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Liquefaction Resistance of Coarse Sand-Fine Mixtures Soil under Two-Way Cyclic Loading

Liquefaction Resistance of Coarse Sand-Fine Mixtures Soil under Two-Way Cyclic Loading

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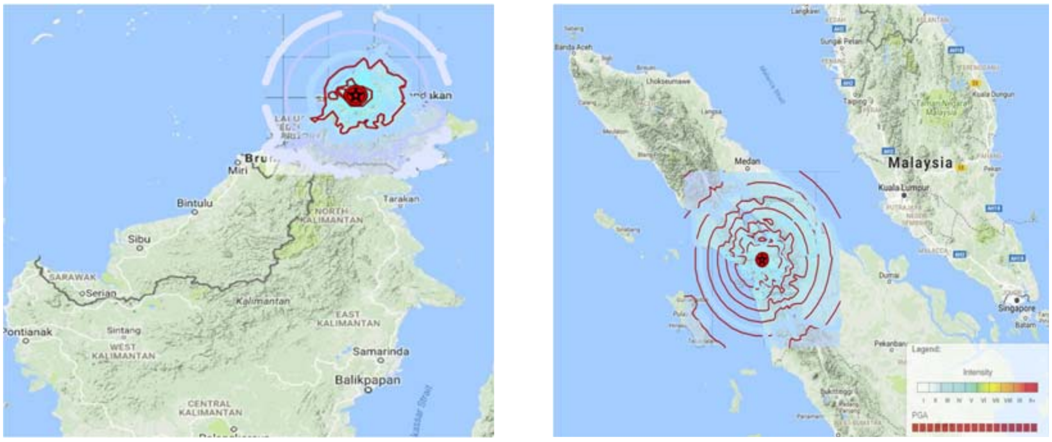
Abstract. Soil liquefaction is one of the devastating consequences of earthquake hazards. Extensive study had been carried out to understand the factors affecting liquefaction resistance of sand and sand-fine mixtures, both in the laboratory and in-situ. However, the findings are still incomplete particularly in terms of particle size, grading characteristics and fines content of sand-fine mixtures. Hence, this paper aims to present the cyclic behaviour of coarse sand-fine mixtures, in terms of liquefaction resistance under two-way cyclic triaxial loading tests. The cyclic loading tests under undrained condition had been performed with various percentage of kaolin as fines content. The sand-fine mixtures were prepared with 15% relative density and tested under 100 kPa of effective consolidation pressure. The cyclic triaxial loading tests were performed with a typical frequency of 1 Hz to simulate earthquake situation. The results showed that, with the increase of fines content in coarse sand-fine mixtures, the smaller the number of cycles required for the initiation of soil liquefaction. However, the number of cycles to initiate liquefaction increased back when fines content in the mixture was greater than 30%. As 30% fines content gave the lowest liquefaction resistance, this value is known as a threshold value in which it is the transition of sand domination to fines. The liquefaction resistance decreased with the increase of fines until it reached the threshold value but increased with fines content thereafter.

1. Introduction

Recent studies carried out by [1] reported that, Peninsular Malaysia felt the tremors which occurred in the South-East Asia region with Magnitude, Mw > 7.0 recorded from 1977 to 2007. Besides that, "*myGempa*" developed by Malaysian Meteorological Department (MMD), recorded that Ranau, Sabah and Borneo experienced 9 weak earthquakes (Mw = 1.0 to Mw= 4.9) and 1 moderate earthquake (Mw = 5.0 to Mw =5.9 over the last 2 years. Moderate earthquake (Figure 1) also occurred at Northern Sumatera which is close to Kuala Lumpur, the capital city of Malaysia. The magnitude, Mw was 5.1 but there was no damage to the structures, occurrence of tsunami or liquefaction incidences had been recorded in Malaysia. However, recent devastating liquefaction incident which occurred at Palu, Indonesia as the result of 7.8 magnitude earthquake on 28th September 2018, was seen as a new chapter in natural disaster research.



