

## CYCLIC BEHAVIOUR OF JOHOR SAND

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**ABSTRACT:** Series of laboratory testing on the investigation of soil liquefaction using cyclic triaxial test had been carried out by researchers around the world but many of the results are contradictory. Thus, it is important to first determine the condition in which the clean sand is most susceptible to liquefaction, then only the liquefaction susceptibility of sand matrix soils could be compared and discussed under this specific condition. This paper presents the undrained behaviour of Johor sand and sand mixed with fines (kaolin) from cyclic triaxial tests. Stress controlled triaxial test apparatus was used to shear the isotropically consolidated soil samples under undrained two-way cyclic loading until the initiation of liquefaction. The liquefaction was defined based on: (i) excess pore pressure was equal to effective confining pressure or (ii) double amplitude strain of 5 % was reached, whichever was achieved first. The results of two-way cyclic triaxial tests on clean sand showed that besides the cyclic stress ratio, the liquefaction resistance of the sand under undrained loading was proportional to effective consolidation pressure and density index. The Johor sand was more liquefiable at its loose state and under low effective consolidation pressure, when subjected to earthquake loading.

*Keywords: Liquefaction, Density index, Consolidation pressure, Excess pore pressure, Fines content*

### 1. INTRODUCTION

Soil liquefaction, the secondary effect of an earthquake; is a transformation of granular material from a solid state into a liquefied state with a significant increase of pore water pressure until the effective stress reaches zero [1]. For many years, research on liquefaction has been a mandatory focus on uniform clean sands, containing little or no fines; with a common assumption that the cyclic behaviour of clean sand is remarkably representing all types of in-situ sand deposits. Unfortunately, empirical evidences including the 2010 Canterbury Earthquake [2], the 2011 Christchurch Earthquake [3] and the 2011 Tohoku Earthquake [4] have shown that the sand matrix soils (sand dominant soil with limiting percentage of fine particles existed within) does actually liquefy.

Lots of the laboratory testing had been carried out by researcher worldwide [5], [6] using the cyclic triaxial testing system. Nonetheless, the research breakthroughs are somewhat conflicting. There is not enough evidence at this point to obtain a global agreement in describing how the fines particles influence the soil liquefaction resistance under dynamic loading.

Head [7] stressed that sand is largely influenced by its composition characteristics such as soil grains, packing density and void ratio. Research by Choobbasti *et al.* [5] found that when density index is fixed the finer the sand, the lower

the resistance towards liquefaction. Thus, it is important to first compare at which testing environment that the clean sand is potentially liquefiable, and then only the liquefaction susceptibility of sand with different fines content could be compared under the fixed testing condition. This paper presents the cyclic behaviour of Johor sand obtained from undrained cyclic triaxial tests. The paper first compares the undrained behaviour of Johor sand using cyclic triaxial testing equipment at different testing condition. Later, the cyclic behaviour of Johor sand with fines was compared at that similar testing condition.

### 2. LABORATORY TESTING

The two-way cyclic triaxial test, in accordance to the ASTM D5311-13M Load Controlled Cyclic Triaxial Strength of Soil [8] was carried out to simulate the cyclic loading on cylindrical size reconstituted soil specimen of approximately 76 mm height and 38 mm diameter.

#### 2.1 Material

The materials used in this study comprise of Johor clean sand and white kaolin as fines soil. The sand-fines mixtures were reconstituted by mixing the low plasticity fines (kaolin) to the parent sand, at seven different percentages by weight which is 5 %, 10 %, 15 %, 20 %, 25 %, 30 %, and 35 %.

30 % and 40 %. The kaolin is having the liquid limit ( $w_L$ ) of 39 %, plastic limit ( $w_P$ ) of 26 % and plasticity index ( $I_P$ ) of 13 %. Based on British Soil Classification System, the kaolin was classified as intermediate plasticity silt (MI). The particle size distribution of Johor clean sand and white kaolin was shown in Figure 1.

