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LIQUEFACTION RESISTANCE OF SAND MATRIX SOILS

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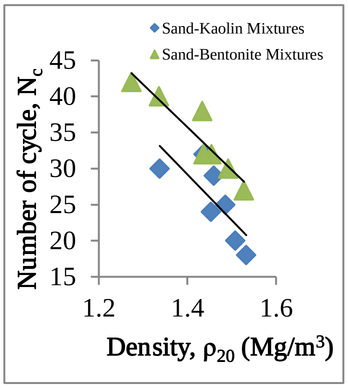
Graphical abstract



Abstract

Numerous researches have been focusing on the roles of fines in liquefaction resistance of sand matrix soils (sand dominant soil that contains little presenting fines). It has been reported that the presence of plastic fines would either imposed additional liquefaction resistance of sand matrix soils or caused reduction to the liquefaction resistance. This paper aims to present the liquefaction resistance of sand matrix soils with respect to different fines content based on the results from cyclic tests using triaxial testing system. The sand matrix soils were reconstituted by mixing the plastic fines (kaolin and bentonite) to the clean sand at seven different percentages by weight. Results showed that liquefaction resistance of sand matrix soils decreases with an increase of fines content until a minimal value and increases thereafter. It was identified that the presence of fine contents to give the minimum liquefaction resistance were 20 % for sand-bentonite mixtures and 25 % for sand-kaolin mixtures. These values represent the threshold fines content for respective mixtures.

Keywords: Cyclic triaxial test; kaolin; bentonite; threshold fines content

Abstrak

Banyak penyelidikan yang memberi tumpuan ke atas peranan butiran halus dalam rintangan pencecairan tanah matriks pasir (tanah dominan pasir yang mengandungi sedikit butiran halus). Telah dilaporkan bahawa kehadiran butiran halus berkeplastikan sama ada akan mengakibatkan penambahan kepada rintangan pencecairan atau menyebabkan pengurangan kepada rintangan pencecairan. Kertas kerja ini bertujuan untuk membentangkan rintangan pencecairan tanah matriks pasir yang mangandungi kandungan butiran halus yang berbeza berdasarkan keputusan daripada ujikaji tiga paksi berkitar menggunakan sistem tiga paksi. Tanah matriks pasir telah disediakan dengan mencampurkan butiran halus berkeplastikan (kaolin dan bentonit)kepada pasir bersih pada tujuh peratus yang berbeza mengikut berat. Keputusan menunjukkan bahawa rintangan pencecairan tanah matriks pasir berkurangan dengan kenaikan kandungan butiran halus sehingga nilai minima dan meningkat selepas itu. Telah dikenalpasti bahawaperatus butiran halus yang memberikan rintangan pencecairan minimum adalah 20 % bagi campuran pasir-bentonit dan 25 % bagi campuran pasir-kaolin. Nilai-nilai ini mewakili kandungan butiran halus ambang bagi masing-masing campuran.

Kata kunci: Ujikaji tiga paksi berkitar; kaolin; bentonit; kandungan butiran halus ambang

1.0 INTRODUCTION

Currently, there has been an extensive research works [1], [2], [3] focusing on the roles of fines in liquefaction resistance of sand matrix soils (sand dominant soil that contains little presenting fines). This is because empirical evidences revealed that not only clean sand is susceptible to soil liquefaction hazard but the sand matrix soils are also liquefiable [4]. It demonstrates the shortcomings of the currently used engineering guidelines, such as the Recommended Procedures and Guidelines for Analysing and Mitigating Liquefaction in California edited by Martin and Lew [5], which stated that clayey soils with clay fraction of more than 15 % are non-liquefiable. Thus, countless researches have been carried out to investigate on how these fine particles influence the soil liquefaction resistance of sand matrix soils. Study in such relationship is increasingly important when there is still no concrete conclusion that can be drawn as to in what manner the plastic fines is altering the liquefaction resistance of sand.