a) Mw = 5.2 at Ranau, Sabah on 8 March 2018.

b) Mw = 5.1 at Northern Sumatera, Indonesia on 13 March 2018

Figure 1. Current moderate earthquake occurred in Malaysia and Indonesia

Research conducted by [1] at shoreline areas of Malaysia reported that the South China Sea is deposited by sand and it also shows the existence of fines. The mixtures of this sand-fines soils are prone to liquefy if earthquake occurred at certain magnitude. Over a decade, most of the researchers laid the effort to define and examine the liquefaction behaviour of sand [2][3], sand with fines [4][5][6][7] and soils reinforced with material [8][9][10]. [11] reported that the liquefaction resistance of granular soils decreased with the increased of non-plastic fines up to 30%.

Several efforts have been laid by past researchers to find the relationship between grading characteristics and particle size distribution of sand matrix soils (sand-fines mixtures) on liquefaction resistance, but they are not sufficient to correlate the characteristics with it. The research done by [12] using Khazar coastal sand mixed with gravel and coarse sand at different percentage shows that when effective grain size (D_{10}), grain diameter corresponding to 30% finer (D_{30}), mean grain size (D_{50}) and grain diameter corresponding to 60% finer (D_{60}) decreases, the liquefaction decreases gradually. On the other hand, liquefaction resistance increases with increasing of D_{10}, D_{30}, D_{50} and D_{60}. The more current study conducted by [13] on liquefied soils in Indonesia shows that uniform sand particles have the potential to liquefy.

According to [14], [4] found that volumetric contraction occurred due to the the particle interaction of loose state silty sand when applied with force, as shown in Figure 2. [15] conducted studies related to sand-fine mixtures on critical state and state parameters. They found that liquefaction resistance decreased when silt content increased to minimal resistance was reached then it increased back as silt content increased.

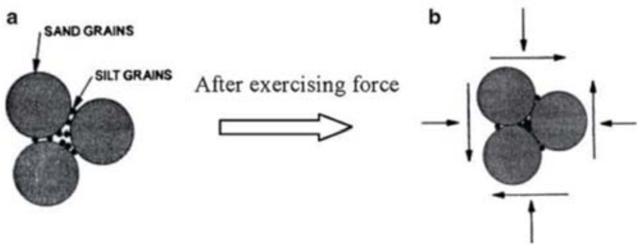


Figure 2. a) Particle structure of silty-sand in loose state b) Volumetric contraction after application of stress [4] [14].

To investigate the effect of coarse sand mixed with various percentage of fines on liquefaction resistance, the cyclic triaxial tests were conducted. From the test results, the most susceptible liquefaction condition of tested soils is presented.

2. Experimental Testing

2.1 Soil Classification Test

Basically, two material types have been used in this study: first, sand obtained from a river at Bandar Tenggara, Johor, Malaysia and the second commercially available kaolin supplied by Kaolin (M) Sdn. Bhd. In order to produce reconstituted samples of coarse sand-fine mixtures with different percentage of fines, the sand was firstly sieved using sieves with the size ranging from 2.0 mm – 0.6 mm. This range of sand size was used as parent sand in this paper. This parent sand was mixed with 0% to 40% by weight of kaolin to produce a sample with different fines content. The compositional characteristics of each reconstituted samples are listed in Table 1. There are 5 samples of coarse sand-fine mixtures with different fines content. All tests through laboratory testing were carried out according to British Standard (BS) 1377-2 except for minimum and maximum void ratio, which was performed with the procedure recommended by [4]. The reconstituted samples of coarse sand-fine mixtures with consist of different percentages of kaolin as fines content have been used for all tests presented in this paper. The originally obtained sand results presented in this paper is for reference and comparison purposes. Three main tests had been carried out namely as the:

- Particle size distribution (PSD) in according to BS1377-2: Clause 9.3 and Clause 9.5
- Particle density (PD) in according to BS1377-2: Clause 8.3
- Maximum and minimum void ratio with the procedure recommended by [4]

Table 1. Compositional characteristics of coarse sand-fines mixture samples.