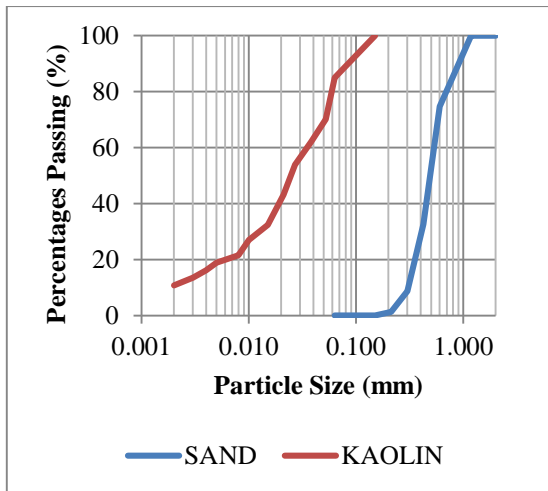


Fig.1 Particle size distribution of soil used

The clean sand used in this study was the natural sand obtained from a river in Johor, Malaysia. The 'Johor' sand has a sub-angular shape with light brown colour. Based on the particle size distribution curve shown in Figure 1, the sand was poorly graded (SP) containing no fines with medium fine particle size in a narrow range. The particle size of clean sand ranges from 0.1 mm to 2 mm while the mean grain size ( $D_{50}$ ) is 0.5 mm. As pointed out by Choobbasti *et al.* [5], poorly graded sand is very susceptible to liquefaction than well graded sand. Hence, this soil is a suitable type for studying the role of fines in liquefaction susceptibility of sand matrix soils. The minimum and maximum densities of the sand were  $1.37 \text{ Mg/m}^3$  and  $1.59 \text{ Mg/m}^3$ , respectively. Based on these values, the density of sand for the required density index ( $I_D$ ) was calculated and prepared for the cyclic loading tests.

## 2.2 Cyclic Triaxial Test

The cyclic triaxial testing in this paper was divided into two stages. Firstly, the Johor clean sand specimen was tested using cyclic triaxial testing equipment under different testing condition to determine the effects of density index, initial consolidation pressure and cyclic stress ratio (CSR) on undrained behaviour of Johor clean sand. By analysing the result, a fixed testing environment was proposed so that the cyclic behaviour of sand with different percentages of

fines content could be compared.

Prior to the saturation process, carbon dioxide gases and de-aired water was flushed through the specimens from the bottom drainage line to the top until an amount equal to the specimen's void volume was collected. Saturation process was carried out with a linear increase of cell and back pressure, keeping a constant difference of 10 kPa effective stress. This process was continued until the minimum B-value of 0.96 was achieved. Then isotropic consolidation was performed and completed in a very short period. Upon the completion of isotropic consolidation, the stress-controlled undrained cyclic triaxial tests were carried on the specimen using the back pressure of 200 kPa. In order to apply the two-way loading, the top cap was locked to the loading ram to enable the application of extension forces using an extension top cap and vylastic sleeve. The cyclic loading in terms of CSR was applied to the specimen accordingly to simulate different loading amplitude. The CSR was calculated as the ratio of the applied shearing stress (one-half of the applied deviator stress amplitude) to the initial effective consolidation stress.

In the first stage, the clean sand specimens were loaded cyclically under various testing conditions; (i) effective consolidation pressure (100 and 200 kPa); (ii) density index of 20% to represent the loose state and 60% to represent the dense state and (iii) cyclic amplitude in terms of CSR at 0.1, 0.2, 0.3, 0.4 and 0.5. For the second stage, the sand-fines mixtures were tested at a fixed testing condition. The soil was reconstituted at same density index, consolidated to a same consolidated pressure and loaded with same value of CSR. By doing so, the cyclic behaviour of sand with various fines content could be compare and evaluated.

It is important to note that the nature of cyclic loading applied to the soil deposit is highly dependent on the loading source, which could be relatively uniform with single frequency or randomly with a range of frequencies. Although various researchers carried out the test with varying frequency ranging from 0.1 Hz [9] to 2 Hz [6], the testing standard of ASTM D5311-M13 [8] states that the frequency of 1 Hz is more preferable. Since the simulation of earthquake loading in a triaxial testing system is always represented by 1 Hz [10], all sand in this study was tested with 1 Hz cyclic frequency.

