diesel ke bawah lebih mudah dalam sampel pasir butir saiz kecil kerana mereka menghadapi tekanan kapilari yang lebih besar untuk membentuk *diesel plume* untuk menembusi ke bawah melalui sampel pasir.

ABSTRACT

Widespread demand for petroleum had lead potential problems associated with underground storage tanks and oil pipelines. Over time, these pipelines and tanks can have corroded and developed leakages. LNAPL had the complex parameter to allow the LNAPL to move through the porous media under saturation condition, which is depressing the capillary fringe zone. Therefore, the capillary height or the depth to reach the capillary height is very important to be define as the depth is representing the location of the remediation work to be carry out. The main objective of this research is to determine the depression of the capillary fringe when encountered with diesel in different grain size of sand samples. The One-Dimensional Column Test had been carried out with the Image Analysis in order to determine the capillary fringe zone in the column apparatus. With the different colours' toning, blue water and red diesel, the captured image is then processed by the MATLAB code to scale the toning. The darkest blue and red represented 100% saturation of water and diesel. By determine the highest level of 100% saturation of water, the capillary height can be figured out. In this research, the result showed that the smallest D_{10} value had the highest capillary height due to its largest adhesive force among sand particles. Besides that, the diesel poured into the sand samples and the depression of capillary fringe zone had been determined. The results showed the diesel can depress more capillary fringe zone in the smaller grain size of sand samples. This can be explained as capillary force is an equilibrium force of adhesive force and gravitational force based on Young-Laplace theory. The capillary force acting same direction as the gravitational force had pushed the diesel downward more easier in smaller grain size sand samples as they had the bigger capillary pressure to form the diesel plume in order to penetrate downward through the sand samples.

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CHAPTER 1

INTRODUCTION

1.1 Background of Problem

Groundwater is one of the most important water sources for irrigation in most of the country. However, the groundwater is very susceptible to be polluted due to contamination. Consuming the contaminated groundwater can have genuine health problems. The infections like hepatitis and dysentery might be caused by waste contamination from septic tank. Leachate contaminated in groundwater may cause the consumer to be poisoned. The potential of sources of groundwater contamination included storage tank, septic systems, uncontrolled hazardous waste, landfills, chemicals and road salts, and atmospheric contaminants.

Contamination of soil by leaking of the light non-aqueous phase liquid (LNAPL) may affect the physical properties of the soil, for example causing the reduction in the maximum dry density and optimum moisture content (Nasehi et al., 2016). The shear strength parameters of oil contaminated soil such as cohesion, friction angle and compressibility properties which could affect the performance of soil structure gradually (Khosravi et al., 2013).

An estimation from Groundwater Foundation, National Ground Water Association United States at 2018, over 10 million storage tanks had been buried underground with the potential to corrode, crack and developed leaks over time. Those tanks may contain oil, chemicals, gasoline, diesel and other liquids types which the density is larger or smaller than the water. An oil spill incident had been found from an aging oil pipeline known as Line 5, in northern Michigan, US in year 2016. There was report claimed Line 5 has spilled 29 times and at least 1.1 million gallons along its length since 1968.

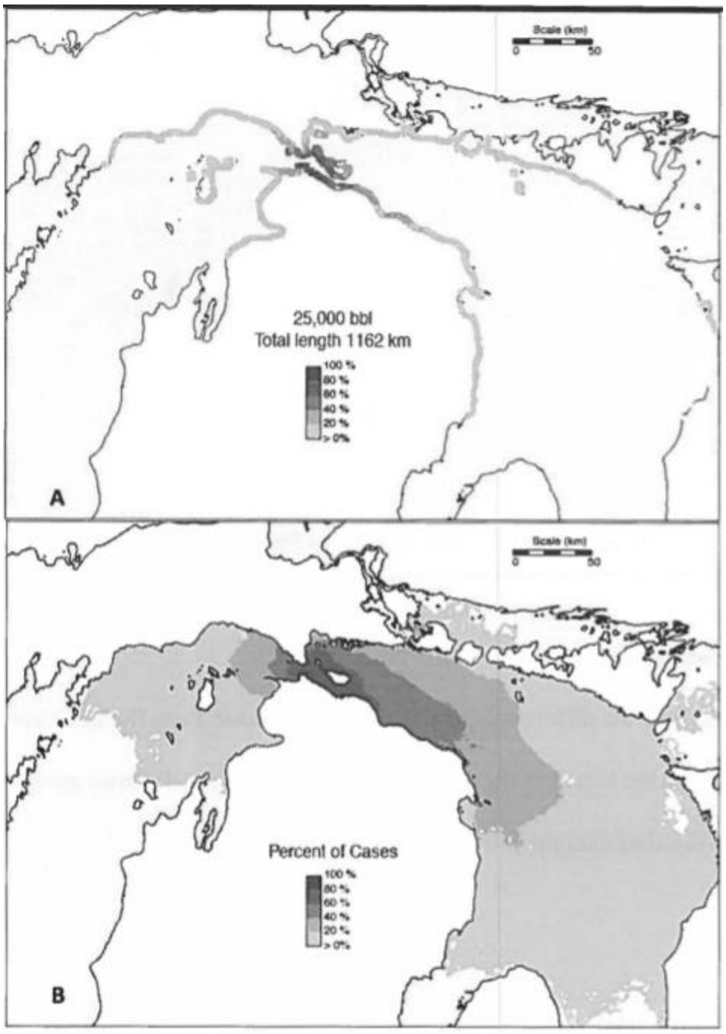

Figure 1.1 Projected oil spill distribution (A) and densities (B) throughout northern Lake Michigan and Huron (Schwab, 2016)

Spilling of organic solvents and other petroleum based product such as petrol and diesel due to leaks from pipelines and underground storage tank has contaminated in the subsurface environment. Nowadays, with the wide usage of the oil consumption and usage, the oil spill events can occur in several ways, above ground, underground or at sea.

