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IMAGE ANALYSIS OF NON-AQUEOUS PHASE LIQUID MIGRATION IN AGGREGATED KAOLIN

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ABSTRACT

Double-porosity is an important feature in soil due to its influence on the migration of fluids within the soil. Conventional ways of measuring fluid saturation involves intrusive use of equipment that may disturb the original setting of the sample being measured. The use of image analysis has overcome this problem but has rarely been applied in research concerning double-porosity soil media. The study presented in this article applies image analysis to study the migration of non-aqueous phase liquid (NAPL) in soil with double-porosoity features. In this study, the laboratory experiments were conducted in a three-dimensional rectangular acrylic model and images were acquired using the photographic technique. Immiscible NAPL was chosen as the fluid applied as it is relatively less studied in double-porosity media compared to miscible contaminants. Aggregated kaolin was used as the double-porosity soil samples. Image analysis was utilized to observe the migration of the NAPL based on migration area coverage, the optical saturation of the NAPL as well as the intensity of the NAPL during migration. The experiments were performed over a range of different moisture content contained in the aggregated soil samples and the effect of different soil moisture content on the migration of NAPL in double-porosity soil was analyzed. The experimental results showed that the rate of NAPL migration will increase as the moisture content increases. In summary, image analysis was found to be a viable method in observing and visualizing the migration of NAPL based on optical saturation, intensity, and area invaded by NAPL in double-porosity soil.

Keywords: double-porosity, moisture content, photographic technique, subsurface contamination.

INTRODUCTION

Contamination of the subsurface by hydrocarbons through accidental spillage or poorly designed disposal is one of the most challenging environmental problems faced by many countries. Some of the most commonly encountered organic subsurface contaminants are petroleum by-products such as benzene, toluene, ethylbenzene and xylene as well as chlorinated solvents, usually from industrial activities (Tian *et al.* 2014). These compounds usually exist in the subsurface in the form of non-aqueous phase liquids (NAPL) because of their low aqueous solubility that comes from their non-polar molecular structure (Pankow and Cherry, 1996). Due to their low solubility in water, residual NAPLs constitute a long-term source of groundwater contamination. NAPLs are able to migrate to the water table and eventually become trapped in the saturated zone as residual ganglia occupying the soil pores and held in place by capillary forces.

The soil structure will also influence the migration of NAPLs. Natural geomaterials frequently exhibit two distinct scales of porosity, with the macro pores surrounding the micro pores (Burger and Shackelford, 2001; Manrique *et al.* 2007). Double-porosity may arise due to root holes, worm holes, fissures and cracks in soil (Beven and Germann, 1982) or due to the aggregated nature of the medium (Ghezzehei and Or, 2003). Fissuring and cracking are common defects in soil usually observed in heavily over-consolidated or desiccated clay (Garga, 1988) whereas aggregation are often found in agricultural soils as well as soils that were compacted on the dry side of the optimum moisture content (Romero *et al.* 1999). Figure-1 illustrates the concept of double-porosity.

Image analysis is a type of computer analysis that is used to extract meaningful information from images. In the field of civil engineering, image analysis is often used (Maas and Hampel, 2006) to study the movement and behaviour of very small or tiny properties such as the propagation of cracks in a structure or the occurrence of boundary layers in flow over immersed objects. Voids or porositiness in soils are hard to see with the naked eye, hence the application of image analysis can be a fitting method to study the migration of NAPL in the subsurface.

In this research, image analysis was used to study the migration of NAPL in double-porosity soil represented by aggregated kaolin clay. The fabric of the aggregated kaolin can be divided into inter-aggregate pores and intra-aggregate pores, as shown by the works of Ngien *et al.* (2012). They have also found that within the same duration, organic contaminants will actually travel further in soil with double-porosity features compared to in single-porosity soil. This is due to the fact that secondary porosity features such as inter-aggregate pores or cracks are usually larger than the primary porosity of the soil media. Therefore, the NAPL has to overcome a relatively lower capillary pressure to enter the secondary porosity features.

