CHEMICAL ENGINEERING TRANSACTIONS

VOL. 63, 2018

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Jeng Shiun Lim, Wai Shin Ho, Jiří J. Klemeš

ISBN 978-88-95608-61-7; **ISSN** 2283-9216

DOI: 10.3303/CET1863115

Investigation of Aqueous and Non-Aqueous Phase Liquid Migration in Double-Porosity Soil Using Digital Image Analysis

Loke Kok Foong[a], Norhan Abd Rahman[b,]*, Ramli Nazir[b], Radzuan Sa'ari[c], Mushairry Mustaffar[d]

[a]Faculty of Civil Engineering, University Teknologi Malaysia, Johor, Malaysia
[b]Centre of Tropical Geoengineering, Faculty of Civil Engineering, University Teknologi Malaysia, Johor, Malaysia
[c]Survey Unit, Faculty of Civil Engineering, University Teknologi Malaysia, Johor, Malaysia
[d]Department of Geotechnical & Transportation, Faculty of Civil Engineering, University Teknologi Malaysia, Johor, Malaysia
norhan@utm.my

The development activity of the country has played a part in climate change and natural disasters, which lead to a negative influence on the geo-environment and health. The issues of leakage and spillage of Non-Aqueous Phase Liquids (NAPLs) and Aqueous Phase Liquids (APLs) contribute to groundwater contamination, resulting in groundwater pollution and rendering the quality of groundwater unsafe for drinking and agriculture. Ensuring availability and sustainable management of water and sanitation for all were the goal and target of the 2030 United Nations agenda for sustainable development, consisting of a plan of action for people, planet and prosperity. This paper investigates the aqueous and non-aqueous phase liquid migrations in the deformable double-porosity soil, which has become important for sustainability of groundwater utilisation and a comprehensive understanding of the behaviour of liquid migration into the groundwater. An experiment model was conducted to study the pattern and behaviour of aqueous and non-aqueous phase liquid migration in deformable double-porosity soil using digital image processing technique. The results of the experiments show that the flow of the APL and NAPL migration was not uniformly downward. Faster migration occurs at the cracked soil surface condition compared to other locations on the soil surface that were not cracked, even when not using liquid such as toluene. The factors that significantly influence the APL and NAPL migration are the structure of the soil sample, fracture pattern of the soil sample, physical interaction bonding between the liquid and soil sample, and the capillary pressure of the fluid. This study indicates that digital image analysis provides detailed information to facilitate researchers to better understand and simulate the pattern of liquids migration characteristics as well as to ensure sustainable consumption of groundwater.

1. Introduction

Natural disasters such as flash flood, earthquake, groundwater contamination, and climate change influence national development activity, which has led to a negative impact on human health and geo-environment. Groundwater contamination is one of the most challenging geo-environmental issues encountered in many countries, resulting in rendering the quality of groundwater unsafe for consumption and agriculture. More problems that are complicated arise when the surface or subsurface experience earthquake vibration, which likely influences the migration of APL and NAPL into groundwater sources. Vibration leads to rearrangement of soil structure, unstable soil structure, cracked soil, and volumetric deformation of soil aggregate structures, which affect the characteristics of pore sizes (Loke et al., 2017). Porous media such as deformable double-porosity soil was identified as two specific sub-region scales with transforming characteristics of the soil, which still need to have more comprehensive understanding with respect to APL and NAPL migration under the phenomena of fractured double-porosity soil. The danger of reproductive toxic chemicals has made actual on-site study infeasible and has been more practically replaced by physical experimental model simulations (Ngien et al., 2016). The most serious contaminants include petroleum hydrocarbons such as toluene, and has been used in this study, which can be classified as a type of liquid whose density is less than water.

Please cite this article as: Loke Kok Foong, Norhan Abd Rahman, Ramli Nazir, Radzuan Sa'ari, Mushairry Mustaffar, 2018, Investigation of aqueous and non-aqueous phase liquid migration in double-porosity soil using digital image analysis, Chemical Engineering Transactions, 63, 685-690 DOI:10.3303/CET1863115

Cracked soil increases hydraulic conductivity and reduces the soil shear strength (Fredlund et al., 2010). Alazaiza et al. (2017) conducted experiments on double-porosity soil media that have contributed to the body of knowledge with critical viewpoint, but the study was limited to common intact aggregated method; reaction such as vibration to the aggregated porous media was never applied.

