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A LABORATORY STUDY OF VIBRATION EFFECT FOR DEFORMABLE DOUBLE-POROSITY SOIL WITH DIFFERENT MOISTURE CONTENT

Loke Kok Foong[1]*, Norhan Abd Rahman[1,2] & Mohd Zamri Ramli[3]

[1] *Department of Hydraulic and Hydrology, Faculty of Civil Engineering, UniversitiTeknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia*
[2] *Centre of Tropical Geoengineering, Faculty of Civil Engineering, UniversitiTeknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia*
[3] *Institute of Noise and Vibration (INV), Faculty of Civil Engineering, UniversitiTeknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia*

*Corresponding Author: *edwinloke84@yahoo.com*

Abstract: Earthquake vibration is a natural disaster that needs to be addressed in ensuring the geo-environment is sustainably secure. A physical laboratory model was conducted to characterize the phenomena of vibrated deformable double-porosity under different moisture content. The double-porosity soil characteristic is formed by aggregating kaolin soil with 32% and 33% moisture content. A vibrating table and seismic accelerometer were installed on soil sample in order to vibrate the whole acrylic soil column to get the peak table acceleration and peak specimen surface acceleration of the soil sample. The results show that the acceleration response analysis for the sample with 32% moisture content has caused sample dis-amplification shaking, while the sample with 33% moisture content has caused the sample amplification shaking and re-compact process to occur due to strong vibration. It was recorded that both vibrated samples have soil structure rearrangement and multi-porosity characteristics identified as problematic double-porosity soil expected to contribute to the speed of liquid penetration. In addition, the microscope result shows both samples have crumbs with diameter less than 0.5cm, which is considered to have granular soil structure.Thus, both samples displayed the characters of soil liquidity as the moisture content for both samples is close to kaolin soil liquid limit at 41%, and granules started to disintegrate at the moisture content of 34%.

Keywords: *Double-Porosity Soil, Vibration Effect, Moisture Content, Acceleration Response Analysis*

1.0 Introduction

Earthquake events were reported at Ranau and Tawau, Sabah, Malaysia (Muguntan *et al.*, 2015; Stephanie 2015). These occurrences have called attention to the vibration effect on double-porosity subsurface system, which is a problem that requires attention to ensure the sustainable safety of geo-environment. In addition, the earthquakes that occurred have caused changes in soil characteristics and deformation of soil media. In Malaysia, earthquake events are regarded as very dangerous phenomena that must be addressed by both professionals and researchers to ascertain the solution to ground vibration effect. According to Muguntan *et al*., (2015), the earthquake incident that occurred at Ranau, Sabah caused damage to underground drainage pipes and water tanks, with estimated losses more than RM500,000.00. The ground and soil failure after earthquake that occurred at Ranau, Sabah is shown in Figure 1. Hence, this study was carried out to characterize the physical phenomena of deformable double-porosity with different moisture content and vibration frequency method in soil.

Figure 1: Ground and soil failure after earthquake at Ranau, Sabah

2.0 Experimental Theory

The structure of the soil is affected by earthquake vibration and moisture content. It is well known that the soils display many different structures at the different scales, and that soils are not completely homogeneous in character. According to Carminati *et al*. (2008), the double-porosity media in usual condition termed as soil display two specific scales of porous media. Different hydraulic properties and pore sizes with two specific sub-regions in soil are used to characterize double-porosity media (Ngien *et al*., 2011). The soils with intra and inter-aggregate pores for aggregated innate soil display pore-size bimodal distribution that can found in compacted soils and agricultural tops-soils (Li and Zhang, 2009; El-Zain *et al*., 2006). In addition, Lewandowska *et al*. (2005) discovered that soil in laboratory can be used to create double-porosity characteristics performed under constant pressure head, initially with double-porosity for one-dimensional infiltration experiments. Furthermore, laboratory prepared aggregate kaolin soil for one-dimensional drying and consolidation experiments were performed by Bagherieh *et al.* (2009). Thus, this study used aggregated kaolin soil to produce the features of double-porosity.