Samples	Percentage of materials by weight (%)		Test Code
	Sand	Kaolin	
Sand	100	0	Sand
Coarse Sand-Fines	100	0	S100K0-C
	90	10	S90K10-C
	80	20	S80K20-C
	70	30	S70K30-C
	60	40	S60K40-C

2.2 Undrained Cyclic Triaxial Test

The GDS ELDYN® triaxial machine had been used for testing each sample in accordance to the ASTM D5311-13M and [16]. The machine has the capability to conduct a cyclic test to a maximum of 5 Hz frequency and maximum cyclic loading of 10 kN. During the testing, all data were automatically logged to the computer. To investigate the liquefaction behaviour of the coarse sand-fine mixtures sample, the undrained condition has been applied during the cyclic loading phase. Due to the cohesionless type of tested samples, the reconstituted samples had been prepared on the triaxial pedestal using split mould with the diameter of 50 mm and 100 mm height. The moist tamping technique was applied due to the present of fines and to build a homogenous sample as had been successfully applied by [6] and [17]. All reconstituted samples were prepared at loose state with 15% of relative density. Once the preparation of sample was completed, the saturation process was carried out. Full saturation was considered achieved when the B-value was more than 0.96, in which the saturation process was terminated and the consolidation stage was started. The effective confining pressure of 100 kPa was maintained during consolidation. After the consolidation stage completed, the cyclic loading with axial amplitude of 0.1 kN and frequency of 1 Hz for earthquake simulation was applied. Two-way cyclic loading was applied to ensure stress reversal, as the characteristic of liquefaction failure mode [18]. The cyclic loading test was terminated when the double amplitude axial strain exceeds 5% or the ratio of excess pore water pressure to the effective stress applied, Ru was equal to 1.0, whichever comes first. The number of cycles, Nc at the termination criteria was taken as representing the liquefaction resistance. High value of Nc is a sign of greater liquefaction resistance and vice versa.

3. Results and Discussion

3.1 Soil Characteristics

Figure 3 shows the particle size distribution curve for all samples from sieve analysis test. The parameters analysed from Figure 3 are listed in Table 2. The sand used in this paper had been classified as poor graded sand (SP) as the coefficient of uniformity, C_U was 2.00 while the coefficient of curvature, C_C was 1.06. According to [19] who used the same kaolin, it is low plasticity fines with the plasticity index of 13% and has been classified as intermediate plasticity silt (MI). It can be seen from Table 2, the C_U for coarse sand-fine mixtures was 1.71 < C_U < 90) and C_C was 0.54 < C_C < 17.04. At 20% of fines, the classification of mixtures changes from SP to SM (silty sand). Figure 3 generally shows that the addition of fines enlarged the ranges of the grading curves. The mean diameter, D_{50} is one of the important parameters for liquefaction analysis. D_{50} for all three types of sand mixtures decreased with the increase of fines from 0% to 40%. As mentioned by [19] and [12], the liquefaction resistance of soils decreased with increase of fines.

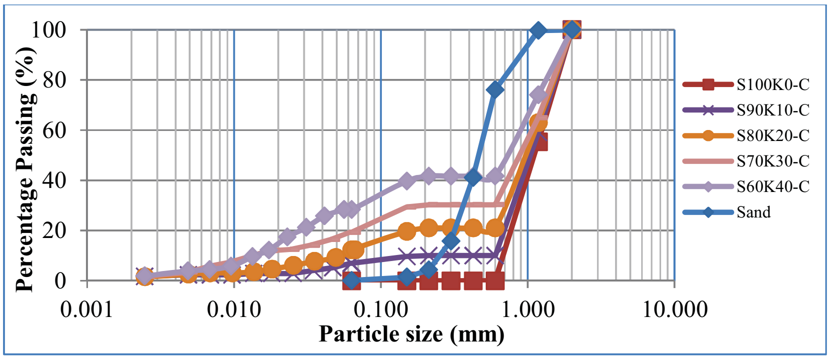


Figure 3. Particle size distribution curve for coarse sand-fine mixtures.