Image analysis method is used in most research fields to investigate the complicated characteristics of contaminants and to determine the liquid saturation rate (Luciano et al., 2010). This study used digital image analysis to understand and analyse the APL and NAPL migration in fractured double-porosity soil. Researchers have conducted the non-intrusive image techniques for physical experiment of flow analysis (Zhu et al., 2015) and liquid migration analysis (Sitthiphat and Siam, 2016). The porosity and cracked soils are very hard to monitor by the naked eye, and for this reason, digital image processing analysis is suitable and acceptable for use in the study of the migration of liquids in fractured double-porosity soil. A physical experimental model was conducted to study the characteristics of APL and NAPL migration in deformable double-porosity soil under the vibration effect by using digital image analysis.

2. Materials and methods

2.1 Fracture double-porosity soil sample preparation

Commercially available kaolin soil type S300 was used as the soil sample in this study to produce double-porosity. The aggregated kaolin soil was prepared based on the method expressed by Loke et al. (2017), where the dried kaolin powder was first mixed with 25 % of moisture content for samples 1 (APL) and 2 (NAPL). Distilled water is constantly poured when mixing the dried kaolin powder to control the moisture content with the mixture. Thereafter, the mixture was kept in a plastic bag to maintain the moisture content and left to cure in cool condition for a minimum of 24 h. After the process of curing, the mixture was passed through a 2.36 mm sieve to obtain kaolin granules for the purpose of creating double-porosity soil structure. The kaolin granules were placed in an acrylic soil column and compressed to a height of 100 mm using compaction machine at a compression rate of 1 kgf/cm^2. The experiments were conducted in acrylic soil column sealed base with dimension of 300 mm high x 100 mm- outer diameter and 94 mm inner diameter. The acrylic soil column has been custom designed to monitor and detect the phenomena occurring inside the whole area of circular column. The setup of vibration table to vibrate the aggregated soil sample was developed by Loke et al. (2016). The vibration frequency for the vibration table was set on the control panel with 0.98 Hz and the vibration process duration was 60 s. The result of fractured soil pattern before and after vibration process for sample 1 and 2 with 25 % moisture content are displayed in Figure 1. The soil sample clearly displays fracturing on the top of soil. The concept of fracture double-porosity was to prove that the vibration effect had caused the double-porosity soil to fracture.

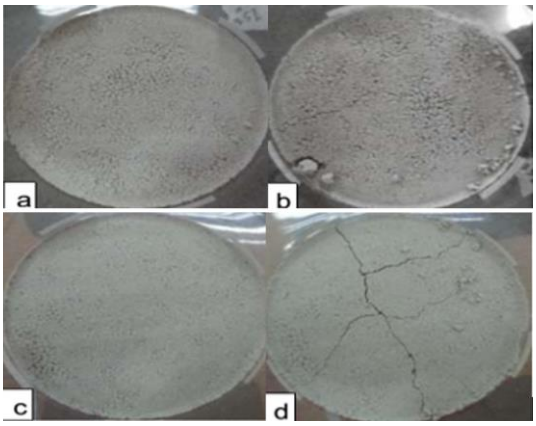

Figure 1: (a) Soil sample 1 before vibration process, (b) Soil sample 1 after vibration process with fracture, (c) Soil sample 2 before vibration process, and (d) Soil sample 2 after vibration process with fracture

2.2 Experimental setup

The fractured double-porosity in soil column was used to measure and monitor the NAPL and water migration inside the whole circular column area with the aim of groundwater contaminate simulation. In each sample, the experiment setup was arranged for APL and NAPL migration image acquisition. A Nikon D90 Digital Single Lens Reflex (DSLR) camera was the main equipment for fluid migration image acquisition and the V shape reflection mirror was used to reflect the whole area of soil column image. The experiment light source came from linear fluorescent lamp - 40 W, which was placed slightly above the soil column. Both experiments began by pouring the liquid instantaneously onto the top centre fractured aggregated soil sample in acrylic soil column. 70 ml of distilled water (APL) and toluene (NAPL) were used in sample 1 and 2. The toluene and water in both experiments were dyed red using Oil-Red-O powder to enhance the visibility during the migration process. After the dyed water and toluene was poured and covered the surface area of the fractured soil sample, the first digital image of fluid migration was taken. The subsequent digital images were taken at specific time intervals to capture the fluid migration pattern for both experiments. A total of 111 images in 36 min for sample 1 and 109 images in 30 min for sample 2 were recorded.

