

INVESTIGATION OF NON-AQUEOUS PHASE LIQUIDS MIGRATION IN FRACTURED DOUBLE-POROSITY SOIL

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Abstract

Groundwater contamination is one of the most challenging issues and become more complicated problems when the surface or subsurface is affected earthquake vibration. Such condition would probably influence the migration of non-aqueous phase liquid into the groundwater sources. This pa-

per investigates the migration of NAPLs in fractured double-porosity soil which is important for the cost-effective remediation clean-up of contaminated groundwater. For this purpose, an experiment model was conducted to study the pattern and behaviour of non-aqueous phase liquid migration in fractured double-porosity soil subjected to vibration by using digital image processing technique. The outcome of the experiments show that the flow is not a uniform migration pattern as the soil structure has been deformed after the process of vibration. The fractured double-porosity soil has swifter liquid migration on the cracked soil surface condition compared to the intact soil surface. It is also noted that the migration time required to reach the bottom layer is longer for lower moisture content compared to the higher moisture content. This study demonstrate that the digital image processing technique is capable to provide the flow rate of non-aqueous phase liquid. It also furnish useful detailed information for researchers and professionals to comprehensively understand migration behaviour.

Key Words: Granular Materials; Groundwater Contamination; Image Analysis Method; Non-Aqueous Phase Liquids; Vibration.

1 Introduction

The national development has played a part in the natural disasters and climate changes which lead to a negative impact on the health issue and geo-environment. Groundwater contamination is one of the most challenging geo-environmental issues encountered in many countries. The issue of leakage from underground storage tank and spillage of hydrocarbon liquid can contribute to the contamination of non-aqueous phase liquids (NAPLs) into the groundwater, resulting in groundwater pollution and rendering the quality of groundwater unsafe for drinking and agriculture. The flow rate and phenomena of the migration of NAPLs into the groundwater resources would be more complicated under the effect of earthquake vibration on double-porosity soil. Vibration leads to cracked soil, rearrangement of soil structure, unstable soil structure and fractured soil deformation.

These problems need to be solved by both engineers and re-

searchers worldwide to ensure the sustainability of geo-environmental and groundwater resources. Two specific sub-region scales with soil transforming characteristics has been identified as deformable double-porosity soil, and a greater understanding with respect to NAPLs migration subjected to fractured double-porosity soil is required. Dangerous toxic chemicals have made actual on-site study unfeasible, and have been practically replaced by physical model experiment simulations. The most critical contaminants are petroleum type hydrocarbons such as toluene, which can be classified as light non-aqueous phase liquids whose density is less than water, which have been used in this study. The light non-aqueous phase liquids migrate through the unsaturated soil and stay on the groundwater surface, while the dense non-aqueous phase liquids penetrate through the saturated soil to settle.

2 Literature Review

The structure of the soil affects the flow rate and characteristic of liquids migration. It is well known that soil is typified by many different structures, and that soil characteristics are roughly not homogeneous. Fractured soil reduced the intact soil shear strength and increased the hydraulic conductivity(1). (2) stated that the flow of liquids through problematic soil such as cracked soil played an essential role. The hydrological behaviour and mechanical properties in fractured soil are significantly changed (1). It is widely acknowledged that the double-porosity media in usual condition is known as soil that displays two specific scales of porous media (3). The soil with intra-aggregate and inter-aggregate pores for double-porosity soil display pore-size bimodal distribution that can found in agricultural tops-soils and compacted soil (4, 5). According to (6), the double-porosity soils have different hydraulic properties of two sub-region media due to different pore size characteristics. Existing research by(7) identified the double-porosity soil as being formed due to earthquake or vibration effect, where the saturated and roughly filled granular soils in specimens of sand and soils exposed to earthquake vibration may lead to greater soil deformations and may liquefy. Furthermore, (7) had demonstrated that liquefaction is not a strictly undrained process via first principles analysis,

but in fact observation of numerous earthquake events shows that the interplay between soil rearrangement, liquid migration, and permeability changes have led to loss of strength. The fracture porosity formation were characterized by water-bearing formations where groundwater flows along the fracture solid rock, while a fracture is created as rock mass is broken down due to tectonic force(8).