There are many studies that report the formation of volatile hydrocarbon in saturated zone, yet the knowledge to determine the composition of the present LNAPL is limited (Baedecker et al., 2011). Some of the experts and professionals correlated that even low volume of oil spill shall result to severe groundwater contamination rather than high volume of oil spill. Therefore, by knowing the percentage composition and the viscosity to the trapped LNAPL, the mitigation process can be proceeded more accurately and efficiency.

LNAPL had the complex parameter which related to the ability to allow the LNAPL to move through the porous media under saturation conditions (Beckett and Huntley, 2015). However, they also mentioned that LNAPL had a complex key which made LNAPL is not a constant of the formation, but rather varies with test conditions, time and changing piezometric conditions. Therefore, to stimulate the condition of the changing piezometric conditions which may trapped the LNAPL, the fluctuating distance of ground water table will be constant along the experiment.

This research project will focus on the Light Non-Aqueous Phase Liquid (LNAPL) which will floated on the groundwater table and migrate through the saturation zone due to two main factor, fluctuation of groundwater table and precipitation. There is a possibility of LNAPLs to migrate further due to interfacial tension and action of capillary depression until they reach saturation zone. Once the LNAPLs encounter the ground water, the probability of the water to be contaminated is high and even they can migrate deeper within the subsurface environment.

The main point of this research project is to determine the how the various soil grain size can lead to the earth subsurface contamination and further study on the capillary fringe zone depression. Hence, the effect of different soil grain size on oil migration in the capillary fringe zone is determined based on the one dimensional column test conducted by observing the oil spill migration.

1.2 Problem Statement

In 1993, a collision between an oil tanker and an LPG carrier one mile from Sentosa Island, it had affect the ecosystem in Kukup, Johor. The oil spill incidents can have a serious impact on the fragile ecosystem of the strait of Malacca, especially the intertidal zone (Jaswar and A.Maimun, 2013). LNAPL had the complex parameter to allow the LNAPL to move through the porous media under saturation condition (Beckett and Huntley, 2015), which is depressing the capillary fringe zone. Therefore, the capillary height or the depth to reach the capillary height is very important to be define as the depth is representing the location of the remediation work to be carry out.

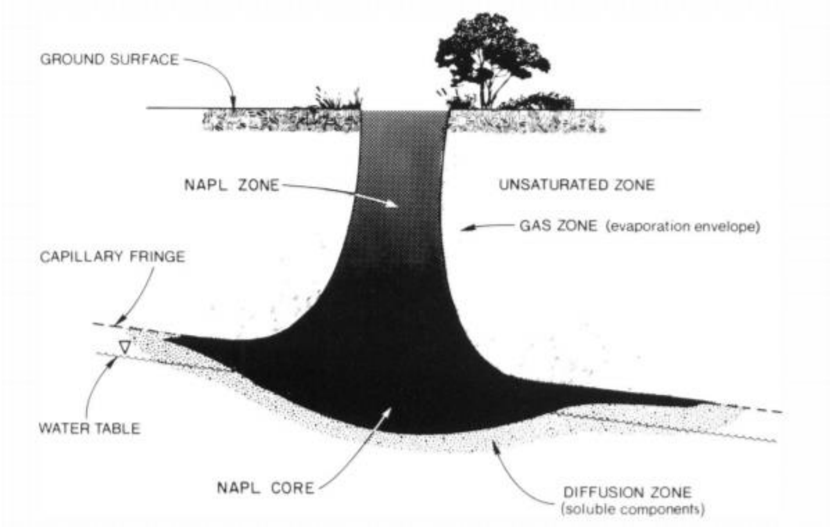

Figure 1.2 LNAPL infiltration schematic (Abriola, 1989)

In the oil spilled incident, the capillary fringe zone in the soil will act as a barrier to prevent the oil migrated into the saturated zone. When the capillary fringe zone become thinner, the risk of the contamination will be higher due to the complex parameter of LNAPL. The figure 1.3 is the illustration of the capillary fringe zone reduction due to the oil migration.

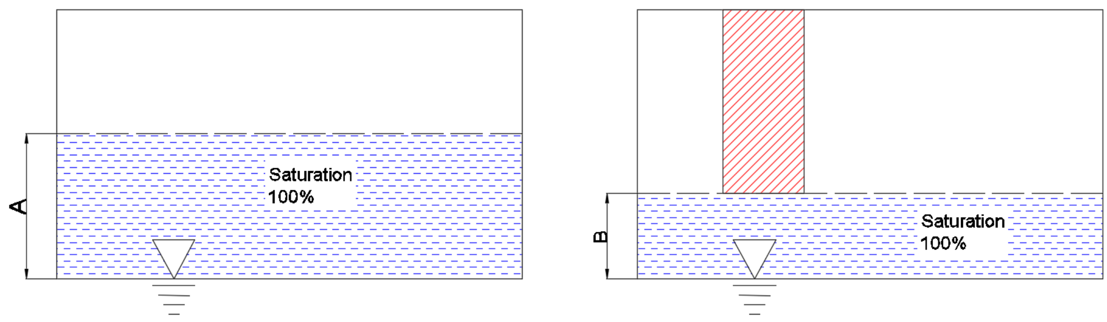

Figure 1.3 Illustration of capillary fringe zone before and after oil spilled event

Current estimation equation presented by Terzaghi and Peck (1948) had a parameter of grain shape constant, C, is hard to be determine based on any guidelines and standards. When the height of capillary fringe zone cannot be estimated accurately, the remediation depth cannot be performing well. Application of equation for estimating capillary height presented Terzaghi and Peck (1948) is difficult based on the grain size diameter, D_{10}, and the grain shape constant, C.

$$h_c(mm) = \frac{C}{eD_{10}}$$

In general, the LNAPL had the lesser density than the water and it will migrate downwards due to the gravitational force, capillary force and viscosity factor. However, the volume of the LNAPL also determine the possibility to lead the LNAPL to the capillary fringe zone. The higher volume of LNAPL spilled, the tendency of the diesel to fill up the void space among the soil is easier. Therefore, determination of volume of oil spill which can lead to capillary fringe zone depression is one of the target of this research also. It is crucial to know the composition percentage of the trapped LNAPL as it can affect the earth materials and livings significantly.