Generally, in earthquake engineering, laboratory equipment has been utilized to evaluate structures or ground responses. The bedrock motion with highest response is called Peak Ground Acceleration (PGA) and the free surface motion with highest response is the Peak Surface Acceleration (PSA). The indication is either amplified or dis-amplified, based on Eurocode 8 that is classified under five ground types (A to E) and generally based on shear wave velocity and standard penetration test, which is an in-situ dynamic penetration test. The value of PSA higher than PGA demonstrates amplification while the value of PGA higher than PSA demonstrates dis-amplification. Therefore, this study used ground response analysis to model the fracture on the soil sample by the propagation of ground motion to the surface because in practice, the ground response analysis was used to determine the crack and amplification of the response. Furthermore, for this laboratory study, the terms PGA and PSA were changed to more suitable names based on the experiment condition, which is known as Peak Table Acceleration (PTA) and Peak Specimen Surface Acceleration (PSSA). Double-porosity soil deformation is due to vibration effect, which, according to Lakeland *et al.*, (2014), water-saturated granular soils such as sands and soil exposed to strong earthquake shaking may liquefy and cause deformations with great destructive power. Lakeland *et al.*, (2014) also show using principle analysis that liquefaction is not a rigidly un-drained process, but in fact is the grain rearrangement, fluid movement and changes in permeability which lead to strength loss in soil structure. Furthermore, according to Masciopinto *et al.*, (2001), formations of fractured porosity are characterized by water-bearing formations, while a fracture is created from a break of the rock masses caused by tectonic force.

Computational and numerical methods in past decades were mainly used in studies of double-porosity media, mostly fractured rock as media by researchers such as (Valliappan and Khalili-Naghadeh, 1990; Bourgeat *et al.*, 1996; Pao and Lewis, 2002; Ryzhik, 2007; Kamaruddin *et al.*, 2011a; Ngien *et al.*, 2012b). Recently, the physical experimental methods on double-porosity soil have begun to be used by researchers such as (Kamaruddin *et al.*, 2011b; Ngien *et al.*, 2011; Ngien *et al.*, 2012a; Sa'ari *et al.*, 2015; Loke *et al.*, 2016). Previously, researchers have mainly used computational methods for the study of double-porosity media, specifically rock as media. Meanwhile, previous researchers also used numerical models for the study of double-porosity soil media but performed real physical experiments less often. The actual physical experiments are very difficult to perform in the laboratory, especially because large fractured rock was naturally hard to find and the actual sample on site was very complicated to relocate to the laboratory and requiring large sums of money. There is also a shortage of practical equipment as few pieces of equipment are available to do the actual experiment.

All of the previously above mentioned experiments on double-porosity media have contributed to an understanding of soil behaviour in double-porosity. The mentioned experiments were limited to common aggregated method and numerical model in double-porosity soil, but without applying any vibration effect to the soil sample. To the best of our knowledge and from having reviewed other research papers, experiments on fracture double-porosity soil under vibration effect still have a gap to evaluate and investigate. Therefore, to achieve the aim of this study, several objectives recognized based on the literature were (i) to investigate the vibration responses of fractured double-porosity soil with different vibration frequency and moisture content, (ii) to identify the surface crack width for fractured double-porosity soil, and (iii) to affirm the fractured double-porosity soil characteristics by using field emission scanning electron microscope (FESEM). Essentially, this study covers the physical laboratory experiment model where an aggregated soil sample was vibrated using a vibrating table involving a specific experimental setup to analyse ground response and double-porosity soil characteristics.

3.0 Materials and Methods

In this study, the laboratory experiment setup and procedure encompassing the physical apparatus, soil sample and aggregation were briefly discussed in subsequent sections. The following brief laboratory experiment methodology flow chart as shown in Figure 2 has been adopted in order to achieve the objective of the study.