2.3 Digital Image Processing Setup

The recorded colour digital images were saved in JPEG format and transferred from digital camera to computer for further image processing using Matlab routine and Surfer Software. A Matlab routine for digital image processing was used to extract area of interest from captured image and to transform the area of interest from distorted image to a scale image via affine transformation method. The method involves converting the JPEG scale images to Red Green Blue (RGB) and Hue Saturation Intensity (HSI) images; extracting HSI digital value from HSI image and saving the HSI value in a text file using American Standard Code for Information Interchange (ASCII) format. First, the surfer software was used to digitize the control point from reference image to extract actual true scale image coordinate as a control point. Area of interest refers to pre-determined migration boundary area for sample 1 and 2 that contain the APL and NAPL. Matlab routine was then used to convert area of interest into RGB and HSI image format, where the values were extracted and saved in ASCII format. Matlab routine was used to loop three times for the subsequent digital image to extract and save the intensity values for all three-section area of interest of the acrylic soil column. Lastly, a map or plot contour pattern of the migration pattern of APL and NAPL in fracture porous media using HSI value was generated.

3. Results and Discussion

Figure 2 shows the crack position, in which the top fractured soil surface was divided with actual size measurement of column circumference for sample 1 and 2. The downward migration pattern of HSI contour plot of dyed distilled water and toluene in the fractured double-porosity soil sample with 25 % moisture content for sample 1 and 2 are shown in Figure 3. In soil sample 1, the selected HSI plots of dyed distilled water are shown in Figure 3a.

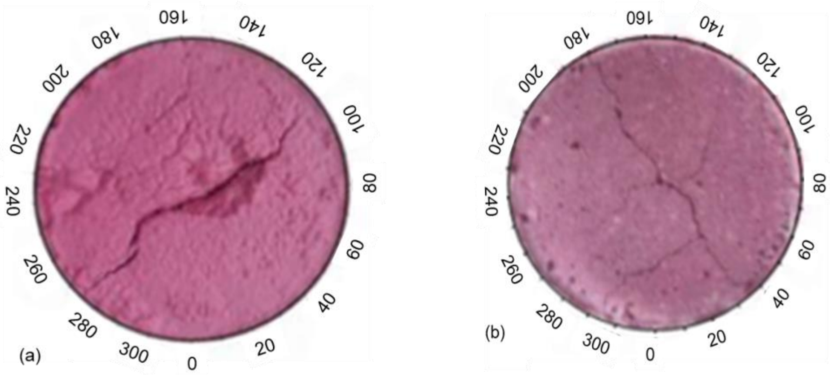

Figure 2: Migrated soil surface with measurement of actual column circumference zone (a) APL sample, (b) NAPL sample

Based on the HSI intensity contour plot result, faster migration occurred at the cracked soil surface condition compared to other locations on the soil surface that were not cracked in soil sample 1 as shown in Figure 3a. The duration for dyed water migration from the top surface to the stop point was 2,160 s and further observation at 3,600 s indicated no further changes in migration pattern. The deepest APL downward migration depth along the soil column was 92 mm out of 100 mm soil sample column. In soil sample 2, the dyed NAPL migration HIS contour plot is shown in Figure 3b. The NAPL migration was similar to the results found in sample 1. The overall duration for dyed water migration from the top surface to the bottom of the soil column was 1,800 s and further observation at 3,600 s showed no changes in migration pattern where the NAPL migration fully reached the bottom of the soil column.