1.3 Objectives

The main objectives of this research are:

1. To determine the soil capillary height of uncontaminated and contaminated sand in the unsaturated zone.
2. To determine grain shape constant in the uncontaminated capillary fringe zone.
3. To investigate effect of oil spill volume in the unsaturated zone.
4. To evaluate the relationship of soil grain size and contaminated oil volume in affecting depression of capillary fringe zone.

1.4 Scope of Work

This research emphasize on how different grain size shape can influence the capillary action within the capillary fringe zone. The main factors such as type of sand sample, 10% smallest grain size diameter, D_{10}, and different volume of diesel spilled which can affect the capillary are also being considered.

This research comprises a few stages which are laboratory tests to define the soil properties and physical modal setup. For laboratory test, two mining sand samples which had high and low silica contents will be used and to be classified respectively based on the laboratory tests. By using the parameters obtained from the laboratory tests, One-dimensional column apparatus was used to conduct this study. The One-dimensional column test or the Image Analysis will be provided with selected 10% smallest grain size diameter value and the selected diesel volume to study the effect of oil spill on the oil migration in the capillary fringe zone.

1.5 Dissertation Outlines

This dissertation comprises of a few chapters which is:

Chapter 1 comprises of an introduction about groundwater contamination on oil spill incident, significant effect of oil spill to the environment and human being, and followed by the problem statement, objectives and scope of work of this dissertation.

Chapter 2 emphasizes on the previous research studies and reviews which relevant with the basic understanding of the dissertation title on the petroleum hydrocarbon, the capillary action, the subsurface environment and others.

Chapter 3 discusses about the research methodology that had been conducted to achieve the provided research objectives.

Chapter 4 provides some research findings from soil properties analysing, image analysing from one dimensional column test and the correlation involved between soil properties with the migration depth of the diesel.

Chapter 5 presents the conclusion obtained from the research findings and few recommendations for the future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In the rapid development social economy, the demand of petroleum had risen significantly among the industrial and the communities. The widespread of the petroleum demand had lead the potential problems which associated with the underground storage tanks and pipelines. Afters years, these underground storage tanks and pipelines started to corrode and develops leaks.

Petroleum and diesel, also known as Non Aqueous Phase Liquid, NAPL. NAPL can be divided into two groups which is Dense Non Aqueous Phase Liquid, DNAPL and Light Non Aqueous Phase Liquid, LNAPL. LNAPL are derived from the crude oil, for example, fuels, lubricants, chemical feed stock and others. LNAPL had the characteristics of lighter density compared to the water while DNAPL is denser than the water. The contamination situation when these two types of NAPL towards underground water were float on the groundwater table for LNAPL and sink to the groundwater to the immiscible layer for the DNAPL. For the remediation for the DNAPL is more directly to the LNAPL, this is because the remediate the DNAPL only required to identify the location of spillage source while LNAPL will flow to others place due to the hydraulic gradient and others reasons as it floats on the groundwater and migrated by the groundwater.

The zone of the LNAPL contaminated was normally the unsaturated zone. The unsaturated zone can be defined as three main layers which are soil water/root zone, intermediate vadose and capillary fringe zone. The (Pearlman, 1999) of LNAPL will be the capillary fringe zone. The soil water/root zone is between the ground surface and the most extreme profundity to which roots can infiltrate. The intermediate vadose zone contains the remaining moisture content controlled by the matric potential. The capillary fringe zone is denoted the last change between vadose zone and saturated zone. Capillarity is because of the appealing powers of water solids and the surface tension of water.

Capillarity, an indication of the cohesion of matter because of strong, short extended forces between contiguous particles. Capillary action (sometimes capillarity, capillary motion, capillary effect, or wicking) is the capacity of a fluid to stream in limited spaces without the help of, or even contrary to, outer powers like gravity. The impact can be found in the illustration up of fluids between the hairs of a paint-brush, in a slender cylinder, in permeable materials, for example, paper and mortar, in some non-permeable materials, for example, sand and melted carbon fibre, or in a cell. It happens due to intermolecular powers between the fluid and encompassing strong surfaces. In the event that the distance across of the cylinder is adequately little, at that point the mix of surface strain (which is brought about by union inside the fluid) and cement powers between the fluid and compartment divider act to move the fluid.

Groundwater contamination can occur from several sources. These include industrial wastes, solid waste disposal sites, waste water treatment lagoons, agricultural areas, cattle feed lots, artificial recharge sites using waste water, mine spills, septic tank tile fields, etc. In some cases, wastes are directly put underground by means of shallow and deep wells and this could result in the contamination of adjoining aquifers. Currently, there are no generally accepted limits for contaminants in groundwater. However, the substances which are of main concern in a drinking water supply can also be considered as contaminants to a groundwater reservoir. Almost all these substances are soluble in water and to make the discussion applicable to any of these substances, the soluble contaminants will be subsequently referred to as contaminants. Therefore, the concept of the contamination modelling of groundwater table should be defined clearly and the process of the modelling should be designed after knowing the problem statement.

After implemented the modelling systems, the capillary height in the apparatus should be defined. This is because the apparatus, tensiometer will be insert to the model in order to obtained the capillary pressure in the soil. The capillary height will be estimated by using an estimation equation developed by Terzaghi and Peck. However, there was an investigation gap at the formula which is the grain size constant. The grain size constant had the direct issues to the void ratio of the soil which may affect the capillarity of the soil.