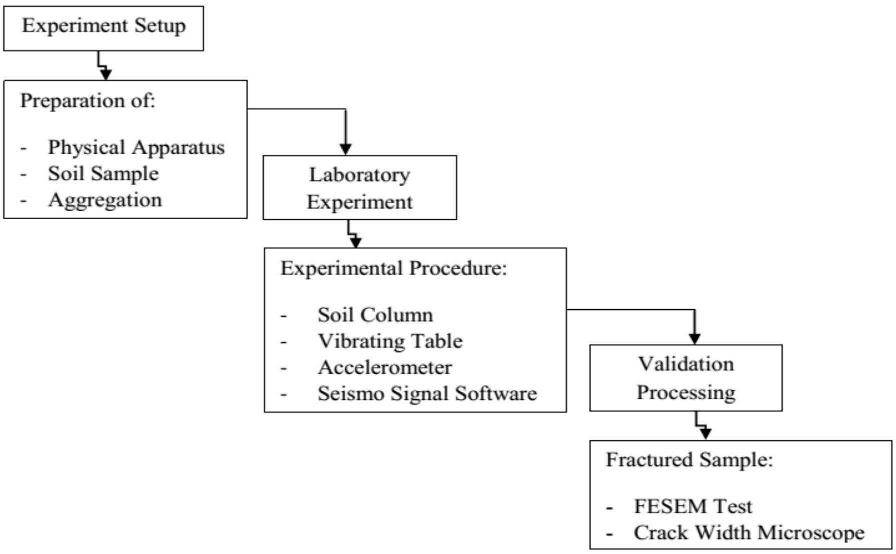
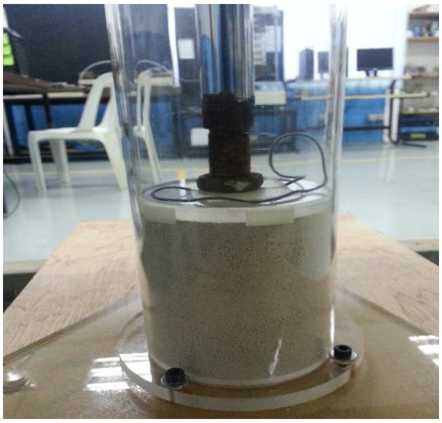


Figure 2: Laboratory experiment methodology flow chart

3.1 Soil Sample Preparation

The soil sample material used for this study to create double-porosity was commercially available S300 kaolin soil. The kaolin soil properties were tested based on British Standard BS1377-2:1990 to obtain the liquid limit = 41%, plastic limit = 27.5%, plasticity index = 13.5% and particle density = 2.65Mg/m^3. The kaolin soil was classified as silt with low plasticity (ML) based on the Unified Soil Classification System (USCS). The method expressed in Bagherieh *et al*. (2009) as previously explained was used to prepare the aggregated soil sample. The preparation of soil sample used different moisture content such as 32% and 33%, which is the nearest value to the liquid limit for kaolin soil. Thus, the dried kaolin powder was mixed with 32% and 33% of moisture content for sample 1 and sample 2, respectively. Thereafter, in a cool condition for a minimum 24hours, the mixed sample was cured and kept in a re-sealable plastic bag for the purpose of preventing the moisture content from being evaporated. Dried aggregate soil that passed 2.36mm sieve for both sample 1 and 2 were placed in a circular acrylic and compressed to a height of 100mm using a simple compaction machine. The acrylic soil column has been chosen to monitor and detect the changes occurring inside the whole area of circular column. The prepared soil sample is shown in Figure 3.

(a)



(b)

Figure 3: Prepared soil sample: (a) Plan view; (b) Side view

3.2 Laboratory Experiment Setup and Procedure

As previously explained, inter and intra aggregate pores created through aggregation process represent the characteristic of double-porosity in a soil sample. The laboratory experiments were executed in a specially designed acrylic soil column sealed base with dimension of 300mm high x 100mm outer diameter and 94mm inner diameter. A vibrating table was used to vibrate soil sample with different vibration frequencies for the deformation process. The acrylic soil column with triangle base plate was placed on the vibrating table and fixed properly by bolt and nut to avoid movement or spring up of the acrylic soil column. It is important to have better visualization of the phenomena occurring in the whole area of acrylic soil column. During the vibration process, PTA and PSSA for both samples were recorded and the fracture porous media investigated. The vibrating table and acrylic soil column with an uncomplicated experimental setup was developed to accomplish this concept economically and effectively. Figure 4 shows the view of 3D laboratory experimental setup.