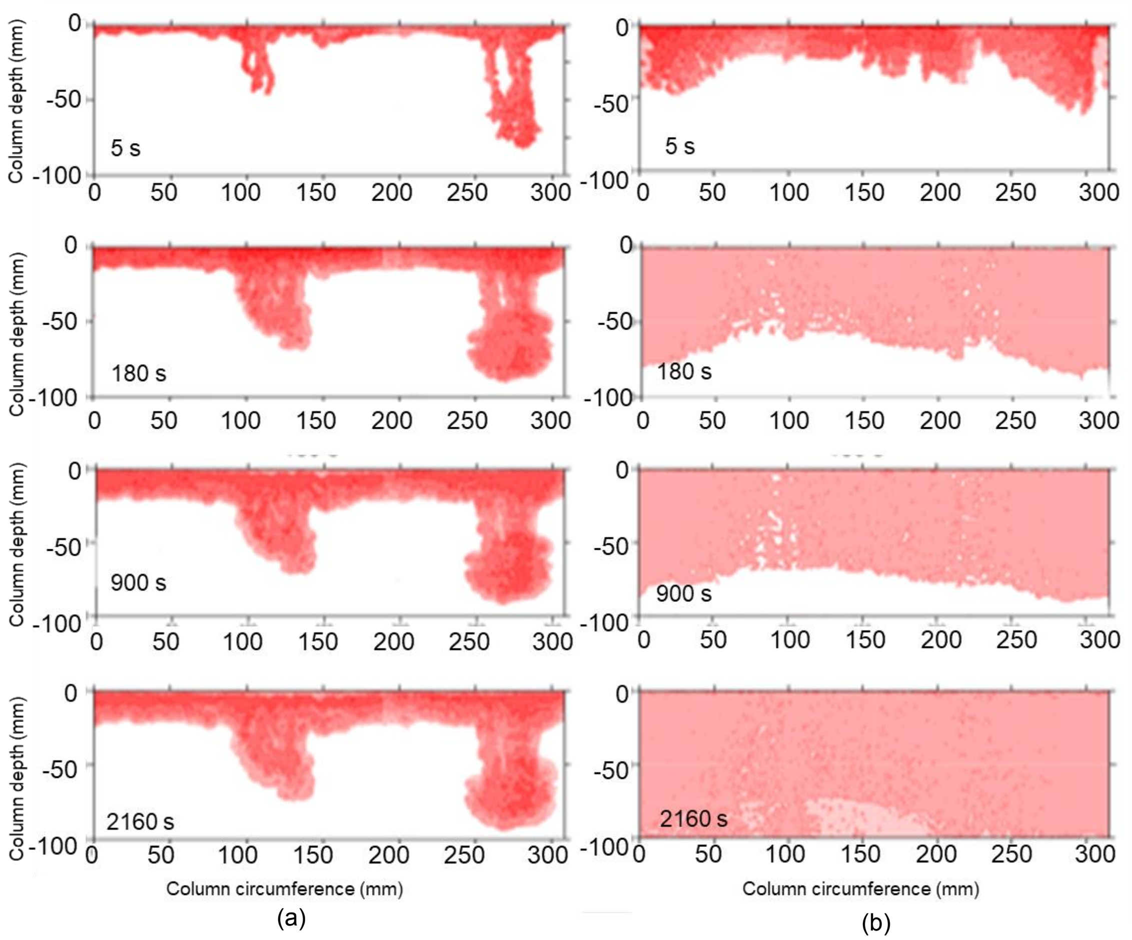

Figure 3: HSI plots of downward migration in fracture double-porosity soil (a) APL sample, (b) NAPL sample

The migration observation of sample 1 shows that the APL migration did not reach the bottom of the soil column and stopped at 92 % downward depth. In contrast, the NAPL migration in sample 2 reached 100 % to the bottom of soil column. The APL migration stopped at 2160 s and did not fully migrate in this study because the water viscosity was 0.00089 kgm^{-1}s^{-1}, while toluene viscosity was 0.00055 kgm^{-1}s^{-1}, a viscosity difference of about 38 % (Assael et al., 2001). Water has a higher viscosity compared to toluene. Dyed water caused the high resistance and friction to gradual migration. This could also be because the physical bonding between toluene and soil is weaker than water and soil. The physical bonding between toluene and soil was attributed to Van Der Waals force that are weaker than hydrogen bonding, which has stronger physical bonding between water and soil. In a previous research by (Sa'ari et al., 2015), an experiment on toluene migration in double-porosity soil with 25 % moisture content without vibration effect was performed. The results of their experiment revealed that the toluene NAPL migration to the bottom took 2,280 s compared to this present study, in which NAPL and APL migration took only about 1,800 s and 2,160 s to reach bottom of soil column. This could be because the fracture that occurred at double-porosity loosened the soil structure in this study compared to previous research migration in intact double-porosity that has stronger and more compact soil structure. The present study supports the previous research by Loke et al. (2017), which stated that the fractured double-porosity soil experienced faster migration compared to the intact double-porosity soil.

