Application of Light Reflection Method to Observe DNAPL Movement in Different Soil Media

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Abstract—In this research, the behaviour of dense non-aqueous phase liquid (DNAPL) was observed in different unsaturated porous media using light reflection method (LRM). Natural sand was used as a porous media that was collected from a river and segregated into different sizes through sieving. Three different sizes of the sand were used in this study. The sands were packed separately in rectangular acrylic columns and then DNAPL was injected from the top of the column. Tetrachloroethylene (PCE) was used as the DNAPL, and it was observed using a digital camera connected to a laptop and controlled using special software. The findings show a significant difference in the migration of PCE through these sands. The migration of PCE in Experiment 3 was much faster than the migration in the other experiments. This is most likely due to the large pores in the sand samples. LRM provides a non-intrusive and non-destructive tool for studying fluid flow for which rapid changes in fluid flow in the entire flow domain is difficult to measure using conventional techniques.

Keyword—Particle size; Image analysis; Porous media; NAPL; Light reflection method.

1. Introduction

Leakage of underground storage tanks and huge pipelines is the main pollution hazard to the groundwater compared to other sources. Non-aqueous phase liquids (NAPLs) have a low solubility in water and occur in the subsurface as a separate phase and are considered as one of the most spread hazardous chemical [1]. Based on density, NAPLs are classified into two types: the first type is light non-aqueous phase liquid (LNAPL) which has density less than water and the second type which is termed dense non-aqueous phase liquid (DNAPL) is denser than water. LNAPL include many hydrocarbon fuel components such as, toluene, benzene, xylenes (BTEX) and ethyl benzene. Tetrachloroethylene (PCE) and trichloroethylene (TCE) are the main examples of DNAPL materials [1]. NAPL migration in the subsurface system depends on its relative density. When LNAPL enter the subsurface system, it will pass through unsaturated soil and migrate downward due to gravity and float on the surface of water table [2] resulting in deterioration of groundwater quality. On the other hand, DNAPL will pass through unsaturated zone and continue its downward migration under the effect of gravity until it reaches the saturated zone [3].

Recently, non-destructive imaging techniques have gained more attention during the last decades which make the characterization and understanding of the multiphase system more accurate [4]. In the past few decades, there was an increasing in the using of image analysis techniques to investigate and measure multiphase fluid contents in laboratory experiments [5]. Accordingly, LRM technique based on image analysis is one of the most important and promising techniques. LRM was used by several researchers to investigate NAPL infiltration using digital cameras under controlled lighting conditions [6]. LRM is considered a cheap technique and requires only limited equipment [7, 8]. This paper qualitatively analyzes the migration of PCE in three different sizes of natural sand using LRM technique. The migration of PCE was monitored using digital camera and capturing of the images was carried out according to specific time intervals.

2. Experimental Setup

In this study, we used a one dimensional rectangular column made of acrylic with a dimension of 30 cm height × 10 cm wide × 5 cm depth. The acrylic material of the column provided a clear view of the medium within. The column was packed separately with the sand and every experiment used a new column. A digital camera Nikon D7100 (Nikon SDN, BHD, Malaysia) was fixed on the same position during the experiments at a distance of 1.5 m from the column. The camera captured images that has 24 mega pixels (6000 × 4000 pixels), and a 12 bit dynamic range that results in 4096 grey levels. The camera was connected to a laptop and the capturing of the images was controlled by (Control My Nikon 5 software).

3. Materials Selection and Preparation

Three experiments were conducted to achieve the goal of this research. Natural sand used for this study was collected from a river in Kuantan, Malaysia. Physical and chemical properties Table 1 shows the main chemical and physical properties of the sand.

Table 1: Chemical and Physical Properties of Sand

Properties	Parameter	Value	Unit
Chemical properties	Mn	77.3	[ppm*]
	Fe	2406.8	[ppm]
	Cu	1.4	[ppm]
	Zn	0.9	[ppm]
	Cd	> 0.5	[ppb*]
	Pb	11.3	[ppm]
	Si	1.3	[ppm]
Physical properties	Density	2.63	[g/cm3]
	Porosity	0.42	
	Mean size, D50	0.33	[mm]
	Coefficient of uniformity, Cu	2.23	