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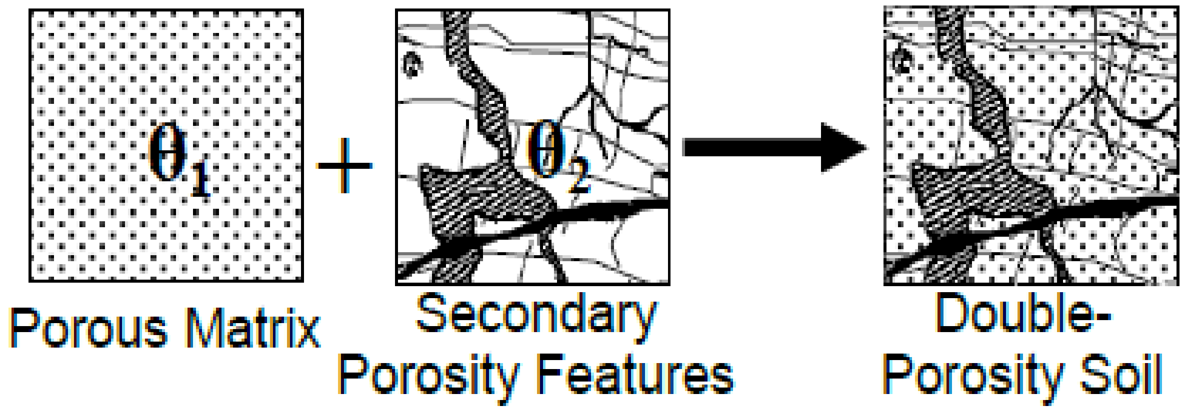

Figure-1. Visualization of double-porosity (Ngien and Ken, 2015).

Although the effect of double-porosity on NAPL migration has been established, the work in this article is one of the first to study the effect of different moisture content in the double-porosity soil on the migration of NAPL. Sa'ari *et al.* (2015) is the only other work in this area and they studied aggregated soil samples containing 25% and 33% moisture content in cylindrical columns, which differs from the moisture contents and acrylic models in this study. The methodology of the experimental work is described in the following section.

METHODOLOGY

Apparatus and material

The experiments were conducted using a Nikon D7100 digital single-lens reflex camera. The aggregated soil samples were housed in rectangular acrylic models that were closed from all sides except the top where the NAPL will be poured in. The inner dimensions of the rectangular models were 10 cm (w) × 5 cm (l) × 30 cm (h) while the compacted kaolin aggregate samples had dimensions of 10 cm (w) × 5 cm (l) × 10 cm (h). There was an empty space of 20 cm in height above the aggregated sample in each rectangular model that was needed to contain the kaolin aggregates prior to compaction. The models were made of acrylic to facilitate viewing of the NAPL migration within the aggregated soil samples. The NAPL applied was represented by toluene, a volatile organic compound that has a density lighter than water. The toluene was dyed red using Oil-Red-O powder to enhance its visibility during migration in the acrylic models. The kaolin powder used to create the kaolin aggregates is of the S300 variety and is commercially available.

Aggregated sample preparation

The kaolin powder was first dried for at least 24 hours before being cooled to room temperature. The cooled kaolin was then mixed thoroughly with water according to the moisture content needed. Three different moisture contents, 28%, 30% and 32%, were applied in this study. Suitable moisture content values range from 25% to 35%. Adding more than 35% water to the kaolin powder will render the mixture too slurry-like, thus unable to form the kaolin aggregates needed to create the double-porosity structure (Sa'ari *et al.* 2015). Conversely, mixing less than 25% water to the kaolin powder will cause the mixture to be too dry instead. In this case, the mixture will be too crumbly and cannot form kaolin aggregates as well. Once mixed, the dough was packed into resealable plastic bags for curing as well as to prevent loss of moisture content. After curing for at least 24 hours, the kaolin granules for the aggregated soil samples were formed by taking the mixture out from the resealable plastic bags and pushing them through a 2 mm sieve. The process of pushing the cured kaolin mixture through 2 mm sieve will take some time as a substantial amount of the kaolin granules need to be created and collected before being transferred into the acrylic model for each experiment.

The amount of kaolin granules needed to form the aggregated kaolin samples to a height of 10 cm can be calculated from the bulk density of the mixture, which in turn can be calculated based on the moisture content and dry unit weight of the kaolin soil. Equation 1 (Azizi, 2000) shows the calculation for the bulk density of the mixture used to create the kaolin aggregates.

$$\gamma = \gamma_d(1 + m.c.) \qquad (1)$$

where γ is the bulk density, *m.c.* refers to the moisture content of the soil and γ_d is the dry unit weight of the soil which in the case of this study was taken as 11 kN/m^3 based on Ngien *et al.* (2012). Referring to the aggregated soil sample dimensions stated in the previous section, the volume of the final compressed sample is equivalent to 0.0005 m^3. The weight of the kaolin granules to be transferred into each of the acrylic models can be obtained by getting the product of the bulk density and volume of the compacted kaolin granules. The final step was compressing the kaolin granules to the desired height before each experiment can commence.

