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UNDRAINED SHEAR STRENGTH OF SAND WITH PLASTIC FINES MIXTURES

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Abstract: More and more empirical evidences have revealed the growing importance of the effects of fines towards the liquefaction susceptibility of sand matrix soils. The limiting value of the threshold fines content (*fth*) is an important criterion in influencing such behaviour. The positive hyperbolic relationship between *fth* and liquefaction resistance, in term of undrained shear strength of sand-non-plastic-fines mixtures have been proven right in previous academic publication. The aim of this paper is to examine whether such positive hyperbolic relationship would observable be as to sand-non-plastic-fines mixtures. Undrained triaxial compression tests were performed on specimens of sand with various percentages of plastic fines (kaolin) by weight. The threshold fines content of sand-kaolin mixtures was observed at 25% of kaolin by weight. The positive hyperbolic relationship was established for sand-kaolin mixtures. Coincidentally, the lowest undrained shear strength was observed at the threshold fines content of sand-kaolin mixtures. Hence, the concept of threshold fines content has been proven to be a corresponding factor for the undrained shear strength of both sand-non-plastic-fines mixtures and sand-plastic-fines mixtures.

Keywords: *Threshold fines content; sand matrix soils, positive hyperbolic curve, liquefaction susceptibility*

1.0 Introduction

Soil liquefaction has only started to be studied extensively by researchers as a modern engineering branch since 1960s, right after the occurrence of two destructive earthquakes, the Alaska and Niigata quakes in 1964. For many years, research on liquefaction have mostly focused on uniform clean sands, containing little or no fines (Figure 1). Outstanding advances have been achieved with common assumption that typical liquefaction behaviour of clean sands represents all types of in-situ sand deposits. Additional of fines will increase liquefaction resistance.

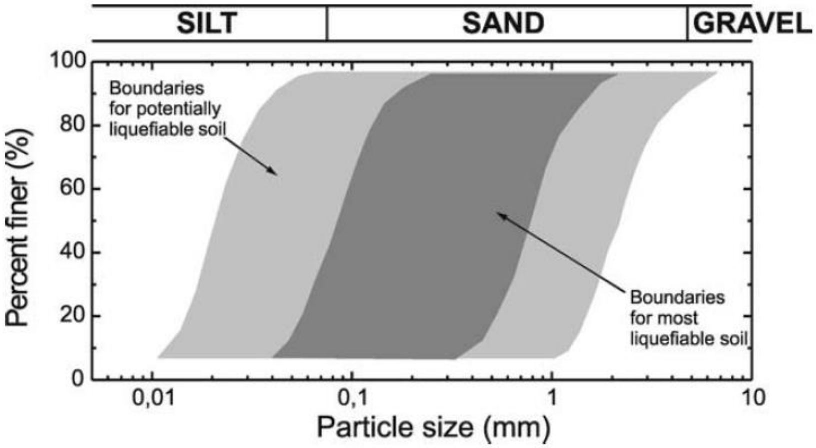

Figure 1: Ranges of grain size distribution for liquefiable soils (Tsuchida, 1970)

Although outstanding advances have been achieved in this research area, the previous research assumption that cyclic behaviour of clean sand are similar to natural sand deposits at field was found to be in disagreement with most current earthquake cases occurred as summarised in Table 1. These empirical observations had significantly formed the research focus in the field of soil liquefaction study regarding the behaviour of sand containing fines. The understanding of empirical observation are constantly being revised as new evidences; mainly looking into on how non-plastic fines give influences towards the liquefaction susceptibility of sand matrix soils through grain fabric.

Table 1: The characteristics of liquefied soils in some earthquakes (Tan *et al.*, 2013)

Year	**Earthquake**	**Characteristics of liquefied soils**
1971	San Fernando	Silty sands
1976	Tangshan	20% clay fraction
1983	Idaho	70% fines and 20% clay fraction
1993	Hokkaido	48% fines and 18% clay fraction
1999	ChiChi	Fines content as high as 36% to 53%
1999	Adapazari	70% fines with plasticity 0 to 25
2009	Olanche	Fines content as high as 15±8%
2010	Christchurch	Grey fine silty sands