*ppm is part per million, ppb is part per billion

Three different sizes retained on sieve 600 µm, 425 µm and 1.18mm were used in this study. These experiments were referred to as Experiment 1, 2, and 3 respectively. The methodology of the three experiments was similar. However, the sole difference was the size of the sand used in the experiments. The sand was washed with water and dried in the oven for 48 hours at 45o C. After drying, the sand was packed by pouring 1 cm layers of sand into the column, using a spatula to mix each layer with the previous one, and then tapped the outer frame of the model using a plastic hammer to achieve a dense pack. Each experiment used 50 ml PCE. Table 2 shows the main properties of PCE. Since PCE is colorless, 0.1 g/L of Oil-Red-O was used to dye the DNAPL for better visualization. Kechavarzi et al. [6] has stated that mixing a small amount of dye is enough. This concentration is deemed to be sufficient to facilitate good visual observation of the DNAPL movement through the acrylic wall of the column. The dye was weighted and then the PCE was added and mixed with the dye using spatula. PCE was injected using injection syringe needle from the top of the column. The needle was pushed to penetrate the soil to about 1 cm below the top of the model before PCE was released to allow the movement of it downward directly and avoid the movement of PCE on the top of the soil. After the injection of PCE, the digital camera starts to capture images automatically every 10 seconds. Consequently, all images were processed using Image-Pro Premier 9.1 software (Media Cybernetics Inc., Silver Spring, MD).

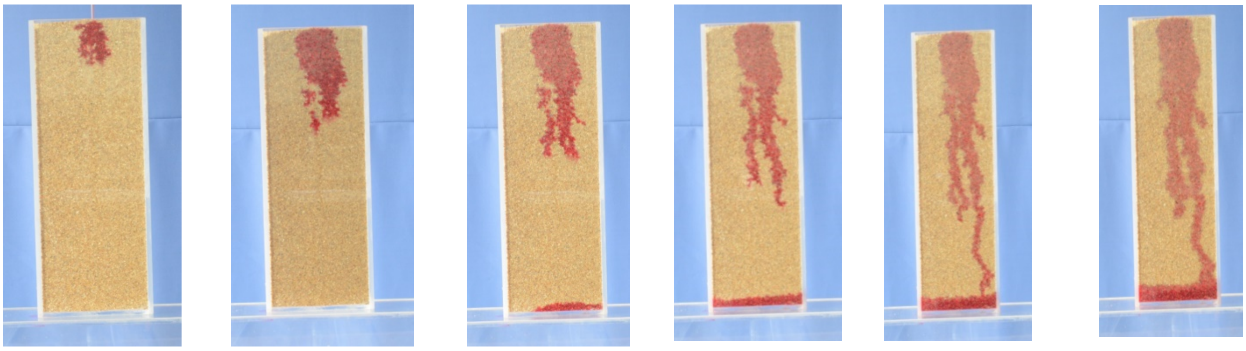
Table 2. PCE Characteristics

Chemical Formula	Density [g/cm^3]	Viscosity	Molar Mass [g/mole]	Melting Point °C	Boiling Point °C
C_2Cl_4	1.62	0.89	165.82	19	121

4. Results and Discussion

A. Experiment (1)

As mentioned before, in this experiment the sand retained on sieve 600 µm was used. The migration of the PCE was relatively fast in the first minute, and then it was slowly declined and the change in the behavior and movement of PCE was very small. It was also observed that some of the PCE was migrated faster that some parts as shown in Fig. 1. This behavior can be due to the uneven compaction of the sand. The PCE was reached the bottom of the column after 4 minutes. The observation of the PCE movement was continued until the change of the PCE behavior stopped. The overall required time for PCE migration was about 124 minutes.