Lastly, the subsurface oil spill remediation also been discussed. Basically, the types of remediation technology for contaminated soil can be separate into three different categories, which are ex-situ remediation, containment remediation and in-situ remediation. The purposes of these three categories also different. For ex-situ remediation, it focuses on removal of contaminants from the site. For containment remediation, it prevents the contaminants from leaving the site. Lastly, in-situ remediation, it eliminates the contaminant on the site. Each of the categories had different method to be carried out and one example will be discussed in this chapter which are physio-chemical cleaning or soil washing [ex-situ remediation], vertical barrier [containment remediation] and in-situ chemical oxidation [in-situ remediation].

2.2 Non Aqueous Phase Liquid (NAPL)

Non Aqueous Phase Liquid (NAPL) is referred to the liquid which characterize with immiscible hydrocarbons in the subsurface. NAPL can be partially dissolve into water with a slow rate which affected by the viscosity of the NAPL. The NAPL can be divided into two main types which is either lighter or denser than water. However, the complex mobilization of NAPL is governed by the capillary force, soil characteristics, buoyancy in ground water, and gravity.

Migration of NAPL in subsurface can be divided into 4 phase of distribution which are free phase, aqueous phase, gaseous phase and solid phase. In the other hand, to lay down the distribution, there was another 4 processes which are Volatilization, Dissolution, Sorption and Biodegradation. Volatilization, happens when nitrogen is in its most natural state of urea, most ordinarily from creature excrement or urea manures. At the point when this happens the nitrogen is changed to ammonia gas (NH_3) and lost into the air. It is well on the way to happen when soils are warm and damp and the wellspring of urea is close to the soil surface (Wang et al., 2008). Dissolution, occurs when a geological material was dissolved by a circulating fluid for example moving ground water table underground (Malaska et al., 2018). Sorption, can be differentiate into absorption and desorption, which indicating the mobility of the environment compound and distribution between soil, sediment compartments, water and sludge (ECETOC, 2014). Biodegradation, where the bioavailability of NAPL affected by few factors, solubility of NAPL, mass transfer of NAPL, and cell adherence to hydrocarbons (Mariaamalraj et al., 2016).

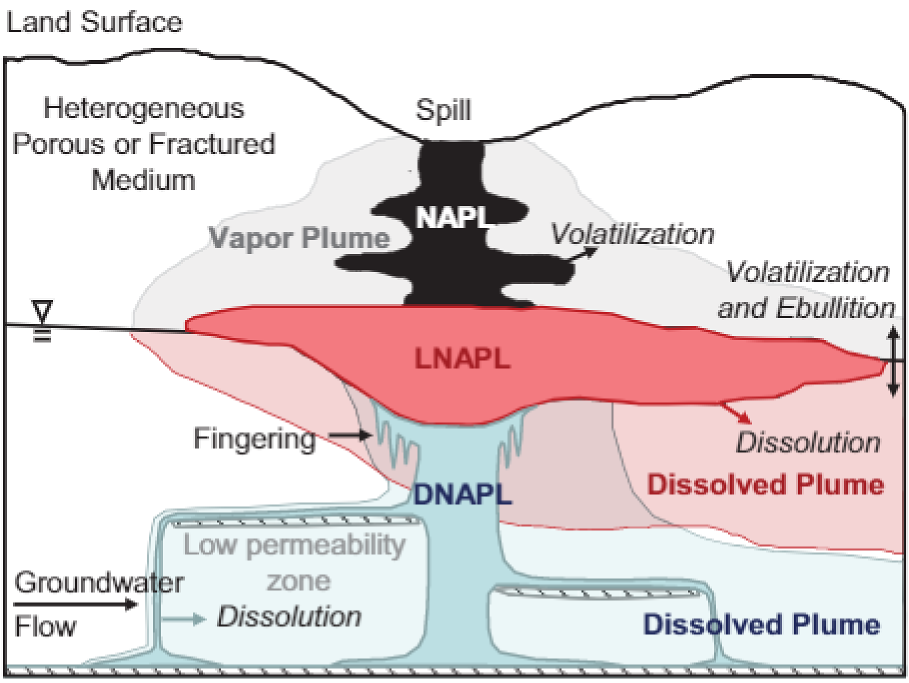

Figure 2.1 Infiltration of NAPL in soil (Essaid et al., 2015)

2.2.1 Dense Non Aqueous Phase Liquid (DNAPL)

Dense non aqueous phase liquid (DNAPL) are available at the various risky waste locations and are suspected to exist some more. Because of the various variables affecting DNAPL migration and density in the subsurface and thus, the guaranteeing multifaceted nature. DNAPL is largely undetected and then are probably going to be a huge restricting variable in site remediation (Huling and Weaver, 1991).

DNAPL phase distribution can be separated into four phase framework which may exhibit in the subsurface in different physical states, those four conceivable phases: gaseous, solid, water, and immiscible hydrocarbon in the unsaturated zone. In gaseous phases, the contaminants may be present as vapours. In solid phase, the contaminants may adsorb or partition onto the soil and aquifer material. In water phase, the contaminants may break up into water as indicated their very own solvency. In immiscible phase, the contaminants may be available as dense nonaqueous phase liquids.

2.2.2 Light Non Aqueous Phase Liquid (LNAPL)

Arrivals of fuels such as gasoline, diesel, heating oils, jet fuel, lubricant oils, on the whole alluded to as light non-aqueous phase liquids (LNAPLs), have for quite some time been administration concerns identified with their dangers presented to human-wellbeing and the earth from contact with synthetic compounds in or direct contact with light non aqueous phase liquid. LNAPLs are among the most normally experienced natural contaminants in the subsurface condition because of their unavoidable use, poor noteworthy transfer rehearses, coincidental discharges amid dealing with, capacity or exchange at fuel fabricating offices, refineries, mass item terminals, corner stores, airplane terminals, army installations, and from littler scale stockpiling at local properties, mechanical offices and ranches (Tomlinson et al., 2017).