Many studies have been conducted on the effect of fines content on liquefaction resistance which focuses on sand-non-plastic-fines mixtures (eg: Cubrinovski *et al.*, 2010) and they agree on one common ground, which is, generally, the grain fabric would compose differently according to the different percentages of fines that exist within parent sand (Figure 2). There are three different phases which are: (i) filling-of-voids; (ii) transition zone and (iii) replacement-of-solid. At the phase where small amount of fines exist in the parent sand, the fines which are relatively smaller than sand particles, only act as the filler of the voids among the sand particles (filling-of-voids phase). When the amount of additional fines has exceeded the existed void within sand grains, the fines will start to dominate the parent sands and are held the responsibility in the soil bearing skeleton (replacement-of-solid phase). It is worth to mentioning that the limiting value of fines content for the transition from the sand dominant to the fine dominant (transition zone) is known as the threshold fines content (f_{th}). Previous research findings (eg: Derakhshandi *et al.,* 2008) show that the transition zone between these two phases is normally occurs approximately between 20% and 40% of fines content. These studies, although they used reconstituted soil specimens; have provide adequate understanding from both aspects of index (compositional characteristic) and engineering (stress-strain behaviour) respectively.

However, earlier research breakthroughs have been contradictory. Several studies stated that the presence of fines decreased the undrained shear strength while other showed that the fines incurred additional undrained shear strength. These arguments are acceptable because the stress-strain behaviour of cohesionless soils is closely related with its compositional characteristic, particularly the density state. Hence, addition of fines has changed the initial composition of the parent sand and gave significant influence to the undrained shear strength. Theoretically, additional of fines will makes the sand matrix soils into a denser configuration and behave more dilative when sheared. This argument was proven by Kuerbis *et al* (1988). At the same skeleton void ratio, the increase of silt content up to 20% resulted in more dilative behaviour in undrained shear strength. However, the increase of silt content may also cause the contractive state of sand matrix soils. Yamamuro and Lade (1998) have observed that increasing the non-plastic silt content in Nevada sand has increased the volumetric contractive characteristic.

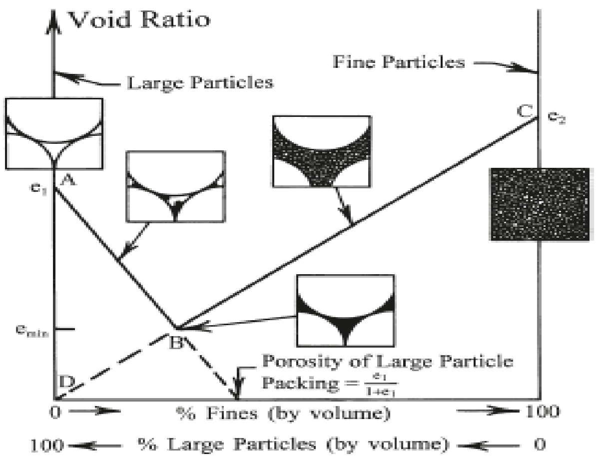

Figure 2: Schematic diagram of fine content threshold value (Lade, 2012)

A few possible reasons could cause such contradiction; one of them is the interpretation of result using different comparison basis. The sole use of density state is inadequate to describe the possible interactions between coarser and finer grains. Thevanayagam *et al* (2002) proposed a conceptual framework (Figure 3) to explain the problem. The introduction of two parameters, intergranular void ratio (e_s) and interfine void ratio (e_f) is believed to be a useful indicator to describe the contact density for sand matrix soils for both low and high percentages of fines. The equations are as follows:

$$e_s = \frac{e+FC}{1-FC} \quad (1)$$

$$e_f = \frac{e}{FC} \quad (2)$$

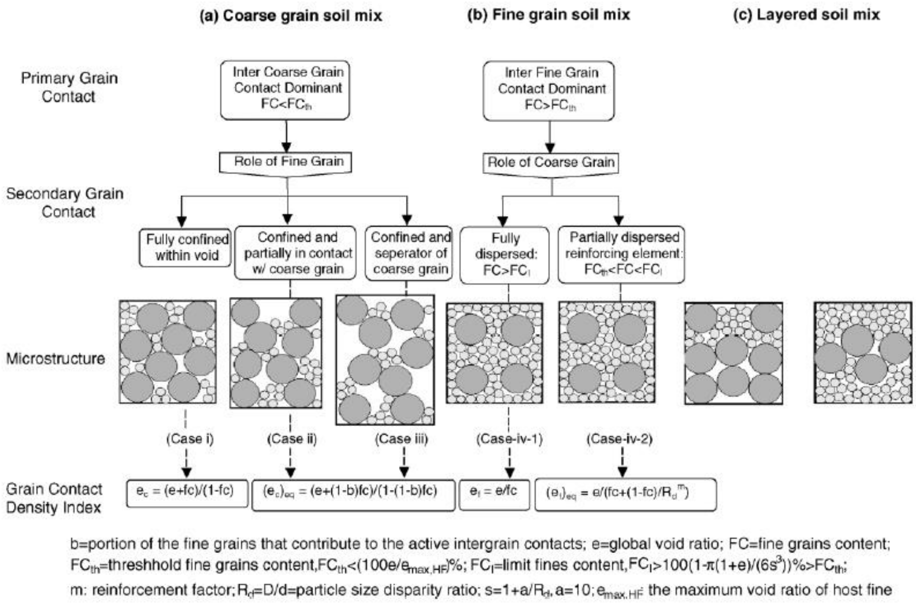

Figure 3: Classification of grain fabric in sand matrix soils (Thevayanagam *et al.*, 2002)

Several researchers have investigated the positive hyperbolic relationship between the threshold fines content towards liquefaction resistance (the undrained shear strength). Most of them have focused only on sand-non-plastic-fines. The experimental results have proven that the concept of threshold fines content is closely related with the undrained shear strength of sand matrix soils. One of them is Polito and Martin (2001) who have used sand-non-plastic-silt mixtures to clarify the effect of non-plastic fines on the liquefaction susceptibility of sands. Their result is shown in Figure 4. However, there are still not many studies in quantifying this conceptual theory by using sand-plastic-fines mixtures conducted. Therefore, the applicability of the threshold fines content for sand-plastic-fines mixtures is still unclear.

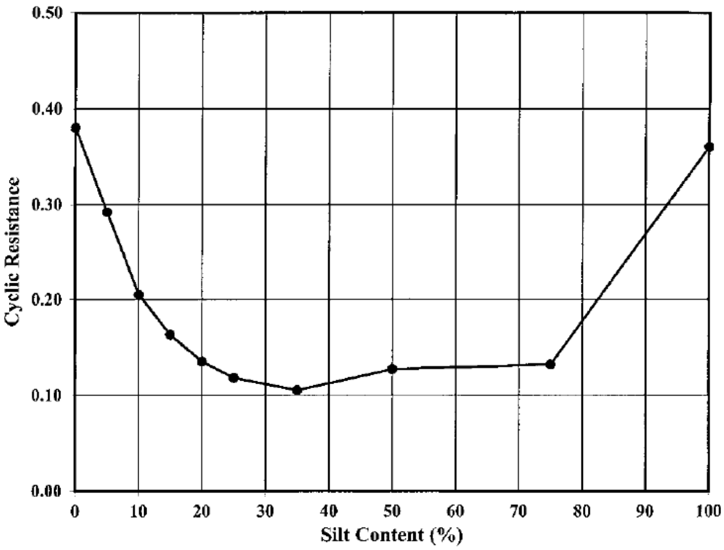

Figure 4: Cyclic resistances of sand-non-plastic-silts (Polito and Martin, 2001)

In lieu of these two, there are two aims in this paper. First is to test whether the concept of threshold fines content also exists for sand-plastic-fines mixtures. Second is to test whether the positive hyperbolic relationship between threshold fines content and liquefaction resistance (undrained shear strength) of sand-plastic-fines mixtures is similar to that in sand-non-plastic-fines mixtures.

2.0 Material Tested

In order to investigate sand-plastic-fines mixtures, two types of soils were used; the parent sand and the plastic fines. The parent sand is uniform graded medium sand with specific gravity 2.63. It was obtained from a river in Johor Bahru, Malaysia. In order to obtain clean sand, it was first rinsed with water to remove impurities before proceeding with the sieve analysis. The fines of white kaolin manufactured by Kaolin (Malaysia) Sdn Bhd were added to parent sand to create sand matrix soils with various fines percentages by weight. White Kaolin has a plastic limit of 38 and liquid limit of 25.