Research by (9) found that the overlapping continuum technique had been the basis theory for the double-porosity soil. Moreover, (1) show that fractured soils based on a continuum mechanics approach is used for inception of unsaturated liquid storage and conductivity functions. In addition, the dual-continuum method is capable of dealing more methodically with fracture matrix interplay compared to discrete-fracture mode (1)(Fredlund et al., 2010). Therefore, this study applied the model concept with the soil that overlaps the three continuums of fracture, primary, and secondary porosity features developed by (10). The double-porosity soil concept contain inter-aggregate and intra-aggregate pores matrix blocks represented by the primary porosity and secondary porosity continuums, respectively, while the vibration effect that had caused the double-porosity soils to fracture was represented by fracture porosity continuums. The double-porosity characteristics in soil could be created in the laboratory, where most of the studies relating to double-porosity soil were carried out by(11). (12) conducted one-dimensional drying and consolidation experiments on laboratory-prepared double-porosity kaolin soil sample. Recently, numerous studies by (6, 10, 13-18) have conducted physical experiments on double-porosity soil media. The previous listed research has contributed to the knowledge of soil characteristics in double-porosity soil, but the studies were limited to intact double-porosity and the reaction such as vibration effect on the double-porosity soil was never applied.

(2) conducted an experimental model to predict the flow rate through a creaked soil network, and found that the soil matrix for seepage rate is small compared to the flow rate through the fractured soil network. Furthermore,(19) identified that a powerful technique in most research fields was image analysis method, which was used to investigate the complicated contaminants behaviour and determination of liquid saturation rate. Therefore, this study used digital image analysis to understand and analyze the liquid

migration in fractured double-porosity soil. Based on the overview by (20), the experiment involved noninvasive imaging techniques, which used observation and characterization of multiphase system for greater precision. Furthermore, (21) proved that image analysis is a reliable technique for rock pore space direct imaging and direct investigation of liquid migration. Therefore, a number of researchers (6, 13, 16-18, 22) have carried out image analysis techniques for liquid migration experiment. As mentioned by (23), image analysis technique in civil engineering field was regularly used to study the object flow absorption and liquid migration of small properties specific to structure crack extension. Thus, the porosity and cracked soils are difficult to visualize by naked eye and for this problem, digital image processing technique was acceptable for use in this study to observe and monitor liquid migration in fractured double-porosity soil.

The widespread problem of difficulty gathering reliable data concerning liquid migration characteristics and the physical experiments model will go a long way in the effort to understand and observe such problem. Previous research by (2) presented a significant of comprehensive understanding of the flow characteristics through cracked soil and suggested further experimental study on more complex crack network is required to study the water flow rate. Therefore, a physical experimental model was conducted to study the characteristic of NAPLs migration in deformable double-porosity soil under the vibration effect by using digital image processing technique (DIPT). Thus, to achieve the purpose of this study, several objectives based on the literature were (i) to determine the behavior of NAPLs migration in fractured double-porosity soil using digital image processing technique, (ii) to differentiate the pattern of NAPLs migration in fractured double-porosity with different soil moisture content. This study covered the double-porosity aggregated soil medium vibrated by using a vibratory table involving a specially assembled acrylic glass soil column. The migration of Toluene was observed in a 100mm height fractured soil sample in acrylic glass circular column. The aggregated soil sample mixed with 25% and 30% water was added to dry kaolin S300 soil in experiment 1 and 2, respectively. Toluene was used as a liquid source. Red powder was used to dye the Toluene to intensify the migration observation. 150ml of dyed Toluene was poured instantaneously on

top of the soil surface for each aggregated soil sample. The image analysis was accomplished by using Surfer programme and Matlab routine to analyse the dye Toluene flow migration pattern and behaviour.

3 Materials and Methods

In this study, the soil sample preparation, experimental setup, and digital image processing setup were briefly discussed in subsequent sections.

3.1 Soil Sample Preparation

To create double-porosity, commercially available kaolin soil S300 was used in this study as sample material. (24) and (25) were used to test the kaolin soil S300 soil properties for the purpose to obtain particle size distribution, Atterberg limits, solid particle density and saturated permeability of the kaolin soil. The kaolin soil S300 was classified under the Unified Soil Classification System (USCS) as silt with low plasticity (ML) based on the value of particle size distribution and Atterberg limits. The properties of S300 kaolin soil sample are shown in Table 1.