The understanding of soil liquefaction is constantly being revised and studied in laboratory investigations and infield evidences. The mainstream of past research works is in the common assumption that clean sand has a dominant effect on liquefaction behaviour while the presence of fines (particles finer than 63 μm) is negligible; this is found to be incorrect [6]. The presence of fines in the sand has long been thought to affect the cyclic behaviour of sand under cyclic loading. Fines content is the most common comparison basis used to characterise the presence of fines in influencing liquefaction susceptibility of sand matrix soils, however the research findings are in contradictory. For soils tested at a constant consolidation pressure of 250 kPa using triaxial testing system, Amini and Qi [7] found that liquefaction resistance of sand containing 50 % fines is the highest while the sand containing 10 % fines is the lowest. The addition of fines would fill up the void spaces between sand grains, resulting in void ratio reduction. The fines particles have minor influence to the overall soil behaviour because the sand grains are still in contact with each other and held the responsibility in soil bearing. However, other researchers [8], [9], [10] found that the liquefaction resistance of sand matrix soils decreases as the fines content increases.

On the other hand, some researchers [11], [12] found that the liquefaction resistance decreases with the addition of fines content up to a certain value then increases with the increase in the addition of fines content. Table 1 summarises some current research findings from [1], [2], [3], [13], [14], [15] [16], [17], [18], on liquefaction resistance of sand matrix soils. It has been reported that the presence of plastic fines would either imposed additional liquefaction resistance of sand matrix soils or caused reduction to the liquefaction resistance. The role of fines on liquefaction susceptibility needs further investigation. Thus, this paper aims to present the liquefaction resistance of sand matrix soils with respect to different fines content.

Table 1 Summary of some findings on liquefaction resistance of sand matrix soils

Researchers	Comparison basis	Research domain / finding
Derakhshandi *et al*. [13]	Clay content	Resistance decreases with increases in clay content up to some minimum value and increases thereafter
Maheshwari and Patel [14]	Fines content	More cycles needed to fail the silty sand specimen with more fines of up to 25 %
Abedi and Yasrobi [15]	Fines content	Resistance decreases with increases in fines content up to some minimum value and increases thereafter
Tsai *et al*. [16]	Fines content	Resistance to silty sand is stronger at higher fines content but to clayey sand it is weaker when the fines content increases
Dash and Sitharam [17]	Density index	At higher density index, liquefaction resistance is independent of silt content
Monkul and Yamamuro [18]	Mean grain size	Liquefaction potential is higher at smaller mean grain size
Park and Kim [1]	Plasticity index	Resistance was reduced at higher plasticity index
Bayat *et al*. [2]	Clay mineralogy	Sand-bentonite mixtures have higher strength than sand-kaolin mixtures with same fines content
Benghalia *et al*.[3]	Fines content	Addition of fines lowered the liquefaction susceptibility of sandy soils

2.0 EXPERIMENTAL TESTING

The laboratory testing using Enterprise Level Dynamic Triaxial System was used to investigate the liquefaction resistance of sand matrix soils. The test materials comprises of clean sand, white kaolin and green bentonite, as shown in Figure 1. The sand matrix soils were reconstituted by mixing the plastic fines (white kaolin and green bentonite) to the clean sand at seven different percentages by weight, as summarised in Table 2.

Figure 1 Materials used to reconstitute sand matrix soils

Table 2 Composition percentages of reconstituted sand matrix soils

Sand Matrix Soils	Percentages by weight (%)			Sample code
	Sand	Kaolin	Bentonite	
Clean Sand	100	0	0	SAND100
Sand-Kaolin Mixtures	95	5	0	SK05B00
	90	10	0	SK10B00
	85	15	0	SK15B00
	80	20	0	SK20B00
	75	25	0	SK25B00
	70	30	0	SK30B00
	60	40	0	SK40B00
Sand-Bentonite Mixtures	95	0	5	SK00B05
	90	0	10	SK00B10
	85	0	15	SK00B15
	80	0	20	SK00B20
	75	0	25	SK00B25
	70	0	30	SK00B30
	60	0	40	SK00B40

2.1 Test Material

The clean sand used to form the sand matrix soils in this study is the natural river sand obtained from Johor Bahru, Malaysia. The sand has sub-angular shape with light brown colour. The particle size distribution of clean sand is illustrated in the Figure 2. The particle size of sand ranges from 0.1 mm to 2.0 mm while the mean grain size (D_{50}) is 0.5 mm. The medium fine particle size sand is very clean which contains no fines and the sand spans in narrow particle size range. Based on the particle size distribution, it can be identified that the clean sand is poorly graded sand (SP) containing no fines. Poorly graded sand is very susceptible to liquefaction hazards than well graded sand [19]. Hence, this soil was suitably used in studying the role of fines in liquefaction susceptibility of sand matrix soils.