Table 2. Soil specimen properties of coarse sand-fine mixtures.

Soil Specimen	Gradation		Grain size				Density (Mg/m^3)		BSCS* system
	C_U	C_C	D_{10}	D_{30}	D_{50}	D_{60}	Minimum	Maximum	
Sand	2.00	1.06	0.24	0.36	0.46	0.51	1.39	1.64	SP
S100K0-C	1.71	0.96	0.70	0.90	1.10	1.20	1.28	1.52	SP
S90K10-C	7.67	3.71	0.15	0.80	1.00	1.15	1.39	1.58	SP
S80K20-C	46.00	17.04	0.03	0.70	0.98	1.15	1.47	1.68	SM
S70K30-C	73.33	1.36	0.02	0.15	0.92	1.10	1.49	1.71	SM
S60K40-C	90.00	0.54	0.01	0.07	0.72	0.90	1.41	1.68	SM

* British Standard Classification System

From the results obtained on the minimum and maximum void ratio test, calculation was performed to determine the minimum and maximum density of the coarse sand-fine mixtures. By plotting the results shown in Figure 4, the trend of the density of each sample can be seen. Both the curves for minimum and maximum density of coarse sand-fine mixtures increased with increase of fines content until the peak values were reached then decreased thereafter. The peak maximum and minimum densities were observed at 30% of fines content. The density curves decreased after reaching 30% of fines content. This trend occurred due to the value of the void ratio of the samples. When fines were added to the coarse sand, the voids decreased with the increase of fines. At 30% of fines, the voids between the coarse sand grains were fully filled by fines. Beyond this fines content, the grain contacts between the sand grain was decreased due to the abundant amount of fines [19].

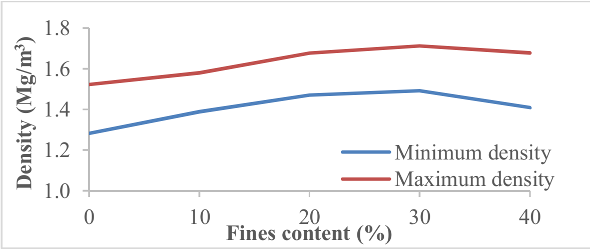


Figure 4. Relationship between density of coarse sand-fine mixtures with percentage of fines content.

3.2 Undrained Cyclic Triaxial Test

Undrained condition during cyclic triaxial test was set to investigate the liquefaction resistance of coarse sand-fine mixtures sample under two-way cyclic loading. Figure 5 shows the typical results from undrained cyclic triaxial test of original Sand sample. Summary of the results on the number of cycles required to cause liquefaction and the failure criteria achieved are shown in Table 3. Table 3 show that, the increase of fines until 30% of fines content, the failure criteria (initiation of liquefaction) was achieved when Ru=1; while fines exceeding the 30%, the failure criteria was changed to 5% strain of double amplitude. The transition failure criteria at 30% of fines occurred at the maximum density of soil where the fines started to dominate the soil matrix causing the samples to behave like clay [20].