PROPERTY	VALUE
Liquid Limit (%)	41.00
Plastic Limit (%)	28.00
Plasticity Index (%)	13.00
Particle Density (Mg/m^3)	2.65
Sand: 2mm to 0.06mm (%)	3
Silt: 0.06mm to 0.002mm (%)	92
Clay: Smaller than 0.002mm (%)	5
USCS Classification	ML
Saturated Permeability, K_{average} (m/s)	5.41×10^{-9}

Table 1. S300 kaolin soil properties

As previously explained, the method established by (12) was used to prepare the aggregated soil sample. The dried kaolin powder was first mixed with different percentage of moisture content to prepare the aggregated soil sample such as 25% and 30% for sample 1 and sample 2, respectively. The selection of moisture content in this experiment was based on the liquid limit and the optimum moisture content for kaolin soil sample in this study was

27%. This is because if the moisture content is less than 25%, the kaolin soil is incapable to form granular because the aggregates are too dry and crumbly (16). Thereafter, in a cool condition with minimum 24 hours, the mixture was cured and kept in a re-sealable plastic bag, with the air in the plastic bag removed before sealing to prevent the moisture content from evaporating. After that, the mixture was broken by hand and passed through a 2.36mm sieve for both samples to obtain kaolin granules. Then, kaolin granules were transported in acrylic soil column and the soil granules compressed to 100mm height using a compression machine. The rationale of 100mm sample height was to ensure the uniformity throughout the depth of soil sample. The prepared aggregated soil sample is shown in Figure 1. The falling head permeability test was carried out to obtain the average permeability of the aggregate soil sample as shown in Table 1 for the average permeability (K_{average}) value.

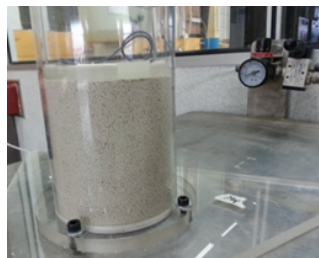


Figure 1. The prepared kaolin soil sample

The physical laboratory experiments were implemented in special design circular acrylic soil column with dimension of 100 mm-outer diameter and 94 mm-inner diameter $\times$ 300 mm high. The acrylic soil column with aggregated soil sample was fitted on the vibratory table in order to prevent any freedom of movement of the acrylic soil column. The vibratory table setup to vibrate the aggregated soil sample was developed by (10) as shown in Figure 2. The vibration frequency of the vibratory table was set at 0.98Hz and a vibration period of 60 seconds has been applied to vibrate the aggregated soil sample based on the method established by (10). The results of fractured soil pattern for sample 1 and sample 2 before and after vibration process are exhibited in Figure 3.

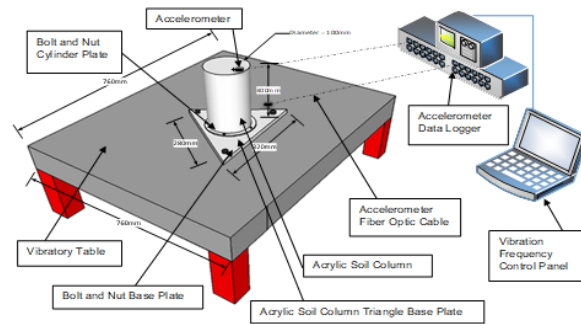


Figure 2. 3D diagram of vibratory table setup

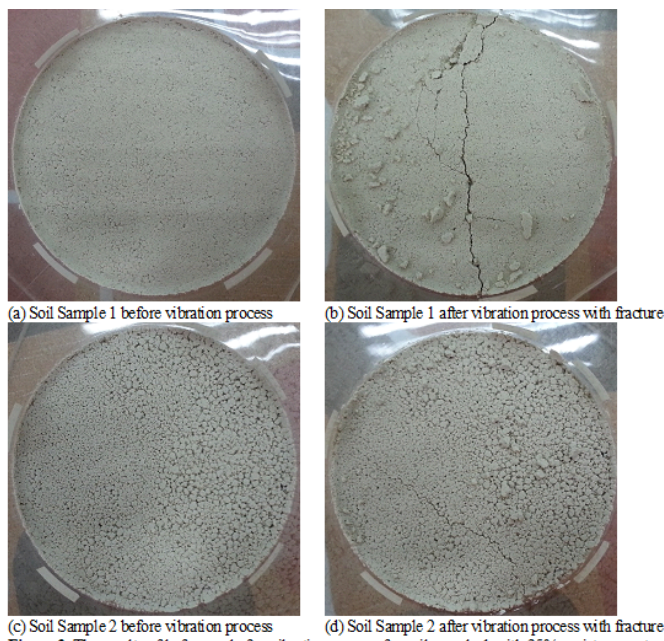


Figure 3. The results of before and after vibration process for soil sample 1 with 25% moisture content and sample 2 with 30% moisture content