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Experimental setup

Each model was placed on a rigid table and the camera situated in front of the model for image acquisition as shown in Figure-2. The camera was set-up and adjusted until a clear image of the kaolin sample can be seen. Throughout the duration of each experimental trial, no movement of either the camera or the rectangular acrylic model was allowed in order to minimize any error that might occur during the analysis stage. Artificial lighting was employed during the experiments. Figure-3 shows the engineering sketch for the experimental setup.

Figure-2. Setup of the experiment.

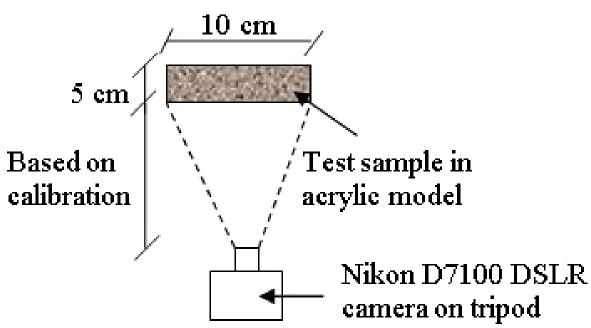

Figure-3. Top view sketch of setup (not to scale).

Image acquisition and processing

After calibration of the camera, the experiments began by pouring the dyed toluene onto the aggregated soil sample within the acrylic model. As soon as the toluene touched the surface of the soil sample, timing for that particular experimental trial will start and the first image is taken. Table-1 shows the image acquisition frequency applied in this research. Normally the movement of such instantaneously-introduced toluene will become slower until it settles down at the bottom of the model, hence the frequency of the image acquisition will decrease accordingly. At the end of the experiment, the images were transferred from the camera to a computer equipped with the Image Pro-Premier 9.1 software which was used to analyse the images.

Table-1. Frequency of image acquisition.

Duration (minutes)	Interval Frequency (seconds)
0 – 1	5
1 – 2	10
2 – 3	15
3 – 4	20
4 – 5	30
5 – 10	60
10 – 20	120
20 - 75	300

RESULTS AND DISCUSSION

Migration of the NAPL in the aggregated kaolin sample containing 30% moisture taken by the photographic technique are shown in Figure-4 where the images, from left to right and top to bottom, were taken at 0, 25, 50, 90, 150, 240, 480, 960 and 2009 seconds, respectively. The resultant images for the samples containing 28% and 32% moisture content looks similar to Figure-4, with the exception of the time it took for the NAPL to reach the bottom of the model.

The graphs of area covered by NAPL migration versus time for the aggregated kaolin samples with moisture content of 28%, 30% and 32% were plotted and shown in Figure-5. The time taken for the NAPL to reach the bottom of the aggregated kaolin samples containing 28%, 30% and 32% moisture content was 2609 seconds, 2009 seconds and 1103 seconds, respectively. From Figure-5, the sample with 32% moisture content showed the fastest coverage by NAPL at 0.0824 cm^2/s whereas the slowest NAPL coverage was in the 28% moisture content sample at a rate of 0.0298 cm^2/s. From this result, it can be seen that the rate of coverage by NAPL in the aggregated kaolin samples increases proportionally with moisture content within the samples. This phenomenon may be due to the larger inter-aggregate pores found in the 32% moisture content aggregated kaolin sample compared to the other samples with 28% and 30% moisture content. Other factors that may have influenced the rate of coverage by the NAPL are capillary forces and wettability of the different fluids present within the aggregated kaolin samples (Ngien *et al.* 2012). The results obtained here also concurred with those from Sa'ari *et al.* (2015).