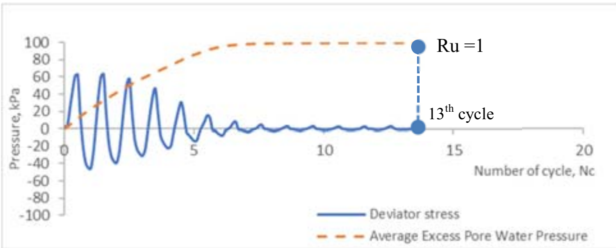


Figure 5. Typical results on sand sample

Table 3. The number of cycles required to cause liquefaction

Sand matrix soils	Number of cycles, Nc	Failure criteria achieved
Sand	13	Ru=1
S100K0-C	17	Ru=1
S90K10-C	15	Ru=1
S80K20-C	11	Ru=1
S70K30-C	9	5% strain
S60K40-C	14	5% strain

The results in Table 3 were illustrated in Figure 6. As can be seen from Figure 6, while the fines content increased, the number of cycles for liquefaction, Nc decreased up to 30% of fines. Then Nc increased when fines was increased from 30% to 40%. The reason why the addition of fines content could make the sand matrix soils more liquefiable is due to the condition of void spaces between the sand grains. [19] and Bayat et al. (2017) had discussed the situation for sand with fines contents. From the results, it shows that the voids could influence the liquefaction resistance.

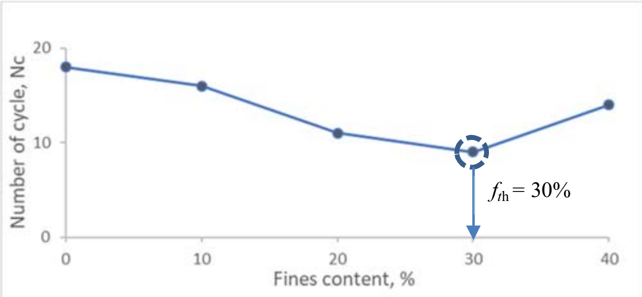


Figure 6. Number of cycles required for liquefaction to occur with addition of fines content.

The decrease of liquefaction resistance with increase of fines is due to the fines which filled the pores in each sample. Comparison has been made with the S100K0-C as a reference. For S90K10-C, with 10% of kaolin added, that small amount of kaolin has infilled the void within the sand grain resulting to liquefaction at Nc= 16. Compared to the S100K0-C, the Nc is much higher with value of 18. This condition is due to the fines that falls between the contacts of the sand grain [21]. As stated by [22], the fines itself has an ability to form a coating on the sand grain surface which behave like lubricant that decreases the liquefaction resistance. It can be seen at Figure 6, where the liquefaction resistance decreased with increase of fines up to 30%. At this phase, the density of the sand matrix has the highest value as shown in Figure 4. It means that the voids have been fully filled by the fines. At this point, the fines content is named as the threshold fines content, f_{th}. Beyond 30% of fines, the fines take the domination of sand on the soils thus decreased the sand grain contact. However, this condition would not decrease the liquefaction resistance, but it would increase the liquefaction resistance due to the characteristics of the fines such as their plasticity. The trend of this finding is similar to the finding by [19] although this paper finding is applicable for coarse sand type mixed with kaolin.

4. Conclusion

Significant influence of fines content on liquefaction resistance of the coarse sand-fines mixtures soil had been observed during two-way cyclic loading tests, simulating the earthquake condition. 30% fines content had been identified as the threshold fines content. Liquefaction resistance decreased with increase of fines for fines content equals or less than 30% of fines. When the fines content increased after this threshold value, the liquefaction resistance increased due to the fines taking over the dominant material from sand grain and as a result the plasticity characteristics of the fines might have taken the responsibility on the liquefaction resistance.

5. Acknowledgement

This research was supported by the Ministry of Education (MOE) Malaysia through the Fundamental Research Grant Scheme (FRGS) (UTM Vote Number 4F316) lead by the second author. The authors are therefore would like to acknowledge the MOE for the opportunity given. The first author would like to also acknowledge Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia Kuala Lumpur for the financial incentives given in carrying out the PhD studies. Acknowledgements are also given to the Universiti Teknologi Malaysia and Universiti Tun Hussein Onn Malaysia for the usage of the triaxial tests equipment for cyclic loading tests.

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