At the first occurrence of LNAPL spillage, LNAPL will be not stable in nature and diffused into void between the soil particles and forming the three-liquid stages with the water, gas and LNAPL. When the discharge volume of LNAPL is large, the LNAPL had the possibility to relocate descending through the pores among the soil particles until it meets the groundwater table. Subsequently, LNAPL will keep on migrate laterally when it reached to the saturated zone, prevalently toward groundwater flow because the LNAPL gravity force will adjusted and balanced by the groundwater buoyancy force (Yadav et al., 2014).

To improve evacuation of LNAPL mass, different types of recuperation techniques might be pertinent. These incorporate air, water or dissolvable flushing or single, double and multi-stage cleansing of LNAPL, soil gas and water. However, as the elements of LNAPL in the subsurface is an element of various parameters which included geo-physical properties of permeable media and the dispersion and synthesis of the LNAPL, the feasibility and adequacy of the variable methods available in the market for a specific site is and inquiry to be replied before any remediation work being carried out. Because of the worldwide bounty of the LNAPL discharge occurrences and since it incorporates a wide scope of components with altogether different parcelling traits and hazard profiles, the LNAPL gasoline had being concerned to bring into studied. There are 7 major groups which contributing as the main segments in the LNAPL gasoline, Benzene (BEN), Toluene (TOL), Xylene (XYL), Ethylbenzene (ETB), Trimethylbenzene (TMB), nC4-nC6 (NC46), and nC7-nC11 (NC711) (Lari et al., 2018).

Table 2.1 Major Groups Contributed in LNAPL Gasoline

	M_W	Mole, %	Mass, %	V. Press (Pa)	Solubility (mole/mole)
BEN	78.11	1.16	0.88	1.26×10^4	40.6×10^{-5}
TOL	92.14	15.17	13.61	3.79×10^3	10.69×10^{-5}
XYL	106.16	16.14	16.68	1.06×10^3	2.91×10^{-5}
ETB	106.17	2.84	2.94	1.77×10^3	3.12×10^{-5}
TMB	240.35	5.16	12.08	287	0.47×10^{-5}
NC46	75.25	32.14	23.55	5.64×10^4	0.73×10^{-5}
NC711	114.31	27.18	30.26	1.91×10^3	0.03×10^{-5}

2.3 Subsurface Zone Classification

Basically, the subsurface environment can be divided into two major zones, which are vadose zone and saturated zone. Tracking back to the history, most of the hydrogeologists had focused their studies on the saturated zone but not the water movement in the vadose zone. However, the vadose zone cannot be neglected in the study of the soil contamination as it has a significant capability to capture, store and release the contaminants. To understand the subsurface zone classification, the hydrologic cycle of the ground water should be studied.

Ground water is a difficult part in the study of hydrologic cycle as it had hidden from the visual and staying in a complex environment of the soil. Although there are the methods of using the monitoring wells to do the direct observation, but the limited number of observation points had made the indirect supplementing observations and high assumptions to be made. The fundamental principles of ground water flow are good enough to manage the characterization of the soil for the further studies in future.

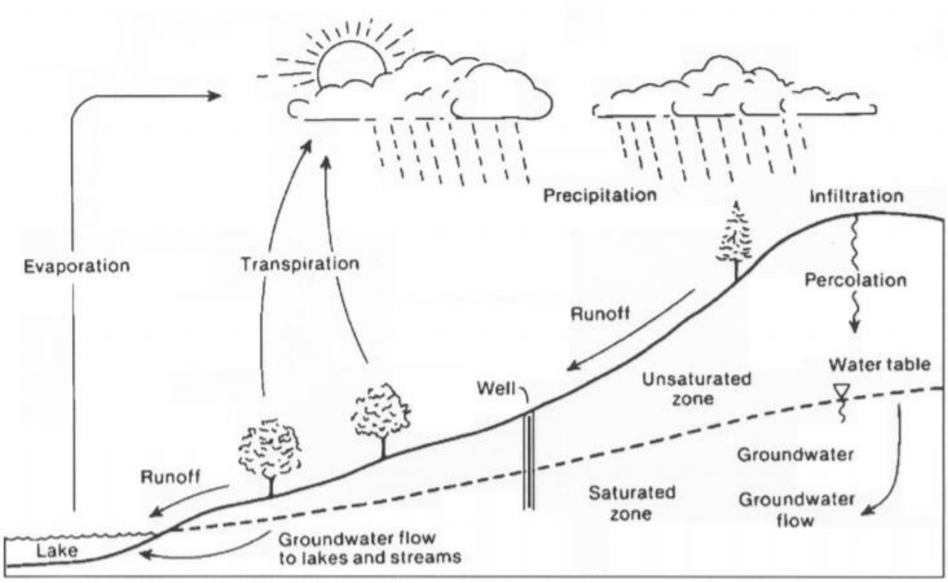

Figure 2.2 The Hydrologic Cycle (Muldoon and Payton, 1993)

2.3.1 Unsaturated Zone

The retention and development of water in the subsurface are energy-related experience (Boulding and Ginn, 2013). Free energy is the common term used to classify the status of water energy. Water will move generally or on the other hand change from a higher to lower free energy level, with the basic factor being contrasts in energy levels starting with one contiguous site to another. Free energy of soil water is affected by three significant kinds of energy possibilities:

- Matric Potential, P_m, a fascination of water to solids in the subsurface. Matric potential emerges from both absorption of water into solids and capillary action in soil pores. The powers causing this energy potential diminish the free energy of water and normally called matric suction. Basically, the smaller the molecule and pore size, the bigger the matrix potential.
- Osmotic Potential, P_o, results from the disintegrated constituents in subsurface water. The fascination of solute particles to water atoms decreases the free energy of water. Therefore, unadulterated water will move over a semipermeable layer to the higher solute concentration.
- Gravitational Potential, P_g, is a fascination of the power of gravity toward the earth's center, $Pg = Gh$, where G is the speed increasing of gravity and h is the elevation over the reference height.