The cyclic loading process was terminated either when the soil reached 10 % of axial strain or when 100 cycles of cyclic loading had been subjected to the soil specimen, whichever encountered first. In this study, the initiation of liquefaction (failure) was defined as either when excess pore pressure is equal to effective

consolidation pressure [11] resulting in a temporary condition of zero effective stress in the specimen ( $r_{u=1}$ ) or when the double amplitude strain of 5 % ( $\epsilon_{DA}=5\%$ ) was reached [12, 13]. Marto [14] pointed out that the two-way cyclic loading typically generates two components of the pore pressure responses, which are known as the resilient response and the permanent response. The pore pressure for the resilient response were observed at the peak of the compression and extension zones, and known as the  $u_{peak(c)}$  and  $u_{peak(e)}$ , respectively. In this study, the pore pressure for the permanent response ( $u_{permanent}$ ) was used to characterise the pore pressure response due to cyclic loading.

### 3. RESULTS AND DISCUSSION

Cyclic triaxial test under undrained condition was conducted on 12 clean sand specimens subjected to different testing condition, at varying density index, effective confining pressure and cyclic stress ratio. Table 1 shows the number of cycles at the initiation of liquefaction for clean sand obtained from two-way cyclic triaxial tests. The respective testing condition and failure criteria for each test were also shown. It is found that loose specimen exhibited large strain on compression side (positive value of deviator stress) whereas dense specimen exhibited dominant deformation on extension side (negative value of deviator stress). This result was also observed by Lombardi

*et al* [9].

Figure 2(a) shows the critical state line obtained from monotonic triaxial tests [15] together with the effective stress paths (ESP) of the loose sand specimen subjected to cyclic loading. It could be seen from the plot that the ESP moved to the left during the cyclic loading. This is because as the volume change of soil was not allowed in undrained test, the positive pore pressure was developed and reduced the stresses accumulated in the soil due to shearing. For the loose sand specimen, it approached the critical state line in a sudden manner when the initiation of liquefaction occurred. Figure 2(b) shows the ESP of the dense sand specimen subjected to cyclic loading. It could be seen from the plot that the ESP also moved to the left during the cyclic loading. However, the dense sand generated the characteristic of butterfly shape ESP before failure. Both the results are comparable to the stress paths of Red Hill sand subjected to cyclic loading, modelled by Lombardi *et al* [9]. The stress path was seen to have moved to the left in a sudden manner, which was caused by large deformation as a result of liquefaction. The dense sand specimen on the other hand, developed a progressive decrement in the shear stress with the addition of the number of cycle. Thus, the stress path was observed in a butterfly shape loop when the condition of zero effective stress was ascertained.

Table 1 Results of cyclic triaxial test on Johor sand

Specimen	Effective confining pressure (kPa)	Density index (%)	CSR	Failure Criteria	$N_c$
SAND1	100	20	0.1	$\epsilon_{DA}=5\%$	40
SAND2	100	20	0.2	$\epsilon_{DA}=5\%$	27
SAND3	100	20	0.3	$\epsilon_{DA}=5\%$	19
SAND4	100	20	0.4	$r_{u=1}$	14
SAND5	100	20	0.5	$r_{u=1}$	10
SAND6	100	60	0.1	$\epsilon_{DA}=5\%$	75
SAND7	100	60	0.3	$\epsilon_{DA}=5\%$	54
SAND8	100	60	0.5	$r_{u=1}$	36
SAND9	200	20	0.1	$\epsilon_{DA}=5\%$	67
SAND10	200	20	0.2	$\epsilon_{DA}=5\%$	52
SAND11	200	20	0.4	$\epsilon_{DA}=5\%$	34
SAND12	200	20	0.5	$r_{u=1}$	26