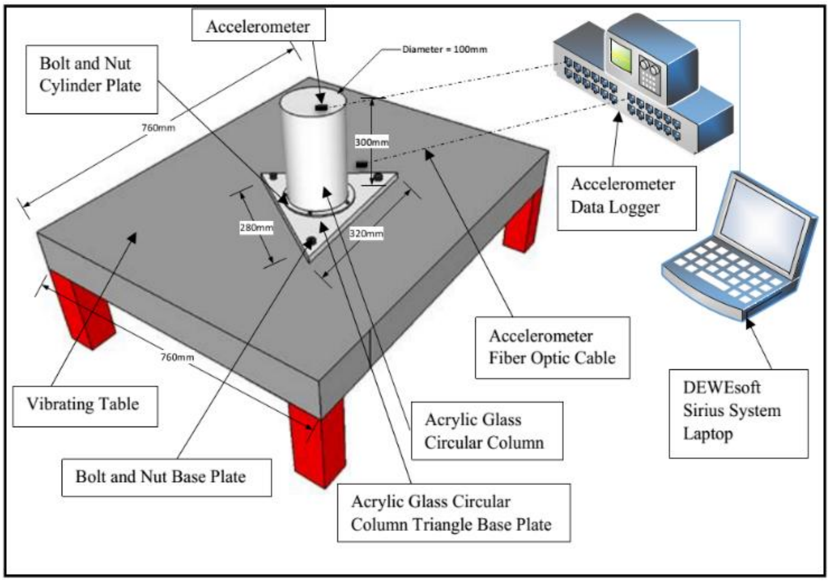


Figure 4: 3D Laboratory experimental setup

The laboratory experimental procedure was first arranged as shown in Figure 4. The soil sample 1 (32% moisture content) and sample 2 (33% moisture content) was prepared as previously explained. The acrylic soil column with both aggregated soil samples was situated on top of the vibrating table one soil sample at a time. Once the acrylic soil column was secured on vibrating table, the first accelerometer was installed on the surface of soil sample and the second accelerometer was installed on top of the vibrating table. The purpose of both accelerometer installations is to obtain the PSSA of the soil sample top surface and PTA of the vibrating table. The laboratory experiments were performed under the temperature of 25^{0}C.

The control panel on vibrating table was set to different vibration frequencies, such as 5Hz, 10Hz, 15Hz, 20Hz, 25Hz and 30Hz. Before carrying out the experiment, it is important to ensure that the vibrating table is functioning correctly, where the vibrating table frequency must be calibrated using the seismic accelerometer with high sensitivity 10000 mV/g and a data logger to check the natural frequency of the vibrating table. The cracks that occur in surface area will be observed and recorded using camera image during the experiment. After that, the surface crack of soil sample was measured using the crack width microscope model 58-C0218. The aggregated soil sample acceleration response process can be obtained by using Dewesoft Sirius System data logger. Furthermore, the frequency of the vibration was analysed using Seismo Signal Software.

3.3 Fracture Validation Procedure

According to Hayden and Voice (1993), the investigation of soil porosity characteristics commonly use the scanning electron microscope (SEM). Thus, the validity of a crack appearing on aggregated soil sample was confirmed and performed using field emission scanning electron microscope (FESEM) test in the Materials Science Laboratory of the Faculty of Mechanical Engineering, UniversitiTeknologi Malaysia. A small aggregated soil sample that after the vibration process was taken from the cored soil sample was used for FESEM test at 25-fold magnification, 100-fold magnification and 500-fold magnification for the purpose of visually checking and examining the soil sample throughout its depth with "zoomed in" image of the sample. The example of FESEM test can be seen in Figure 5.

Figure 5: Field emission scanning electron microscope (FESEM) test

4.0 Results and Analysis

4.1 Acceleration Response of the Fracture Double-Porosity Soil

Based on the objectives of the study, the results were presented below. The results for Peak Table Acceleration (PTA) and Peak Specimen Surface Acceleration (PSSA) for both samples as well as the calibrated vibrating table natural frequency are shown in Table 1. As shown in the table, the vibrating table control panel frequency as mentioned earlier was differentiated from the calibrated vibrating table natural frequency. Thus, we use the calibrated natural frequency as vibrating table frequency since the natural frequency was obtained from the calibrated seismic accelerometers with high sensitivity. Referring to Barry *et al.*, (2008); Peng *et al.*, (2012), most of the earthquake waves have a frequency of less than 20Hz, where in this study the natural frequency that has been used was in the frequency range below 20Hz. Based on Table 1 and the observation during the experiment, sample 1 started to crack at the frequency of 0.39Hz, where the values of PTA (1.0g) and PSSA (0.97g) were very close. Meanwhile, sample 2 started to crack before the frequency of 0.34Hz, where the value of PTA (1.08g) was lower than the value of PSSA (1.56g) which means that the shaking of the surface is higher than the ground shaking. Therefore, to analyse the acceleration response, it was necessary to produce the graphs of natural frequency versus PTA and PSSA value based on the result shown in Table 1.