3.2 Experimental Setup

The intra-aggregated and inter-aggregated pores created through aggregation and vibration as previously explained represented the fractured double-porosity characteristic in the soil sample. The

acrylic soil column containing fractured double-porosity soil was used to observe and measure the non-aqueous phase liquids migration that occurs inside the entire circular column area with the purpose of not invading and not destroying the original soil sample setup. In each sample, the image acquisition setup for NAPLs migration is as shown in Figure 4.

The dominant equipment for NAPLs migration image acquisition system was the Nikon D90 DSLR digital camera and a V shape reflection mirror was used to reflect the whole image of circular column area. The Nikon D90 DSLR camera was fixed with medium size image format of 3216 x 2136 pixels, which resulted in each pixel having the size of 5.6 x 5.6 m. The setup of digital camera during the experiments was set at minimum shutter speed of 1/640 second and ISO speed set at ISO-2500, which has been implemented for all the soil sample experiments. To overcome the problem of insufficient image acquisition, this experiment used the V shape mirror that was adjusted until a clear image and the whole circular soil column area could be seen, allowing 100% of the circular soil column surface to be exposed in a single view of image acquisition throughout the experiments. Thus, the images of the NAPLs migration throughout the whole area of soil column circumference can be initially captured by just a single click on the DSLR digital camera. The light source for sample 1 and sample 2 comes from linear fluorescent lamp-40 watt that was placed slightly above the circular soil column.

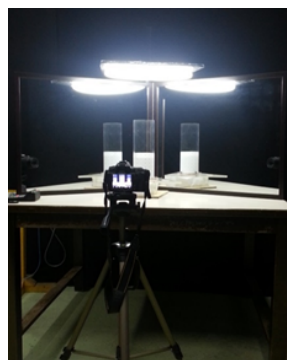


Figure 4. Digital image acquisition setup

Both experiments were first sheathed in white paper with pre-drawn gridline (20mmx20mm) onto the soil column as a control point on

the reference image. Once the reference image was taken, the pre-drawn gridline paper can be removed from the circular soil column. Both experiments began by pouring the dyed toluene instantaneously onto the top center of fractured aggregated soil sample in circular acrylic soil column. The quantity of 150ml dyed toluene was used in sample 1 and sample 2. After the toluene water had covered the whole surface area of the fractured soil sample, the first digital image of dyed toluene migration was taken in a room temperature of 23°C. The dyed toluene migration pattern at a specific time interval was captured for the rest of the subsequent digital images. The subsequent digital images totaled 37 images in 110 seconds for sample 1 and 19 images in 57 seconds for sample 2.

3.3 Digital Image Processing Setup

The recorded images in JPEG format then were transferred from digital camera to computer for further image processing using Surfer Software version 10 and Matlab routine. The first step in using Surfer Software version 10 is to digitize the control points for the area of interest on reference image to extract the control point image coordinates. Area of interest, referred to as pre-determined migration boundary area (V shape reflection image and front image) for sample 1 and sample 2, contained the dyed toluene as shown in Figure 5. The image transformation required the coordinate of the control points and the true grid coordinate on pre-drawn grid line.