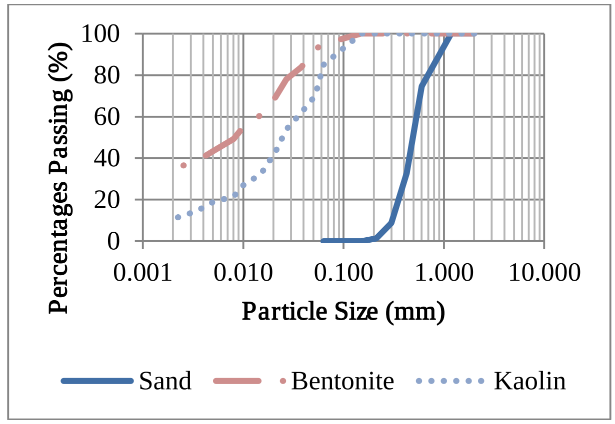


Figure 2 Particle size distribution of the materials used to reconstitute sand matrix soils

The sand was mixed with two types of commercially available plastic fines; the low plasticity fines (kaolin), manufactured by Kaolin (Malaysia) Sdn. Bhd. and the high plasticity fines (bentonite) manufactured by Harliburton (Malaysia) Sdn. Bhd.. The kaolin has the liquid limit (w_L) of 39 %, plastic limit (w_P) of 26 % and plasticity index (I_P) of 13 %, while the bentonite has the w_L of 290 %, w_P of 59 % and I_P of 231 %. The w_P is almost similar but the w_L has a big difference. Thus, using the plasticity chart, the kaolin was classified as intermediate plasticity silt (MI) while the bentonite was classified as extremely high plasticity clay (CE). From the particle size distribution of the kaolin and bentonite shown in Figure 2, it illustrated that bentonite contains more clay size particles (about 35 %) than kaolin (about 15 %). It verified that the kaolin contain more silt while bentonite is clay soils.

The minimum density (ρ_{min}) and maximum density (ρ_{max}) of the reconstituted sand matrix soils ranges from 1.22 to 1.47 Mg/m^3 and from 1.56 to 1.87 Mg/m^3 which were plotted against the fines content as shown in Figure 3. Both the density curves increases as the fines content increases up to certain peak values, then decreases thereafter. The noticeable peak value has been defined by previous researchers [20], [21] as the threshold fines content (f_{th}). From this study, it seems that the f_{th} obtained from the ρ_{max} and ρ_{min} of sand matrix soils coincides with each other. The f_{th} of sand-kaolin mixture is at 25 % of kaolin content while the sand-bentonite mixture is at 20 % of bentonite content. The results are within the ranges of transition zone (20 % to 40 % of fines content) [4].

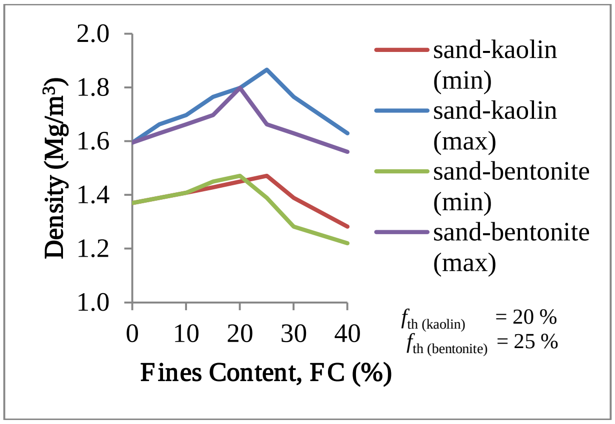


Figure 3 Density curve of reconstituted sand matrix soils

2.2 Cyclic Triaxial Test

The stress controlled cyclic triaxial test was carried out as the main test in order to investigate the liquefaction resistance of sand matrix soils, in accordance with ASTM D5399 M13 Standard Test Method for Load Controlled Cyclic Triaxial Strength of Soil [22]. All the sand matrix soils were reconstituted to cylindrical soil specimen with the size of 38 mm diameter and 76 mm height. The soil samples were prepared into 20 % density index (ρ_{20}) to represent loose state condition by using the undercompaction method.