Table 1: Results of calibrated vibrating table natural frequency and soil sample acceleration responses

Table Natural Frequency (Hz)	*Acceleration (g)*	
	Sample 1 [w/c: 32%] (PTA / PSSA)	*Sample 2 [w/c: 33%] (PTA / PSSA)*
0.29	(0.79 / 0.52)	(0.93 / 0.83)
0.34	(0.92 / 0.69)	(1.08 / 1.56)
0.39	(1.00 / 0.97)	(1.10 / 1.79)
0.49	(1.31 / 0.96)	(1.35 / 0.99)
0.68	(1.69 / 1.13)	(1.74 / 1.20)
0.98	(2.26 / 1.37)	(2.15 / 1.82)

Figures 6 and 7 shows the graphs of natural frequency versus PTA and PSSA for sample 1 with 32% moisture content and sample 2 with 33% moisture content, respectively. As can be seen in the result of acceleration response analysis in Figure 6, the crack and fracture point started at the frequency of 0.39Hz, where it has the same result as the observation crack that began at 0.39Hz frequency during the experiment. Based on the analysis, the graph showing sample 1 experienced less seismic shaking, where the aggregated soil sample has dis-amplification shaking from the start until the end of vibration. The dis-amplification shaking at 0.39Hz shows that the values of PTA (1.00g) and PSSA (0.97g) were very close to each other because the crack and fracture point have started. After the crack and fracture point for soil sample 1, it is seen that the soil is still in a compacted condition even though the surface still shows fracture of soil sample. Thus, according to Eurocode 8 for ground type classification, sample 1 has ground type C, which has a stiff clay and hard soil since the sample from the start until the end of vibration is still in the condition of dis-amplification shaking.

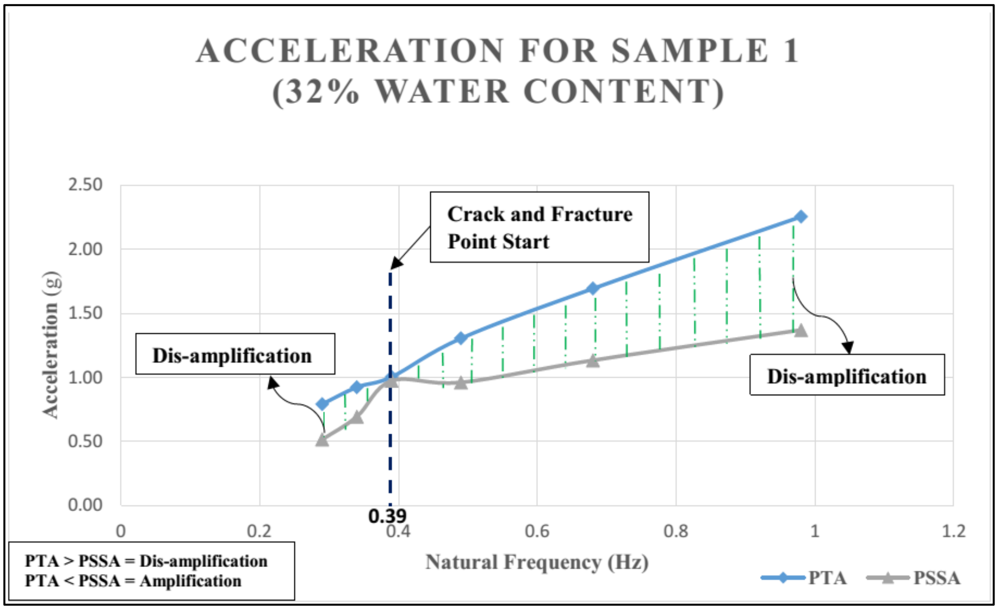


Figure 6: Result of acceleration responses (PTA and PSSA) analysis for sample 1

Referring to the result of acceleration response analysis in Figure 7, the first intersection point occurs at 0.30Hz of frequency that shows where the crack and fracture point started, while it has the same result as the observation crack that began before the frequency of 0.34Hz. The area in between the first intersection and second intersection has shown amplified shaking because the soil started to loosen and weaken as the fracture and crack on soils have started. According to Eurocode 8 for ground type classification, sample 2 has a ground type D, which has soft clay and loose to medium soil, since the soil sample 2 has amplification shaking. In practical terms, the amplification shaking occurs in soft soil, loose soil and deposited soil, which experience greater seismic shaking compared to dis-amplification that has compacted soil and hard soil. The dis-amplification shaking that occurred in the area after second intersection point at the frequency of 0.44Hz has showed that soil sample 2 started to experience re-compact process due to the strong vibration force in the boundary condition, even though the soil sample surface still shows fracture. Thus, sample 2 recorded the amplification shaking compared to sample 1 that had dis-amplification shaking. These phenomena demonstrated that sample 2 has a weaker soil structure compared to sample 1, which has a stronger soil structure because sample 1 has less seismic shaking during the vibration process.