Note:  $\epsilon_{DA}=5\%$  : 5 % axial strain at double amplitude  
 $r_{u=1}$  : ratio of excess pore pressure to consolidation pressure = 1  
 $N_c$  : number of cycle  
 CSR : cyclic stress ratio

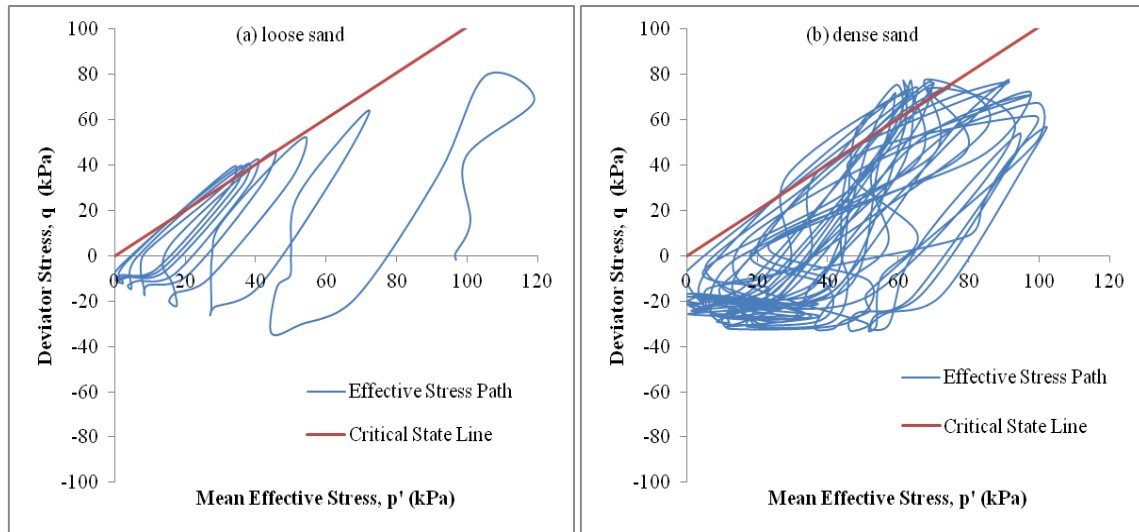


Fig.2 Effective stress paths of Johor clean sand subjected to two-way cyclic loading

### 3.1 Effect of Confining Pressure

The effect of confining pressure was investigated by performing the two-way cyclic triaxial tests with initial effective confining pressure ( $\sigma'_{3c}$ ) of 100 and 200 kPa, respectively. Figure 3 shows the effect of initial effective confining pressure towards liquefaction susceptibility of Johor clean sand under triaxial testing system. The results show that additional number of cycles ( $N_c$ ) was required to initiate the liquefaction at a high initial effective confining pressure with the same CSR. The liquefaction curve shifted to the right when the initial effective confining pressure was increased from 100 to 200 kPa. For an example, it can be seen from the figure that for a constant CSR value of 0.2, the  $N_c$  for  $\sigma'_{3c}$  of 100 kPa was 27 while it was 52 for  $\sigma'_{3c}$  of 200 kPa. The findings of Della *et al* [16] and Krim *et al* [17] also showed that liquefaction resistance of sand is proportional to the effective confining pressure. The liquefaction could occur at low confining pressure but as the confining pressure increased to a higher value, the sand becomes denser thus having better resistance towards liquefaction. In addition, the results also agreed on the common ground with the general concept of liquefaction susceptibility of sand. Generally, the liquefaction only occurred to the soil at shallow depths. Youd *et al* [18] indicated in the summary of NCEER workshop that loosely deposited sand with depth of less than 15 m is susceptible to liquefaction. At shallow depths, the effective confining pressure is low.