The existence of threshold fines content; at where the fines start to dominate the parent sands and holding the responsibility in soil bearing skeleton was an important parameter in this paper. In order to characterise this value for sand-plastic-fines mixtures particle, density tests were carried out using different fines fraction added into parent sand. Specimens with seven different fines content were used in this paper. The compositional characteristic of all specimens are summarised in Table 2. The techniques used to determine minimum and maximum void ratios followed the techniques recommended by Yamamuro and Lade (1997). The minimum and maximum void ratios of all sand matrix soils specimen are shown in Figures 5a and 5b. The noticeable value of threshold fines content is at 25% of kaolin by weight. This is however dissimilar to that calculated using the parameters introduced by Thevanayagam *et al* (2002), in which the threshold occurred when 40% of kaolin by weight was to be added into parent sand.

Table 2: Compositional characteristic of sand-kaolin mixtures

Weight percentages		Density		Type of void ratio			
Sand	kaolin	Minimum	Maximum	Minimum	Maximum	Intergranular	Interfine
100	0	1.37	1.59	0.92	0.65	0.78	-
90	10	1.41	1.70	0.87	0.55	0.90	7.09
85	15	1.43	1.76	0.84	0.49	0.96	4.44
80	20	1.45	1.80	0.81	0.46	1.05	3.19
75	25	1.47	1.87	0.79	0.41	1.13	2.40
70	30	1.39	1.76	0.89	0.49	1.42	2.31
60	40	1.28	1.63	1.05	0.61	2.92	2.08