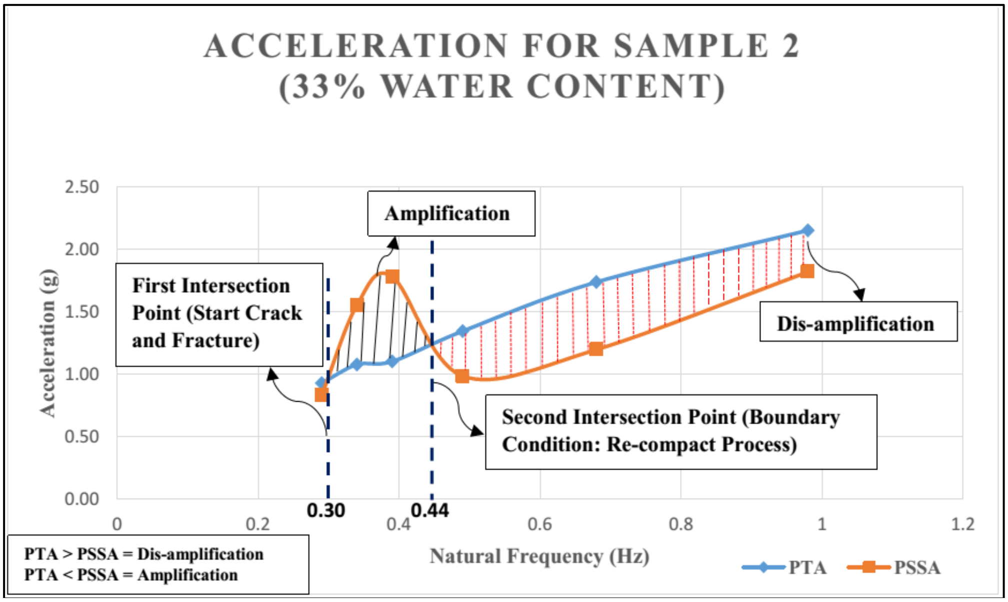


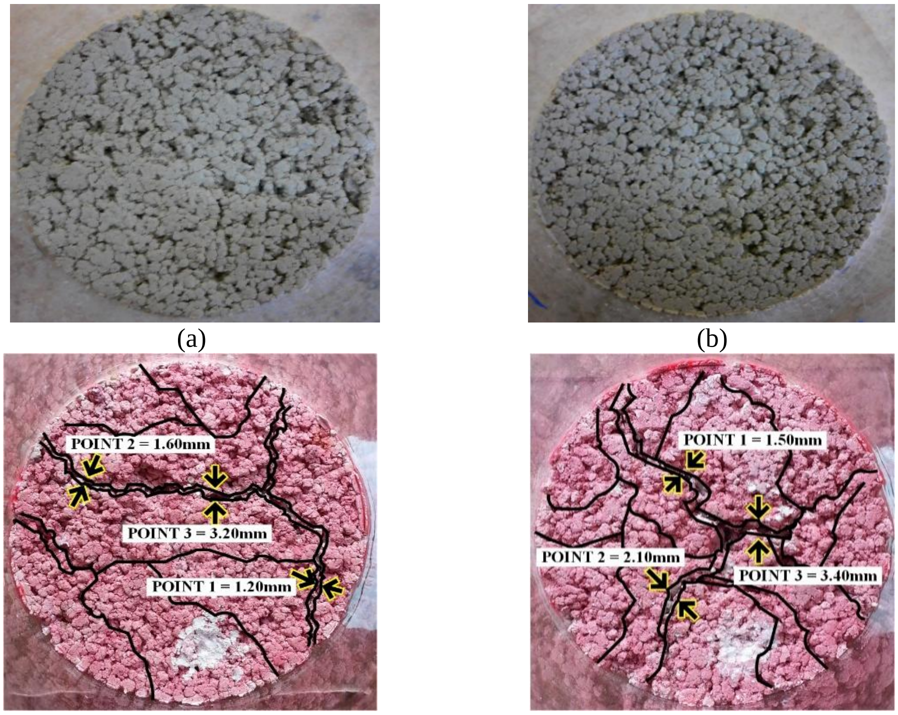
Figure 7: Result of acceleration responses (PTA and PSSA) analysis for sample 2