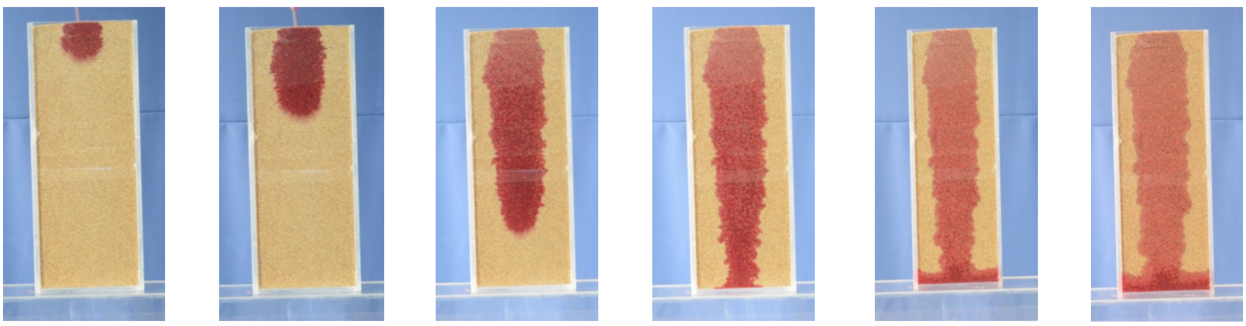


(a) (b) (c) (d) (e) (f)

Figure 1: PCE migration in 600 µm sand after (a) 10 sec (b) 20 sec (c) 30 sec (d) 60 sec (e) 240 sec (f) 124 min

B. Experiment (2)

In this experiment the sand retained on sieve 425 µm was used. A significant difference in the behavior of PCE migration was observed. The migration of the PCE was more rapid compared with Experiment 1. This behavior can be explained due to the larger pores volume between sand particles. The PCE reached approximately the half of the model in the first 30 seconds, and reached the bottom of the column after 60 seconds which is around one-fourth of the time needed in Experiment 1. The shape of PCE diffusion was more regular compared with Experiment 1 as shown in Fig. 2. Furthermore, it is obvious that no significant difference in the PCE behaviour after the fourth minutes as shown in Fig. 2 (e) and Fig. 2 (f).

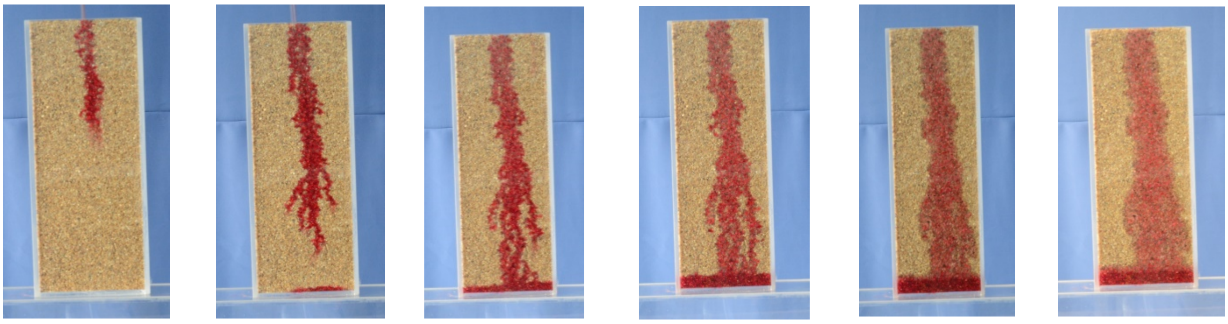


(a) (b) (c) (d) (e) (f)

Figure 2: PCE migration in 425 µm sand after (a) 10 sec (b) 20 sec (c) 30 sec (d) 60 sec (e) 240 sec (f) 124 min

C. Experiment (3)

In this experiment the sand retained on sieve 1.18 mm was used. As expected, the migration of PCE was dramatically rapid compared with the Experiments 1 and 2 where the PCE reached the bottom of the column only after 30 seconds. This is due to the fact that the pore volume is larger than that of experiment 1 and 2 which lead to larger permeability that increased the velocity of fluid movement. The observation was continued until 124 minutes similar to the previous experiments. No significant difference was observed in the behavior of PCE after the second minutes as shown in Fig. 3.



(a) (b) (c) (d) (e) (f)

Figure 3: PCE migration in 1.18mm sand after (a) 10 sec (b) 20 sec (c) 30 sec (d) 60 sec (e) 240 sec (f) 124 min

5. Conclusion

Three laboratory experiments using LRM technique were conducted to investigate the migration of the DNAPL modeled by PCE in natural sand with different sizes. The results show a significant difference in the migration movement of PCE through these sands. The migration of PCE in Experiment 3 was much faster than the migration other experiments. This is most likely due to the large pores in the sand samples. LRM provides a non-intrusive and non-destructive tool for studying fluid flow for which rapid changes in fluid flow in the entire flow domain is difficult to measure using conventional techniques.

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