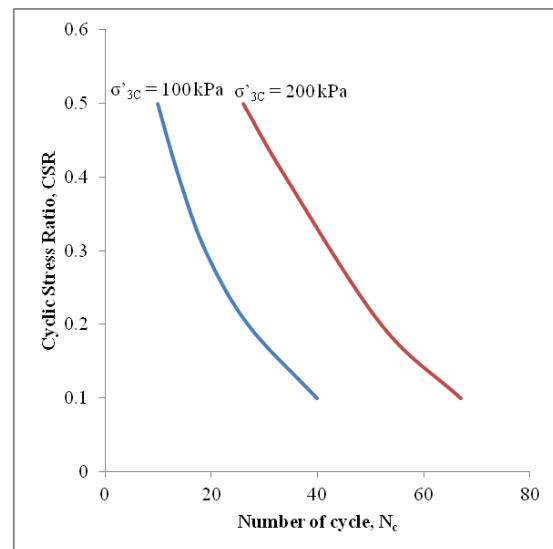


Fig.3 Effect of confining pressure on cyclic behaviour of Johor clean sand at initial density index of 20 % and subjected to 1Hz cyclic frequency

### 3.2 Effect of Density Index

The effect of density index ( $I_D$ ) was investigated by performing the two-way cyclic triaxial tests with initial density index of 20 and 60 %. Figure 4 shows the effect of density index towards liquefaction susceptibility of Johor clean sand under two-way cyclic triaxial tests. From the figure, for CSR of 0.3, the  $N_c$  at  $I_D$  of 20 % was 19 while the  $N_c$  at  $I_D$  of 60 % was 54. The results showed that additional number of cycles was required to initiate the liquefaction at high  $I_D$  with the same CSR. The liquefaction curve shifted to the right when the  $I_D$  was increased from 20 % to

60 %. The findings of Krim *et al* [17] and Lombardi *et al* [9] also showed similar findings. From their research, they concluded that the liquefaction resistance of sand is directly proportional to the density index. Head [7] indicated that the sand is considered loose for 20 %  $I_D$  and dense for 60 %  $I_D$ . Thus, the results obtained in this study are similar to other types of sand [9, 17] in which the loose state of Johor sand is also more susceptible to liquefaction than the dense state.

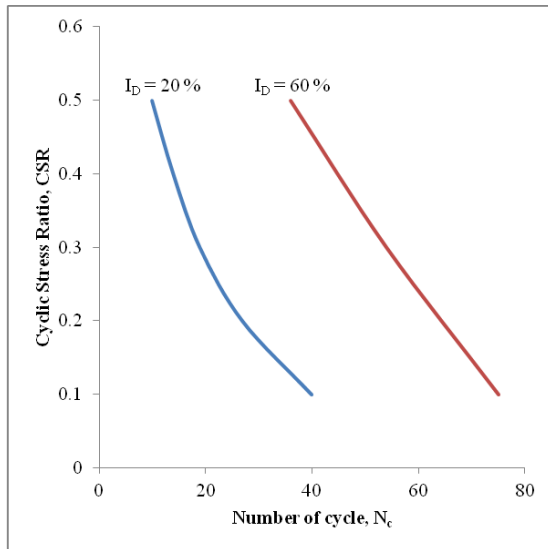


Fig.4 Effect of density index on cyclic behaviour of Johor clean sand at 100 kPa effective confining pressure and subjected to 1Hz cyclic frequency

In general, the results obtained in this study are in agreement with the concept of liquefaction susceptibility of sand as stated by Kramer [19] whereby the liquefaction is more prone to occur in loose sand. When there is an external loading exerted on saturated sand under the undrained condition, the response of cyclic softening on sand differs in accordance to density state. For loose sand of low density and with contractive tendency, the loading was too quick for the pore water to escape. In response to the compressibility of soil, the pore pressure would build up to counter the external load. At a point where the pore pressure is exceeding the contact stresses between sand grains, the soil was observed to flow like a liquid form. On the other hand, liquefaction hardly occurs to the sand in high density state. Dense sand is not susceptible to flow liquefaction because its strength is greater in undrained condition than in drained condition [20]. Due to its dilative behaviour in nature; the pore pressure would easily escape from the matrix of dense sand grain during cyclic loading. Thus, dense sand has more resistance to liquefaction compared to loose sand.