The measured values of dyed APL and NAPL migration as a function of column circumference for every 30 mm column circumference are shown in Figure 4 and Figure 5 for sample 1 and 2. Based on the result in Figure 5, it was found that the cumulative saturation depth of APL migration at 270 mm column circumference displayed the most critical migration downward within 30 s as shown by the steepest gradient of the graph lines within that duration and continue to gradually incline horizontally until the end of the experiment. The second and third critical migration was at 120 mm and 90 mm column circumference, within 60 s as shown by the sharp gradient of the graph lines within that duration and continue after 60 s to gradually incline horizontally until the end of the experiment. Meanwhile, the rest of the column circumference positions continue a slow, decreased migration from start until the end of the experiment.

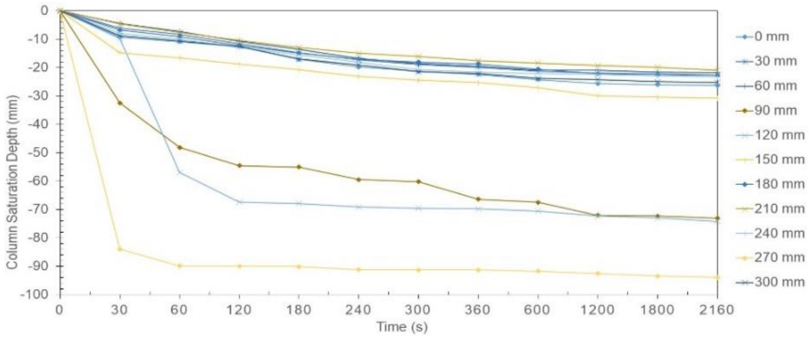

Figure 4: Measured values of APL saturation depth as a function of time for every interval 30 mm column circumference zone

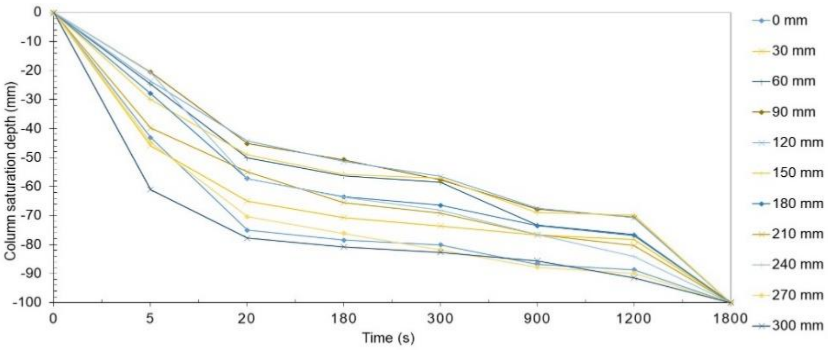

Figure 5: Measured values of NAPL saturation depth as a function of time for every interval 30 mm column circumference zone

Based on Figure 5, the fastest and most critical migration downward to a cumulative saturation depth of NAPL migration occurred at 300 mm column circumference within 5 s as demonstrated by the steepest gradient of the graph lines within that duration, and after 5 s showed a gradual downward decline until the end of the experiment. 0 mm and 270 mm column circumference showed the second and third fastest critical penetration within 20 s as demonstrated by the sharp gradient of the graph line within that duration and continue after 20 s to gradually incline horizontally until the end of the experiment. Meanwhile, the remaining column circumference positions displayed slight decreased migration from start until the end of the experiment. The calculated migration speed rate for the higher and overall average speed for every 30 mm column circumference zone was demonstrated in Table 1.

Table 1: Migration speed rate for every 30 mm column circumference

Column circumference zone (mm)	Migration speed rate (mm/s)			
	Soil sample 1 (APL)		Soil sample 2 (NAPL)	
	Higher flow between initial to 30 s	Average flow for all the time interval	Higher flow between initial to 30 s	Average flow for all the time interval
0	0.311	0.052	2.871	0.490
30	0.206	0.044	2.298	0.400
60	0.149	0.041	1.646	0.296
90	0.355	0.101	1.369	0.256
120	0.329	0.193	1.582	0.290
150	0.491	0.065	1.996	0.353
180	0.229	0.043	1.862	0.331
210	0.156	0.039	2.656	0.467
240	0.265	0.048	1.382	0.254
270	2.799	0.275	2.796	0.485
300	0.292	0.051	4.068	0.690

Sample 1 shows the highest migration speed rate from initial to 30 s was at 270 mm column circumference zone with the migration speed rate of 2.799 mm/s. The overall average APL migration speed rate for sample 1 is 0.087 mm/s. Sample 2 displays the highest migration speed rate from initial to 30 s at 300 mm column circumference zone with the migration speed rate of 4.068 mm/s. The overall average NAPL migration speed rate for sample 2 is 0.392 mm/s. For both samples, the highest migration flow occurred at the column circumference position that displayed the larger fractured soil structure.