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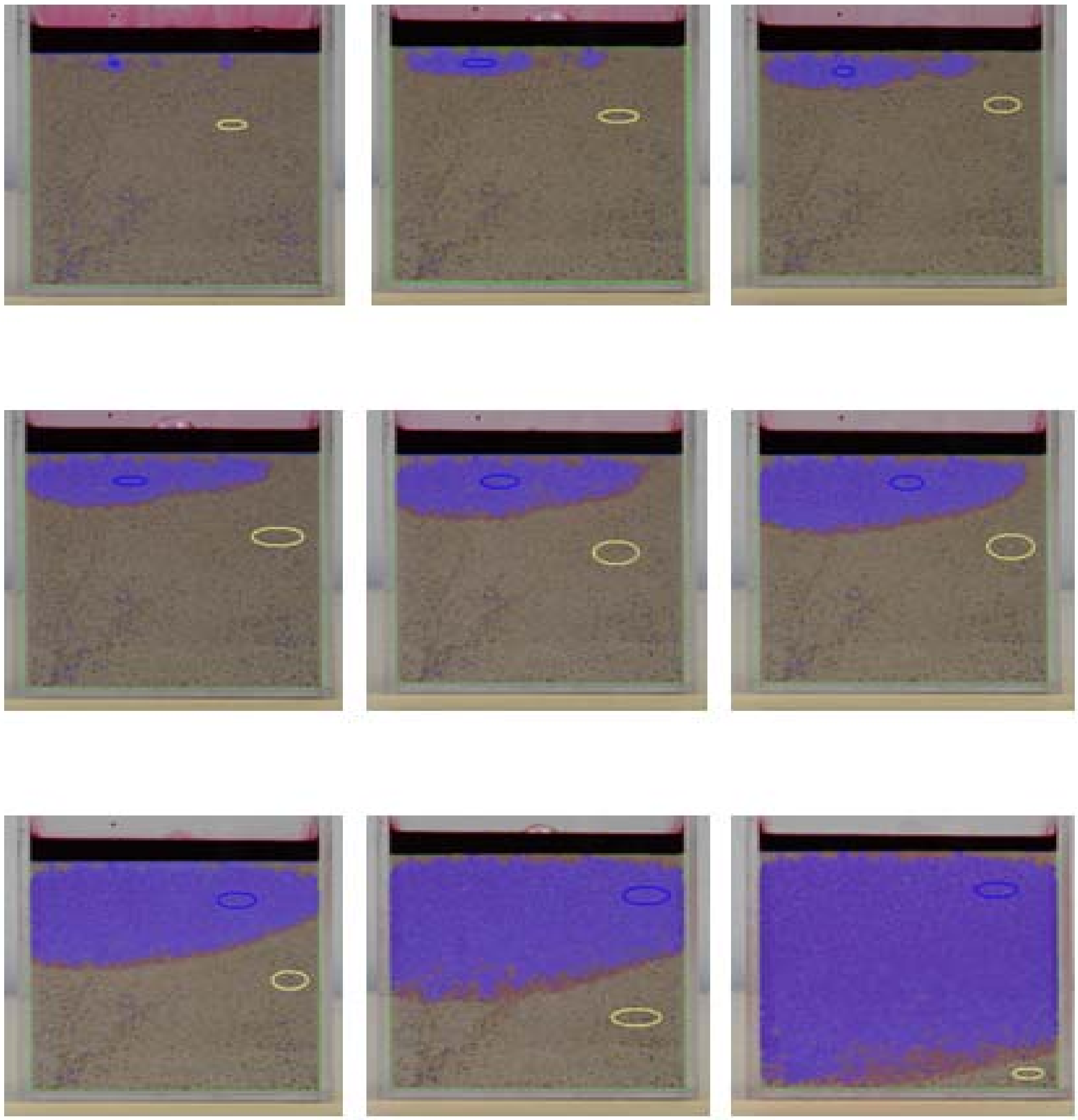

Figure-4. NAPL migration throughout the experiment for aggregated kaolin sample with 30% moisture content.

Besides area coverage by NAPL, optical saturation of the NAPL in the aggregated kaolin samples was also extracted through image analysis. The optical saturation in this case refers to the saturation in terms of luminosity for the area of interest, which means areas of the aggregated sample where dyed toluene is visible through the walls of the acrylic model. Figure-6 shows the optical saturation extracted from the images of the NAPL migration versus time for all three samples. Based on Figure-6, the optical saturation value will increase as moisture content increases. The highest saturation captured in the sample with 32%, 30% and 28% moisture content is 77.6460 luminosity, 75.0735 luminosity and 73.8972 luminosity, respectively. Again, the larger inter-aggregate pores between the kaolin aggregates with higher moisture content may be the cause for the increasing saturation trend.

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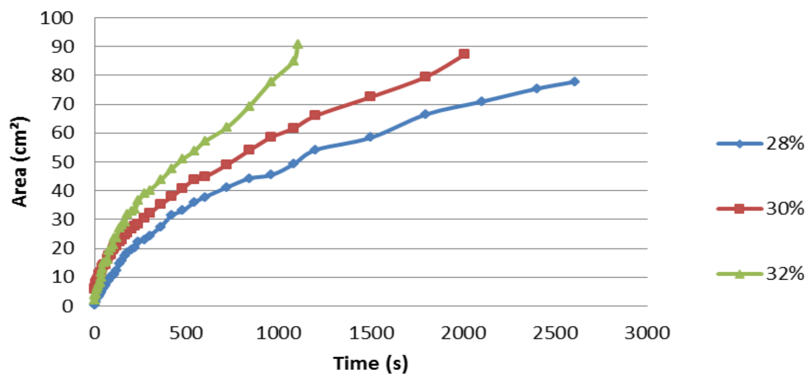

Figure-5. Graph of NAPL coverage area versus time.