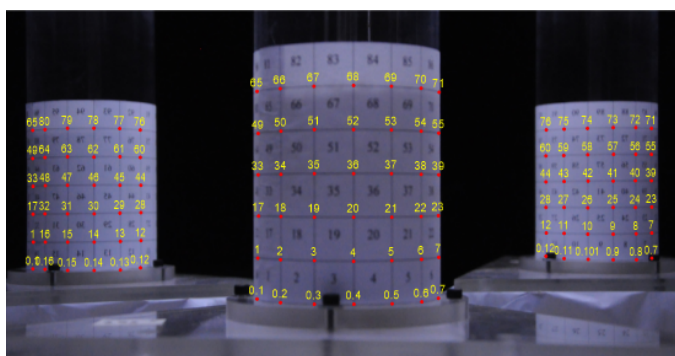


Figure 5. Control point position on reference image cover the area of interest for V shape reflection image and front image

Once the image control point has completed, Matlab routine was used to convert data from area of interest into hue saturation intensity digital image format and red-green-blue. The hue saturation intensity value and red-green-blue value from image were extracted and saved in text files using American Standard Code for Information Interchange format. Furthermore, Matlab routine was used to loop the subsequent digital image three times to extract and save the intensity values for all three section areas of interest (V shape refraction image and front image) of the circular acrylic soil column. Finally, Surfer Software version 10 was used to plot the contour behaviour pattern of dyed toluene migration based on the hue saturation intensity values. The hue saturation intensity contour plot of dyed toluene migration behaviour can provide detailed information to facilitate researchers to understand the pattern of dyed toluene migration characteristic.

4 Results and Discussion

The results after the NAPLs migration process for the top soil surface with the divided measurement of actual size column circumference zone for sample 1 and sample 2 to visualize the crack position is shown in Figure 6. The downward migration pattern of HSI plot of dyed Toluene in the fractured double-porosity soil sample with 25% and 30% moisture content for sample 1 and sample 2, respectively, are shown in Figure 7. When the HSI plot in curve joint the right and left boundary has formed, the circular shape was clearly apparent in two-dimensional shape; however, the actual non-aqueous phase liquid migration in the circular acrylic soil column was one-dimensional. Both samples used 150ml dyed NAPLs that was poured instantaneously on top of the soil samples surface by using glass funnel to ensure that the dyed NAPLs penetrated in one-dimension. The dyed NAPLs would have migrated into the test sample before the whole soil sample surface was covered.

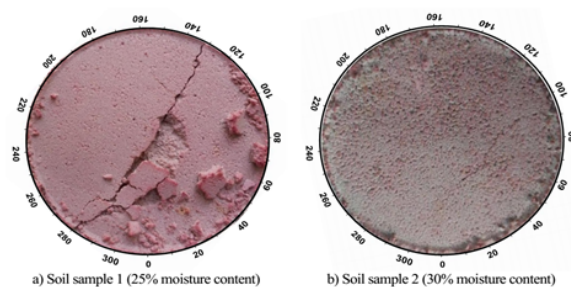


Figure 6. NAPLs migrated soil surface with measurement of actual column circumference zone for sample 1 and sample 2

In sample 1, the selected HSI plots of dyed NAPLs migration are recorded at intervals such as 1, 36, 60, and 110 seconds, respectively. Based on observation and the HSI intensity contour plot results, the flow of dyed toluene migration did not consistently penetrate the front x-axis horizontal line as the fractured double-porosity soil was non-homogenous. Rapid migration occurred at the cracked soil surface condition compared to locations that were not cracked in soil surface as shown in Figure 6. The dyed NAPL completely migrated over the whole top surface soil surface area into the featured soil sample of the test, which took about 60 seconds. Meanwhile, the duration for dyed toluene migration from the top surface to the bottom of soil column was 110 seconds and further monitoring at 300 seconds showed no changes in the migration pattern. At one second after the commencement of the experiment, the dyed NAPL migration reached halfway of the test sample at the location of fractured soil surface as shown in Figure 7. The dyed NAPL migrated fastest between 80 to 150mm and 250 to 300mm along the soil column circumference zone, and the fractured line at 130 mm and 280mm could be clearly visualized as shown in Figure 6. The NAPL migration can be seen by comparing Figure 6a (1 seconds) where the darker colour tone indicating the high NAPL saturation appeared around the top of the sample to Figure 6a (110 seconds) where the darker colour tone had disappeared from the top of the fracture double-porosity soil.