4.2 *Measurement of Surface Crack Width*

Figure 8 illustrated the result of before and after surface crack and fracture with red colour dye to ease the process of observation for sample 1 and sample 2, respectively. The test samples displayed distinctive aggregation of kaolin granules after the vibration effect and the width of the cracked surface in the vibrated sample was measured by using crack width microscope model 58-C0218. Thus, Table 2 shows the result of surface crack width measurement. The result shows a percentage difference of about 20% for the smallest surface crack point and the medium surface crack point has difference percentage of about 24%, while the biggest surface crack point has difference percentage of about 6%. Thus, the surface crack for sample 1 (32% water content) and sample 2 (33% water content) have the percentage difference in the range of 6% to 24%. This indicates that the surface crack width for sample 2 is larger compared to sample 1. Hence, the result showed that sample 2 with largest and biggest crack can cause a state where the liquid penetration rate is faster than sample 1. Therefore, the vibrated double-porosity soil has larger pores and surface crack compared to a normal standard double-porosity soil experiment performed by Ngien *et al*. (2011) and Sa'ari *et al*. (2015) without applied vibration effect.

Table 2: Surface crack width measurement for sample 1 and sample 2

	Width Measurement (mm)		
Sample	*Crack Point 1 (Small)*	*Crack Point 2 (Medium)*	*Crack Point 3 (Large)*
1 (32% Moisture Content)	1.20	1.60	3.20
2 (33% Moisture Content)	1.50	2.10	3.40