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 equals to the void volume specimen was collected. Saturation process was carried out with a linear increase of cell and back pressure with constant differences of 10 kPa effective stress. This process was continued until the minimum B-value of at least 0.96 was achieved.

Following the saturation and isotropic consolidation process, the drainage valve was shut for the soil specimen to be subjected to an undrained cyclic loading condition. The stress-controlled undrained cyclic triaxial tests were carried on isotropically consolidated specimen at back pressure of 200 kPa. The applied cyclic loading of 0.1 cyclic stress ratio (CSR) was applied to the specimen to simulate the earthquake loading amplitude. The CSR was calculated as the ratio of the applied shearing stress to the initial effective consolidation stress. In order to model the earthquake condition, 1 Hz cyclic frequency was used [22].

3.0 RESULTS AND DISCUSSION

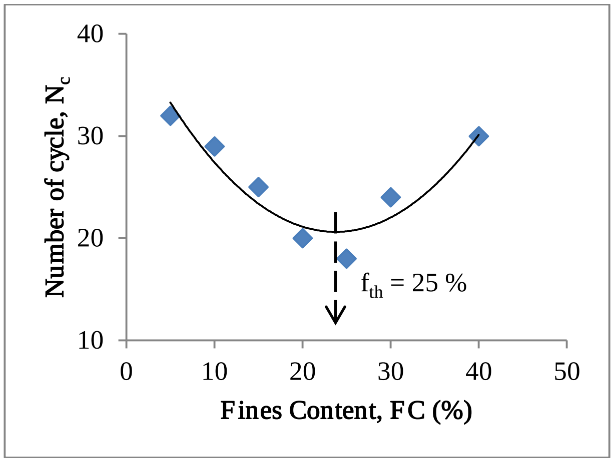
The results of 15 two-way cyclic triaxial tests performed on sand matrix soils of 20 % density index, at the testing condition of 100 kPa effective consolidation pressure and subjected to 0.1 CSR with 1 Hz cyclic frequency are presented in this section. The initiation of liquefaction (failure) is defined as either when excess pore pressure is equal to effective consolidation pressure [23] or when the double amplitude axial strain of 5 % is reached [24]. The liquefaction resistance of sand matrix soils is represented by the number of cycles (N_c) required to initiate the liquefaction. Table 3 summarises the N_c required to initiate liquefaction at cyclic stress ratio of 0.1 on sand matrix soils with various fines content.

Table 3 Number of cycles to initiate liquefaction for sand matrix soils

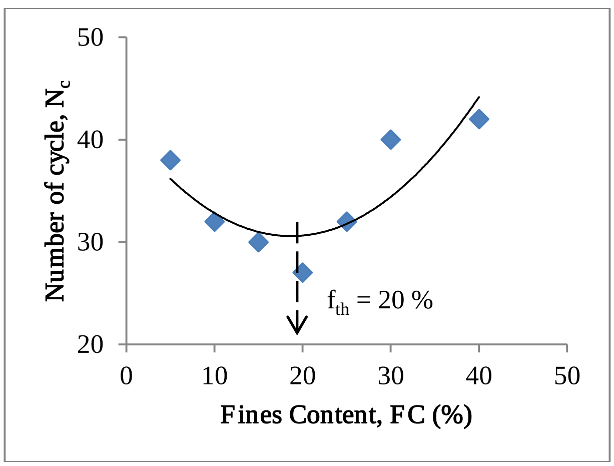
Fines Content (%)	Number of cycles to initiate liquefaction, N_c	
	Clean sand	
0	40	
	Sand-kaolin	Sand-bentonite
5	32	38
10	29	32
15	25	30
20	20	27
25	18	32
30	24	40
40	30	42