2.3.1.1 Development of Vadose Zone

When the contaminants migrating the vadose zone, they will tend to move slowly compare to the saturated zone as the processes decelerates the water movement rate. As in the rooting zone, contaminants may be cleared and incorporated into the plant tissue, or bringing away by transpiration until excess water enters the soil and moves them further down to the soil layer (Boulding and Ginn, 2013). In generally, the vadose zone had divided into three major categories:

- **Soil water / root zone**. This zone is between the ground surface and the most extreme profundity to which roots can infiltrate. It is portrayed by large variances in the amount and nature of moisture in response to the transpiration and evaporation. The rooting zone is usually called as the soil water zone in hydrogeologist writing.
- **Intermediate Vadose**. This zone contains the remaining moisture content controlled by the matric potential. In coarse grained materials, the measure of water held by matric potential is weak while in the fine grained materials, the forces to hold the moisture is way higher. Since this zone likewise contains a lot of air in pore spaces, gravitational water achieving this zone moves moderately gradually to the immersed zone by unsaturated stream until the point when it comes to the capillary fringe zone.
- **Capillary Fringe**. This zone is denoted the last change between vadose zone and saturated zone. Capillarity is because of the appealing powers of water solids and the surface tension of water.

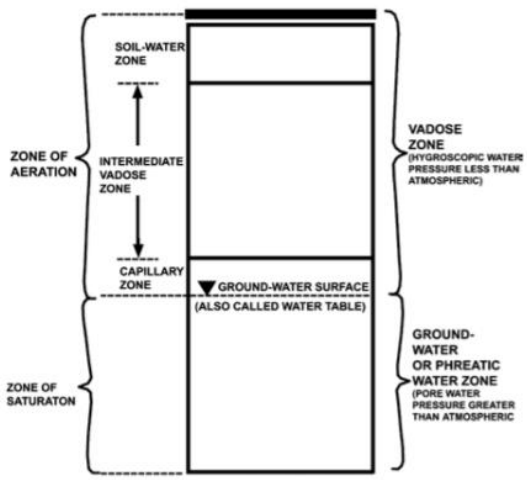

Figure 2.2 Distribution of Fluid Pressure in the Ground with respect to the Groundwater Surface (Boulding and Ginn, 2013)

2.3.2 Saturated Zone

At whatever point a spill of huge measure of contamination happens, the pollution stage isn't totally occurred in the unsaturated zone and migrates to the water table. The groundwater contamination by LNAPLs and DNAPLs will be various also, LNAPL contaminants will in general amass at the water table while DNAPL contaminants penetrate through the immersed zone what's more, will in general cumulate on the aquifer base (Konečný et al., 2003). stated when the sufficient LNAPL is released, the LNAPL may migrates through the unsaturated zone down to the water table and the capillary zone which is the zone that retained water by the capillary force on top of the water table. Then, when the NAPL migrated to a zone with the rising of water saturation, the lateral migration may be occurred. The lateral migration is defined by the distribution pressure in LNAPL. In general, the principal of migration is supposed to follow the groundwater flowing direction, but LNAPL contamination may occur in other direction which determining by the hydraulic gradient causing by the LNAPL accumulation. Therefore, rapid accumulating of LNAPL may cause the compression and the collapse of capillary fringe.

When the accumulated of LNAPL on the water table, the water table will be fluctuated and move the water table up and down which will be resulting the pores remaining and forming the residual saturation. Said that the dropped of water table, the LNAPL residual saturation may remain under the water table when the water table return to the initial level. A comparable circumstance may happen as a result of remediation works where LNAPL collects in the cone of despondency caused by pumping, bringing the remaining of immersion after the pumping is ended.

2.4 Capillarity

Capillarity is an indication of the cohesion of matter because of strong, short extended forces between contiguous particles. For examples, the bending meniscus in test tubes and the dousing up of fluids by sponge balanced the adhesive and surface tension of fluid. In liquids and other deformable media, capillary forces, a term to describe the adhesion and cohesion will generally limit the surface zone of a given volume and are in charge of the spherical shape of secluded drops. The thought of forces was fundamental to the early improvement of the present physics study. The principal precedent was the gravitational forces, by which extensive masses pull in one another. Capillarity previously emerged in the historical backdrop of thoughts as an abnormality to the law of fascination. The activity of capillary forces in cylinder lifts a wetting liquid, a characteristic that appeared to negate the Aristotelian idea of a “natural” condition of rest in which unwieldy issue attempts to reach as low position as could be expected under the circumstances (Pomeau and Villermaux, 2006).

2.4.1 Reservoir Scenarios (Oil/Water System)

The most critical parameters that affecting the capillary pressure is the interfacial tension and the wetting angle of the fluid. These parameters always change significantly due to the pressure and temperature for any given fluid or solid system. Those accurate measurement or estimation may be made in the laboratory by rearranged the system in the capillary tube, however it is not suitable for rock analysis. In figure 2.3 shown a mode of capillary pressure in oil and water system. The height of the interface is referred to the free water level in which the capillary tube radius contributing to infinity where the zero capillary pressure and the height, h is 0. When the absolute pressure, P_{FWL} occurred, there is the interface of the system. Then, the capillary force will occur in the capillary tube and resulting the water to rise to a height, h.