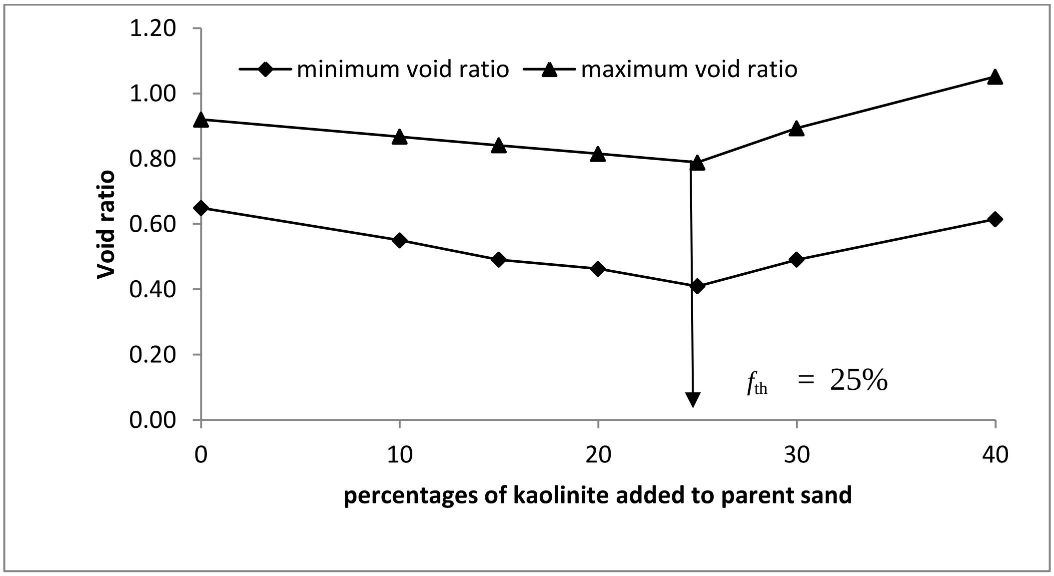

Figure 5a: Threshold fines content obtained experimentally

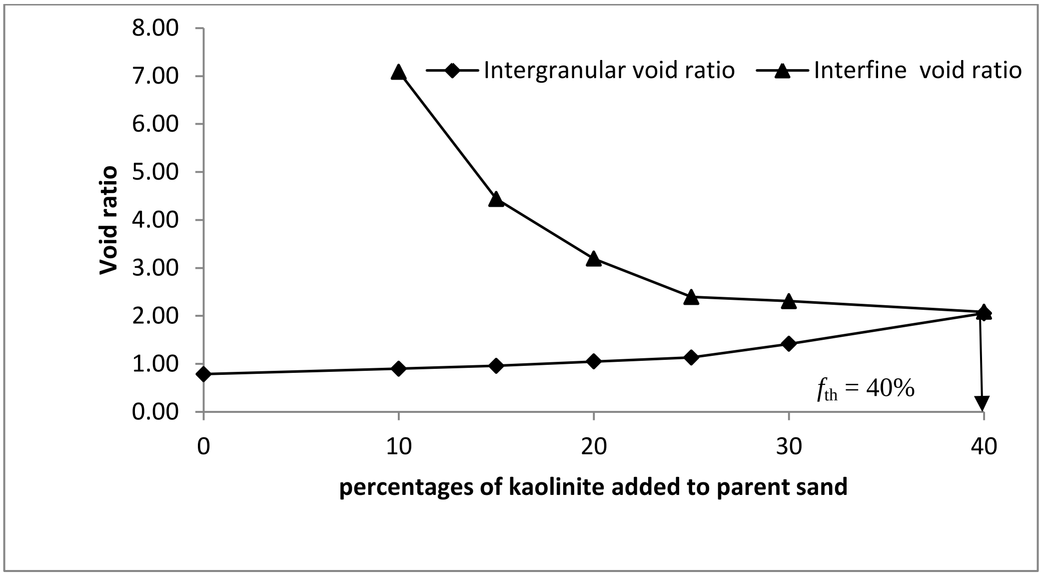

Figure 5b: Threshold fines content obtained by computation

3.0 Experimental Procedure

In order to investigate whether the existence of threshold fines content would influence the undrained shear strength of sand-plastic-fines mixtures, monotonic undrained triaxial compression tests were conducted on sand with various percentages of fines by weight. The testing is in accordance with the BS1377:1990. The specimens' diameter and height were 50mm and 100mm respectively. All specimens were produced by the dry pluviation method to achieve 50% of relative density.

Prior to saturation process, de-aired water was flushed through the specimens from the bottom drainage line until an amount equal to the void volume specimen was collected from the upper drainage line. This process enables a minimum B-value of 0.96 to be obtained. After the saturation process was completed, the specimens were isotropically consolidated to the desired confining pressure prior to shearing. For each set of sand matrix soil specimen, an initial effective pressure of 50kPa was subjected to the specimen.

4.0 Result and Discussion of Monotonic Undrained Compression Test

A series of undrained triaxial monotonic loading tests were carried out to test whether the positive hyperbolic relationship between threshold fines content and liquefaction resistance (undrained shear strength) of sand-plastic-fines mixtures is similar to that found in sand-non-plastic-fines mixtures. The reconstituted samples were continually sheared even after they reached their peak deviator and the tests would be terminated when it reached to 25% of axial strain. Generally, the specimens reach its peak deviator stress at the ranges of between 16.3% and 23.4% of its axial strain. The 25% of kaolin added into the specimens caused the specimens not only to reach its peak deviator stress the soonest but also accommodated with the lowest peak deviator stress. The results of undrained triaxial monotonic loading tests were summarised by plotting undrained shear strength versus axial strain as shown in Figure 6. The undrained shear strength is half of the peak deviator stress of the tested specimens.