In sample 2, the interval of 1, 24, 36, 57 seconds, respectively, was selected for dyed NAPL migration HSI plot as shown in Figure

7. The NAPL migration was similar to the result found in sample 1. The flow of dyed NAPL migration was not uniformly downward at the front boundary horizontal line due to the non-homogeneity of the fractured double-porosity soil structure. One second after the initiation of the experiment, the dyed NAPL migration reached one quarter through the test sample at the location of fractured soil surface as shown in Figure 7. The migration can be considered as one-dimensionally downward because the dyed NAPL poured on top of the test sample had covered the whole sample surface. It took about 24 seconds for the dyed NAPL to completely disappear from the whole top soil surface area into the fractured soil sample of the test. Meanwhile, the overall duration for dyed NAPL migration from the top surface to the bottom was 57 seconds and further observation at 180 seconds showed no changes in migration pattern where the NAPL migration to the bottom of the soil column reached 100

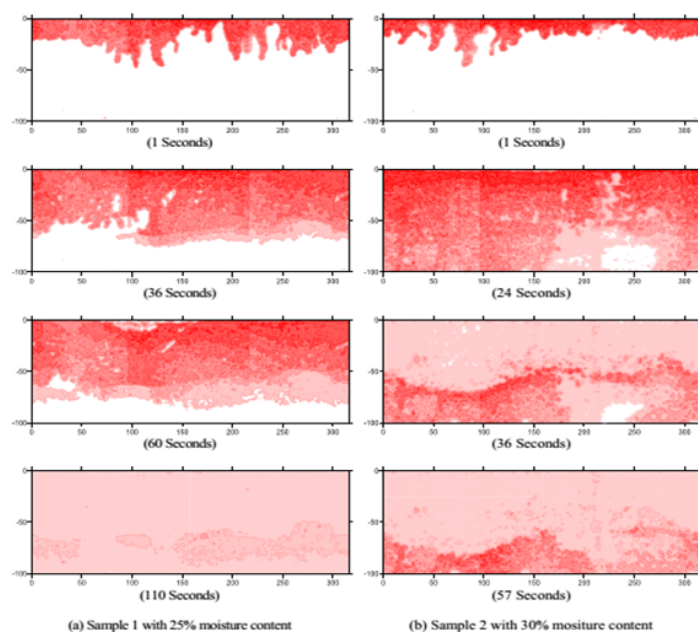


Figure 7. HSI plots of downward dyed NAPL migration in fractured double-porosity soil for sample 1 and sample 2
From the result, it can identified and differentiated that soil sample

2 had the faster migration compared to soil sample 1 as less time was taken for NAPL to reach the bottom of the soil column in soil sample 2 (57 seconds). Moreover, the difference between samples 1 and 2 was in migration speed time and migration behaviour. As shown in Figure 3, the inter-aggregate pores of soil sample 2 are quite massive compared to soil sample 1. This condition of inter-aggregate pores and fractured kaolin soil may cause the faster downward penetration of NAPL with increase in soil sample moisture content. Capillary pressure would influence the migration of the NAPL because the larger pore size may reduce the capillary pressure that NAPL has to overcome to migrate in those soil pores. This experiment showed soil sample 2 (30% moisture content) with coarse grain structure resulted in massive inter-aggregate pores compared to soil sample 1 (25% moisture content). Therefore, when comparing higher and lower moisture content, the higher moisture content in fractured double-porosity results in less time taken to reach the bottom of soil column, while the lower moisture content in fractured double-porosity taken longer time to reach the bottom of soil column.

5 Conclusion

A physical laboratory experiment on NAPL migration in fractured double-porosity soil with different moisture content had been carried out. This experiment was designed to investigate the dyed toluene behaviour and to differentiate the pattern in the fractured double-porosity soil in circular soil column. The digital image processing technique using Matlab routine and Surfer Software version 10 was applied to analyze the NAPL migration data obtained from captured digital image. The physical laboratory experiment successfully provided the results of various behaviours and differentiated the pattern of NAPL migration at different moisture content of 25% and 30%. Both samples indicated that 100% NAPL migrated to the bottom of soil column and the air bubbles were continuously observed at the soil sample surface of NAPL reducing due to the liquid wettability in the soil sample. The NAPL migration behaviour soil sample 2 have been observed the flow rate migration faster about 52% compared to soil sample 1. The results proved

that the factors significantly influenced the dyed toluene migration in soil samples 1 and 2 was the soil sample fractured pattern, soil sample moisture content, soil sample structure and the capillary pressure of dyed toluene. In conclusion, the hue saturation intensity value and contour plot of dyed toluene migration could produce detailed particulars to professionals to understand and simulate the behaviour of dyed toluene migration that could be used to identify the remediation method most suitable to sustainable groundwater utilization.

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