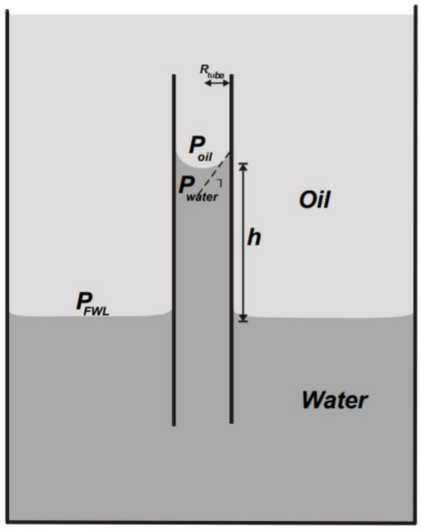

Figure 2.3 Capillary Pressure in oil/water system. (Glover, 2015)

Besides that, there was another parameter which contribute to result the difference of the capillary pressure in the model, which is the diameter of the tubes. The different diameter in the tubes representing the different pore size in the soil. The bigger diameter representing the bigger pore size in soil and resulting smaller capillary rise and capillary pressure.

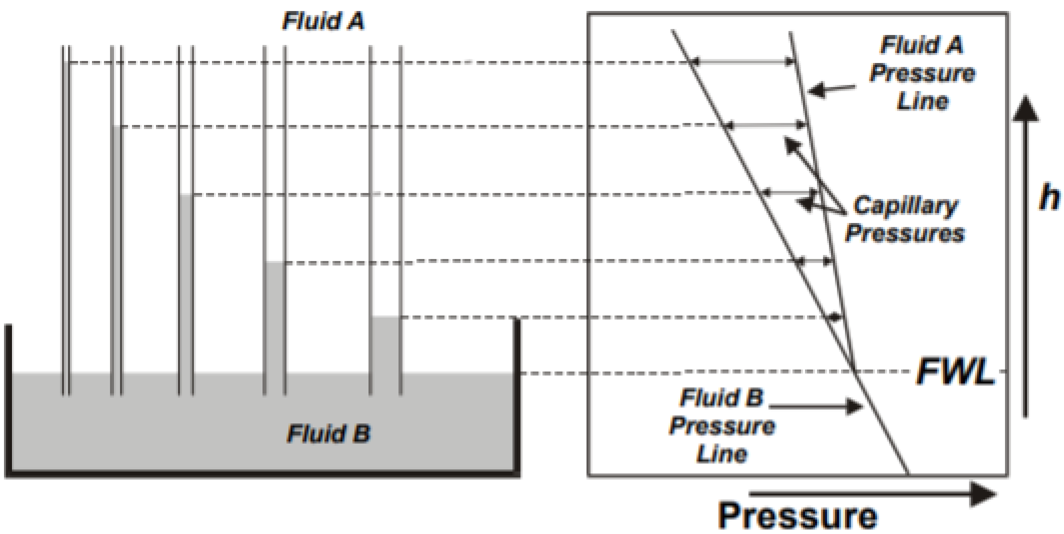

Figure 2.4 Capillary rise and capillary pressures (Glover, 2015)

2.5 Soil-Water Characteristic Curve

Soil-water characteristic curve (SWCC) is a theoretical model which normally been used to estimate the unsaturated permeability function. In studying of the flow process in the unsaturated zone, the function of permeability plays an important role. Although the permeability function can be determined by doing the laboratory tests, however, it is costly and time consuming if carrying out the direct measurement in laboratories. SWCC is the alternatives way to estimate the unsaturated permeability function by carrying out a theoretical model (Rahimi et al., 2015).

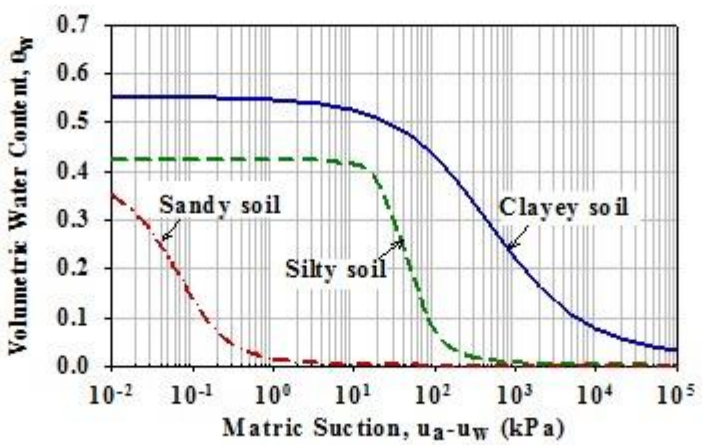

Figure 2.5 Soil-water Characteristic Curve of different soil types (Fredlund and Rahardjo, 2012)

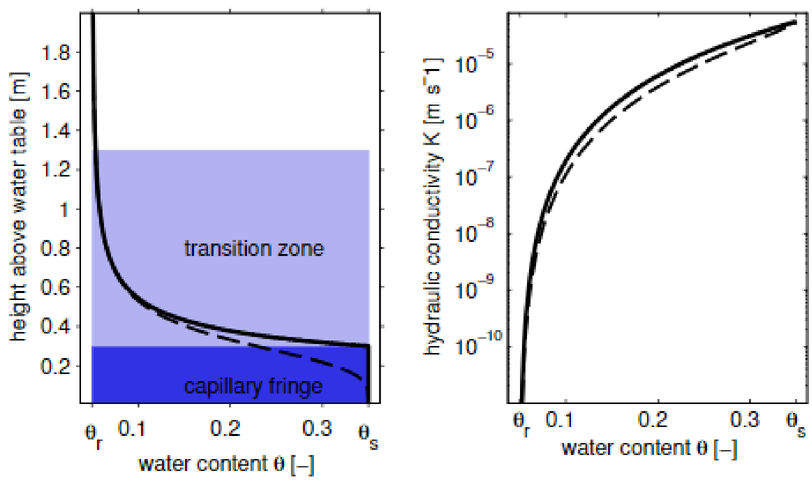

Figure 2.6 Indication of capillary fringe zone by SWCC (Klenk et al., 2015)

2.6 Oil Spill

Oil, an energy sources in most of the industrial and social community, with the growing of the social economy, the increasing of oil demands is significant until the new energy sources can be replaced. Therefore, more and more mining, exploration, storage and transportation of oil products had been developed and causing the oil leakage or oil spill incidents to be occur more frequently. LanZhengChang oil product pipeline is one of the largest domestic oil product pipeline project in China. On 30th December 2019, a diesel leakage accident took place and caused the surface water pollution and underground water pollution at the nearby river, Chishui River and Wei River (Song et al., 2011).