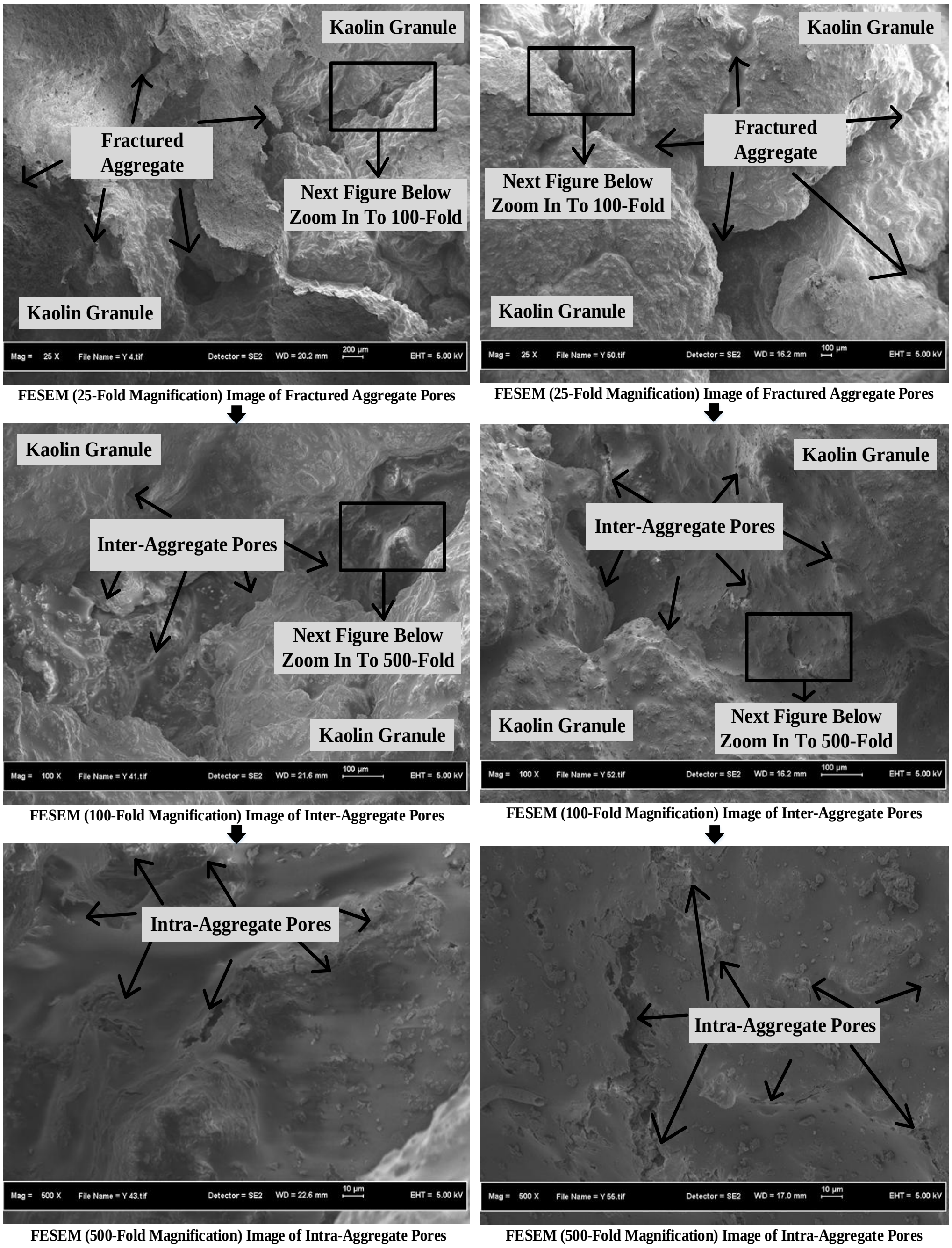


(c) (d)

Figure 8: Result of fractured double-porosity : (a) Sample 1 before vibration; (b) Sample 2before vibration; (c) Sample 1 after vibration; (d) Sample 2 after vibration

4.3 Validation of the Double-Porosity Soil Characteristics

The result of depth zoom in image of vibrated double-porosity for 32% and 33% moisture content at 25-fold, 100-fold and 500-fold magnification is shown in Figure 9. The resultant FESEM test at 25-fold magnification shows crack and fracture at the soil sample surface, while resultant FESEM test at 100-fold magnification has shown the inter-aggregate pores. The FESEM test at 100-fold magnification has also exposed that the inter-aggregate pores and individual kaolin granules split up among themselves. Further magnification of both soil samples to 500-fold indicated intra-aggregate pores. Through the FESEM test, it was clearly shown that the fractured double-porosity soil structure was verified with the deformable characteristics of fractured aggregate pores, inter-aggregate pores and intra-aggregate pores that created the fractured double-porosity formation. From the FESEM test result, soil sample 2 has more porosity compared to sample 1. Both samples have a similarity in that the soil is coated with a layer of liquid that causes a shining image when viewed by FESEM zoom in image. Both samples also have a coarse granule structure and displayed the characters of soil liquidity because the moisture content for sample 1 and sample 2 are close to the 41% liquid limit for kaolin soil. Thus, the fractured double-porosity characteristics with multi-porosity were expected to contribute to the speed of liquid penetration and migration.



(a) (b)

Figure 9: FESEM zoom in image of vibrated double-porosity with 25-fold, 100-fold and 500-fold magnification: (a) 32% water content; (b) 33% water content

5.0 Conclusions

A physical laboratory experiment on deformable double-porosity soil with different moisture content under vibration effect was conducted. The experiments have successfully obtained the result of acceleration responses by the vibrating table that proved the soil samples were fractured. Through field emission scanning electron microscopy (FESEM) test, the deformable double-porosity soil was verified and confirmed to have fractured. Sample 2 has shown amplification shaking due to the weakened soil structure, while sample 1 has dis-amplification shaking because soil sample 1 had a stiff soil structure. Furthermore, soil sample 2 (33% moisture content) has caused the cracking process to appear faster compared to soil sample 1 (32% moisture content). Moreover, the surface crack width for soil sample 2 is large compared to sample 1 and this can cause rapid liquid penetration. Through the result of FESEM test, both samples show wettability of the fluids present in the aggregated soil because the moisture content percentage is close to the kaolin soil liquid limit at 41% and kaolin granules started to disintegrate at 34%moisture content. Since both soil samples have multi-porosity characteristics, it has been identified as problematic fractured double-porosity soil. It also indicates that the vibrated double-porosity soil have larger pores compared to a common standard double-porosity soil experiment performed by Ngien *et al*. (2011) and Sa'ari *et al*. (2015) without vibration effect. The effect of moisture content percentage on the kaolin soil granule was significant as it was proved that the surface crack width and seismic acceleration response values were different for both samples. Therefore, the fractured double-porosity soil has characteristics of soil structure rearrangement and change in existing moisture content. In addition, high permeability value was expected to be an influential factor in movement of the fluid in subsurface system.

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