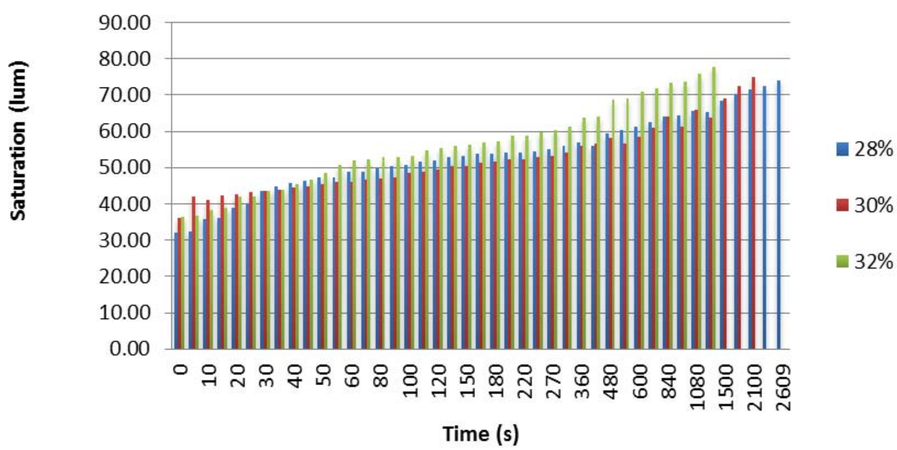

Figure-6. Optical NAPL saturation values versus time.

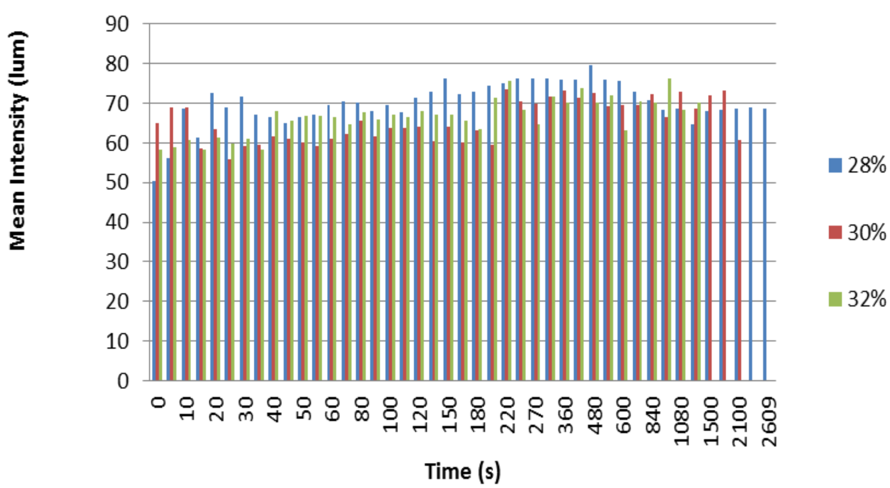

Figure-7. NAPL intensity values versus time.

The third component resulting from the image analysis was the intensity of the NAPL within the area of interest, which can be seen versus time in Figure-7. The highest intensity values found for the samples with 28%, 30% and 32% moisture content were 79.5338 luminosity, 73.5777 luminosity and 76.2671 luminosity, respectively.

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On the other hand, the lowest intensity values were 50.2558 luminosity, 55.9557 luminosity and 58.2528 luminosity for the soil samples with 28%, 30% and 32% moisture content, respectively. It can be observed from Figure-7 that the intensity fluctuates in all three samples but the fluctuations did not went below 50 luminosity or exceed 80 luminosity. This was probably due to the artificial lighting applied during the experiments producing light intensities of between 50 to 80 luminosity.

CONCLUSIONS

Laboratory experiments on NAPL migration in double-porosity soil have been carried out. The double-porosity characteristic of the aggregated kaolin samples was visually confirmed through the obvious aggregation and the presence of inter-aggregate pores. A photographic technique was used to capture the migration of the NAPL in the soil samples. Image analysis was applied on the images taken and the results shown in graph plots. It can be concluded that the rate of NAPL migration in double-porosity soil increases proportionally to the moisture content based on the coverage area, optical saturation and intensity of the NAPL. The presence of inter-aggregate pores accelerates the rate of NAPL migration in double-porosity soil when compared with previous similar experiments that used single porosity soil. In summary, NAPL showed a speedy migration in double-porosity soil throughout the research while increasing moisture content will in turn increase the rate of NAPL migration through the double-porosity soil.

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