ITOPF, the International Tanker Owners Pollution Federation, had made a statistics report on the oil tanker spillage on 2016. On past 10 years, the oil spillage incidents had been recorded as minor and moderate spillage was 42 cases while the major spillage recorded was 14 cases. The total volume of oil spillage was around 42,000 tonnes. In the statistics report, ITOPF also stated the causes of most of the spillage which included, collision, grounding, hull failure, equipment failure, explosion and others unidentified reason. Fortunately, by following the trend of innovation, the quantities of oil spilled had been controlled and decreased, although the oil demand was still increasing due to the development of social economy. The figure had shown the trend of decreasing of the quantity of oil spilled from tankers worldwide from 1970 to 2016 (Roser, 2019).

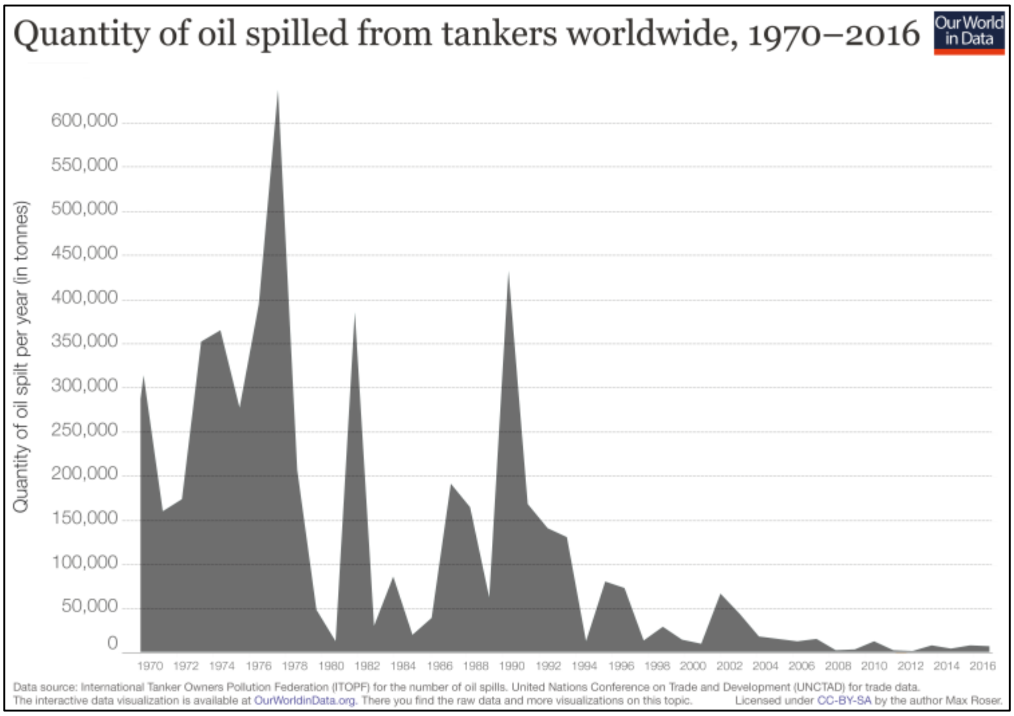

Figure 2.7 Tankers oil spilled quantity, 1970-2016 (Roser, 2019)

2.6.1 Oil Spill Scale

The amount of the oil spillage will affect the scale and magnitude of remediation and response. For example, different scale of leakage and spillage to the ground had the different response resources. In United State, the sizes of the coastal oil discharges had been defined as three categories, small (<10,000 gal), medium (10,000 – 100,000 gal) and major (>100,000 gal). Besides that, the tiered preparedness and response can be practiced to the scale of response when the oil spill incidents occurred (Fingas, 2016).

- Tier 1 – Minor spills, where incidents can be control quickly, required few hours of remediation response.
- Tier 2 – Moderate spills, where incidents can be control with resources support, required few days or weeks of remediation response.
- Tier 3 – Major spills, where incidents cannot be control in the short time, required weeks and months of remediation response

2.7 Grain Shape Constant

In the implementation of empirical relation, Terzaghi and Peck 1974, on rough approximation for the maximum height h_c *(cm)* to which lifted water by the capillary force given by soil may write as:

$$h_c = \frac{C}{eD_{10}}$$

where e is the void ratio, D_{10} is the 10% smallest diameter of grain size and C is an empirical coefficient which depending the grain shape constant and the surface impurities. Generally, C has a value between 0.1 to 0.5 cm^2.

In the theoretical background of this equation, Terzaghi and Peck stated that the greater capillary height will rise when the very fine-grained soil materials, however, the rising rate will be much slower as the low permeability in the fine-grained soil materials (Peck et al., 1974).

Based on the various of the empirical coefficient of C, the wide range of the capillary rise, h_c was been determined by different soil types as the table below. It is found very critical to have the right empirical coefficient value to determine the capillary height for the soil sample which depending on the soil microscopic properties.

Table 2.2 Capillary Height based on different Soil Type

Soil Type	**D_{10} (mm)**	**h_c (mm)**
Coarse Sand	2.00 – 0.60	15 – 50
Medium Sand	0.60 – 0.20	50 – 150
Fine Sand	0.20 – 0.06	150 – 500
Silt	0.06 – 0.002	500 – 15000
Clay	> 0.002	> 15000