### 3.3 Liquefaction Susceptibility of Johor Sand

Laboratory test results showed that besides CSR, the liquefaction resistance of the sand under undrained cyclic loading was also proportional to the initial effective confining pressure and the density index. In this study, the cyclic resistance of soils had been expressed in terms of the  $N_c$  required for the liquefaction to occur. It has been found that the higher the CSR, the lower the  $N_c$  required for the liquefaction to initiate. For the effect of initial effective confining pressure, the  $N_c$  obtained was lower for 100 kPa than for 200 kPa at the same value of CSR. In term of the effect of initial density index, the  $N_c$  was lower for 20 %  $I_D$  than for 60 %  $I_D$  at the same value of CSR. Thus, from this study the most liquefiable condition for Johor clean sand under 1Hz cyclic frequency of two-way triaxial tests was being at its loose state condition ( $I_D = 20\%$ ) and confined with low effective confining pressure (100 kPa).

Figure 5 shows the liquefaction susceptibility curve of sand obtained from this study under the testing condition of  $I_D = 20\%$  and confined with initial effective confining pressure of 100 kPa. The liquefaction susceptibility curve is the plot of CSR versus  $N_c$  which divided the sand into two zones; liquefaction and non-liquefaction. The shape of the curve was in general agreement with the curve obtained by previous researchers [10], [11].

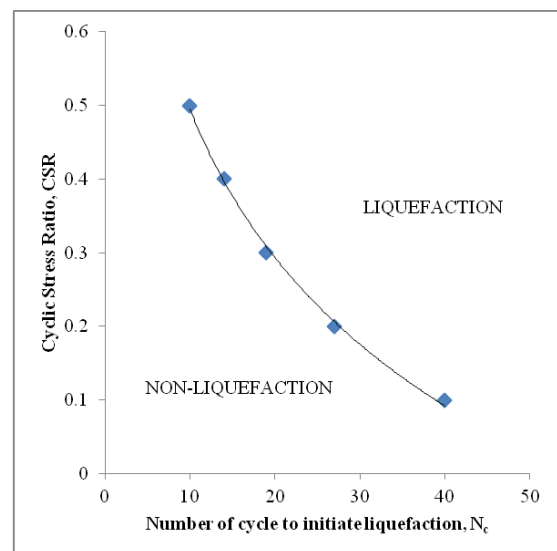


Fig.5 Liquefaction susceptibility curve of Johor clean sand at initial density index of 20 %, initial effective confining pressure of 100 kPa and cyclic frequency of 1Hz

Through the regression analysis, the CSR was correlated with the  $N_c$  to form the liquefaction susceptibility curve in natural logarithmic relation. The coefficient of determination ( $R^2$ ) of 0.99

indicated that it is a very good relation [21]. Statistically it means that 99% of the total variation of  $N_c$ , as a dependent variable, is explained by the regression line using the  $\log_e$  CSR, as the independent variable. Hence, the liquefaction susceptibility curve obtained could be used to divide the liquefaction and non-liquefaction zones with great accuracy. The equation of the liquefaction susceptibility curve is as follows:

$$N_c = -18.71 \ln(\text{CSR}) - 3.17 \quad (1)$$

In which,  $N_c$  = number of cycle  
 CSR = cyclic stress ratio

### 3.4 Liquefaction Susceptibility of Johor Sand with Fines

Based on the results of cyclic triaxial test on Johor clean sand, the fixed testing environment for the testing on sand with different fines content was selected. The sand-fines mixtures was reconstituted to loose state condition ( $I_D = 20\%$ ), confined with low effective confining pressure (100 kPa) and cyclic loaded with CSR of 0.1 at 1 Hz frequency.

The initiation of liquefaction in terms of  $N_c$  for sand with different fines content is illustrated in Figure 6. The cyclic resistance was seen to decrease with the increased of fines content up to a minimum value. Then, the resistance increased thereafter with the increased of fines content. From the plot, it was identified that the minimum liquefaction resistance were with FC=25 % for sand-kaolin mixtures. By smoothing the result into a curvilinear relationship, it can be seen that the minimum liquefaction resistance of sand with fines is actually could be defined as occurred in between 20 % to 25 % of fines content.