Figure 4 shows the variation of N_c required to initiate the soil liquefaction against fines content for sand matrix soils. Similar trends are observed for both sand-kaolin and sand-bentonite mixtures. The liquefaction resistance of sand matrix soils deemed to be considered as two totally opposite behaviour across the addition of fines content. In the first part, the liquefaction resistance for sand matrix soils decreases with the increases of fines content. Then, for the second part, after reaching a certain minimum value the liquefaction resistance increased with an increasing of fines content. From the plot, it is identified that the minimum liquefaction resistance are 25 % for sand-kaolin mixtures and 20 % for sand-bentonite mixtures. These values obtained from the cyclic triaxial tests are found to coincide with the values obtained from the density curves. Similar trends was also addressed by other researchers including [3], [12], [17]. Hence, it could be confirmed that this finding justifies the concept of threshold fines content as one significant parameter in explaining the influence of fines content on the liquefaction susceptibility of sand matrix soils.

In the first part, the density of soil is increasing with fines content because the fines particles fill the void spaces between sand grains. The liquefaction resistance would decrease and increase again across ascending order of fines content. This is due to the fines particles have minor influence to the overall soil behaviour since the sand grains are still in contact with each other and held the responsibility in soil bearing. The reduction of sand particles causes the reduction of liquefaction resistance. In the second part, as the void spaces are almost completely filled, addition of fine particles displaced the sand grains from each other. Thus, the density is decreasing with an increasing of fines content beyond the value of f_{th}.



(a) Sand-Kaolin mixture



(b) Sand-Bentonite mixture

Figure 4 Number of cycles to initiate liquefaction against fines content

Generally, the addition of fines particles within the matrix soil sand increases the overall density of the sand matrix soils. Hence, the liquefaction should be higher at higher density. However, Yamamuro and Lade [25] indicated that the fines create unusual metastable structure within the matrix of sand. Upon isotropic compression and shearing, the fines particles tend to slide into the void spaces resulting with the soil having a volumetrically contractive behaviour. From this study, as the cyclic loading was carried out under undrained condition, the contractive behaviour of sand matrix soils resulted with the soils to produce greater tendency for liquefaction to occur. The results shown in Figure 5 are also in close agreement with the findings of other researchers [26], [27]. As also observed through the plots in Figure 5, the value of N_c varies for different type of sand matrix soils although having similar density (ρ_{20}) at 20 % density index. The value of N_c seems to be higher for the sand-bentonite mixtures, compared to the sand-kaolin mixtures. This is because the composition and the clay mineralogy of the fines present in the mixtures varied. Hence, the engineering characteristics is deemed to be related not only with the density but also the plasticity behaviour of sand matrix soils [28].

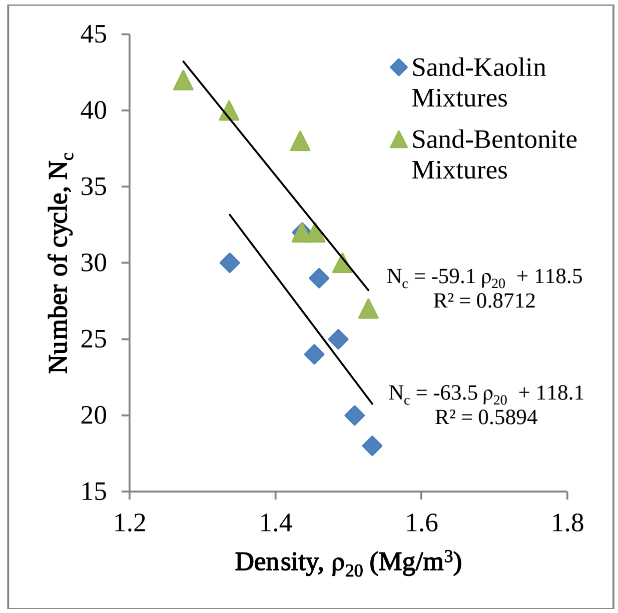


Figure 5 Liquefaction resistances of sand matrix soils against soil density at 20 % density index

4.0 CONCLUSION

The undrained stress controlled cyclic triaxial tests had been successfully carried out in determining the liquefaction resistance of sand matrix soils. It can be concluded that the liquefaction resistance of sand matrix soils is minimal at the threshold fines content of 20 % for sand-bentonite mixture and 25 % for sand-kaolin mixture. The liquefaction resistance has seen to decrease with the increased of fines content up to the threshold value and increased thereafter. The value of threshold fines content could be indentified from the density curve.

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