4. Conclusions

A physical laboratory experiment on APL and NAPL migration in fractured double-porosity soil with 25 % moisture content has been carried out. This laboratory experiment was designed to investigate and differentiate the APL and NAPL migration characteristic and pattern in the fractured double-porosity soil placed in acrylic circular soil column. The digital image processing technique using Matlab routine and Surfer software was applied to extract and analyse the APL and NAPL migration data acquired from captured digital image. From the results observed, both experiments indicate that in comparison to the APL migration, the NAPL migrated faster from top surface to the bottom of soil column. The significant finding is that the NAPL had fully migrated to the bottom (100 %), but the APL migration stopped at 92 % of the soil column depth. The overall average fluid migration speed rates for experiment 1 and 2 were 0.087 mm/s and 0.392 mm/s, where the APL and NAPL migration speed rate was faster than 0.04 mm/s in the previous research by Sa'ari et al. (2015). This is because the present study applied the effect of vibration on the double-porosity and the additional capillary force exerted by the fluid pressure on top of the fractured soil sample. From the result, it can be inferred that the factors that significantly influence APL and NAPL migration are the structure of the soil sample, fractured pattern of the soil sample, viscosity of liquid, physical interaction bonding between the liquid and soil sample, and the capillary pressure of the fluid. In conclusion, this study indicates that the fractured double-porosity soil under vibration effect with NAPL migration has very bad consequences for groundwater resources. The current model makes a more practicable contribution to future sustainable groundwater protection and remediation separator.

Acknowledgments

This study was supported by the Research Management Centre (RMC), Universiti Teknologi Malaysia under Research University Grant – Tier 1 (PY/2016/06547) from the Ministry of Higher Education Malaysia. The first author was supported through the federal training award by the Public Service Department, Malaysia.

Reference

Alazaiza M.Y.D., Ngien S.K., Bob M.M., Kamaruddin S.A., Ishak W.M.F., 2017, Influence of macro-pores on DNAPL migration in double-porosity soil using light transmission visualization method, Transport in Porous Media, 117, 103-123.

Assael M.J., Avelino H.M.T., Dalaouti N.K., Fareleira J.M.N.A., Harris K.R., 2001, Reference correlation for the viscosity of liquid toluene from 213 to 373 K at pressures to 250 MPa, International Journal of Thermophysics, 22 (3), 789-799.

Fredlund D.G., Houston S.L., Nguyen Q., Fredlund M.D., 2010, Moisture movement through cracked clay soil profiles, Geotechnical and Geological Engineering, 28 (6), 865–888.

Loke K.F., Rahman N.A., Nazir R., 2017, Experimental study on unsaturated double-porosity soil phenomena under vibration effect, Jurnal Teknologi, 79 (4), 65-72.

Loke K.F., Rahman N.A., Ramli M.Z., 2016, A laboratory study of vibration effect for deformable double-porosity soil with different moisture content, Malaysian Journal of Civil Engineering, 28 (SI3), 207-222.

Luciano A., Viotti P., Papini M.P., 2010, Laboratory investigation of DNAPL migration in porous media, Journal of Hazardous Materials, 176, 1006-1017.

Ngien S.K., Chin P.Q., Hasan M., Ali M.I., Tadza M.Y.M., Rahman N.A., 2016, Image analysis of non-aqueous phase liquid migration in aggregated kaolin, ARPN Journal of Engineering and Applied Sciences, 11 (10), 6393-6398.

Sa`ari R., Rahman N.A., Latif A.N.H., Yusof Z.M., Ngien S.K., Kamaruddin S.A., Mustaffar M., Hezmi, M.A., 2015, Application of digital image processing technique in monitoring LNAPL migration in double porosity soil column, Jurnal Teknologi, 72 (3), 23–29.

Sitthiphat E.A., Siam Y., 2016, Investigation of average optical density and degree of liquids saturation in sand by image analysis method, KKU Engineering Journal, 43 (S1), 147-151.

Zhu J.F., Xu D.L., Liu Z.Y., 2015, A modified graphical method to target the regeneration stream flow rate for water-using networks, Chemical Engineering Transactions, 45, 229-234.