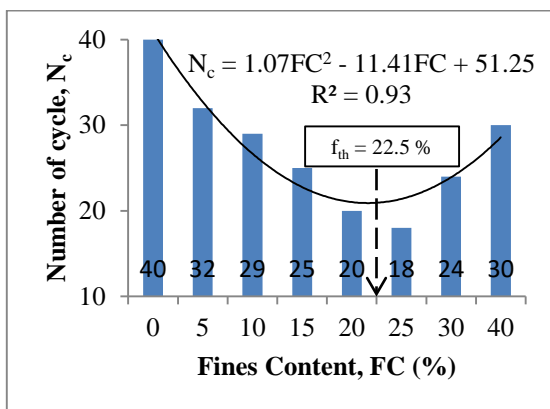


Fig.6 Number of cycles to initiate liquefaction against fines content of sand matrix soils ( $\sigma'_{3c} = 100$  kPa, CSR=0.1 and  $f = 1$  Hz)

The relationship of liquefaction resistance with the fines content for Johor sand-fines mixtures is curvilinear. Tan *et al.* [22] pointed out that it is because of the interaction between two material that having large different in their particle size. The sand particles have coarse particle size as compared to kaolin soil that is fines, as illustrated in Figure 1. The addition of fines particles initially infill the void space in between the sand grains. Thus, it causes the segregation between the sand particles and lowered the resistibility of sand towards liquefaction. The sand-fines mixtures with higher fines content is thus liquefied at a lower value of  $N_c$  as compared to sand-fines mixtures with lower fines content. However, there is a point where the void has been fully filled with fines where further increasing of fines would not reduce the void ratio any more. The addition of fines beyond this point would decrease the density of soil since the excessive fines particles now are not only occupied the location between sand grains, but also pushing the sand grains apart. Thus, the sand-fines mixtures are now shifting from sand-dominant soil to fines dominant soils. The liquefaction resistance is thus higher if higher fines content existed within the matrix of sand. Figure 6 shows the transition behaviour of the sand-fines mixtures from sand-dominant to fines-dominant. The corresponding fines content for the transition behaviour is known as threshold fines content ( $f_{th}$ ) [23]. Specifically, the  $f_{th}$  could be identified as the fines content that corresponding to the minimum liquefaction resistance of sand-fines mixtures. From the plot in Figure 6, the  $f_{th}$  could be determined as 22.5 %. By using the statistical formulation, a relationship between the liquefaction resistance and the fines content of sand-fines mixtures had been generated as follows:

$$N_c = 1.07FC^2 - 11.41FC + 51.25 \quad (2)$$

In which,  $N_c$  = number of cycle  
 FC = fines content in %

### 4. CONCLUSION

The undrained behaviour of Johor clean sand under the two-way cyclic triaxial tests had been determined successfully and the following conclusion had been drawn:

1. The response of cyclic softening on Johor clean sand differs in accordance to density state; liquefaction was more prone to be occurred in loose sand. The loose sand approached the critical state line in a sudden manner when the initiation of liquefaction occurred while the dense sand generated the characteristic of butterfly shape effective stress path and took a longer period before

- eventually failed.
- The higher the cyclic amplitude or cyclic stress ratio during cyclic loading, the smaller the number of cycles required for the initiation of liquefaction.
  - The higher the initial confining pressure, the denser the sand thus the better resistance towards liquefaction.
  - The Johor sand was more liquefiable at loose state ( $I_D = 20\%$ ) and under low effective consolidation pressure (100 kPa), when subjected to earthquake loading. At this specific condition the liquefaction susceptibility curve, used as a boundary for liquefaction and non-liquefaction, had been established and could be used as a guideline for engineers in preliminary design.
  - The relationship of liquefaction resistance, in terms of number of failure to initiate liquefaction, with the fines content for Johor sand-fines mixtures is curvilinear. At cyclic stress ratio of 0.1, the threshold fines content is found to be 22.5%.

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