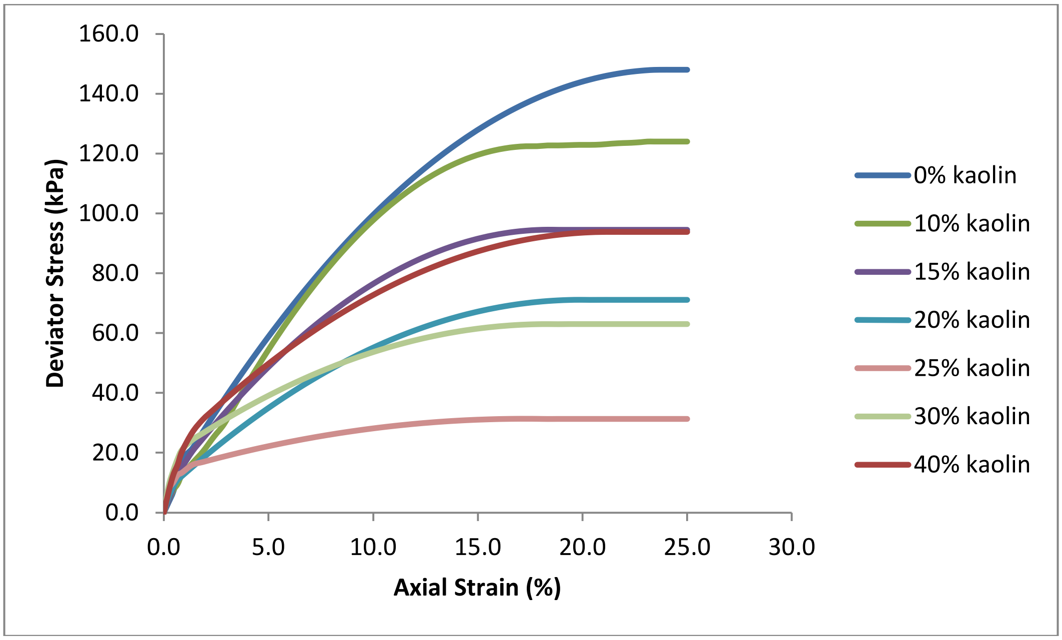

Figure 6: Peak deviator stress of sand-kaolin mixtures

Figure 7 shows the undrained shear strength of each specimen with varied weight percentages of kaolin being added. Based on Figure 7, it can be seen that the undrained shear strength of the sand-plastic-fines mixtures decreases when the percentage of added plastic fines is low. The trend is totally in reverse behaviour when the plastic fines percentage added has exceeded the critical value. The lowest undrained shear strength has occurred when 25% of kaolin fines have been added to the parent sand. This particular percentage of fines is corresponds to the threshold fines content of sand-kaolin mixtures. In addition, it is worth to highlight that this plotted curve also shows an exact similarity to the maximum and minimum void ratio curve (Figure 3), which translate into having a positive hyperbolic relationship. Therefore, the earlier hypothesis stating that there is a positive hyperbolic relationship between threshold fines content and liquefaction resistance between the sand and the kaolin mixtures can be accepted. This finding is similar to the observation on the sand-non-plastic mixtures carried out by Xenaki and Athanasopoulos (2003). Hence, the concept of threshold fines content (as already mentioned in introduction part) is not only applicable to sand-non-plastic-fines mixtures but is appropriate in explaining the behaviour of sand-plastic-fines mixtures as well.

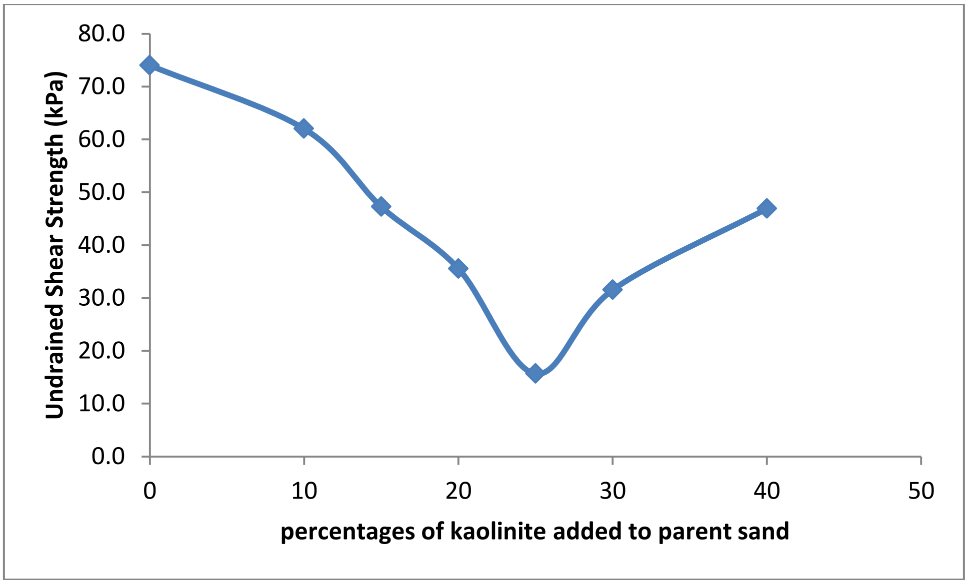

Figure 7: Undrained shear strength of sand-kaolin mixture

However, the concept of threshold fines content is not yet applied in evaluating the initiation of liquefaction among the industries. One of the classical examples to illustrate this is the most universally used design chart introduced by Seed and Idriss (1971), as shown in Figure 8. Although several modification and refinement have been made, the evaluation chart is still based on the concept which shows that higher values of cyclic stress ratio is required to trigger liquefaction for higher fines percentages at a given value of Standard Penetration Resistance. This is therefore needs to be reviewed in the future.

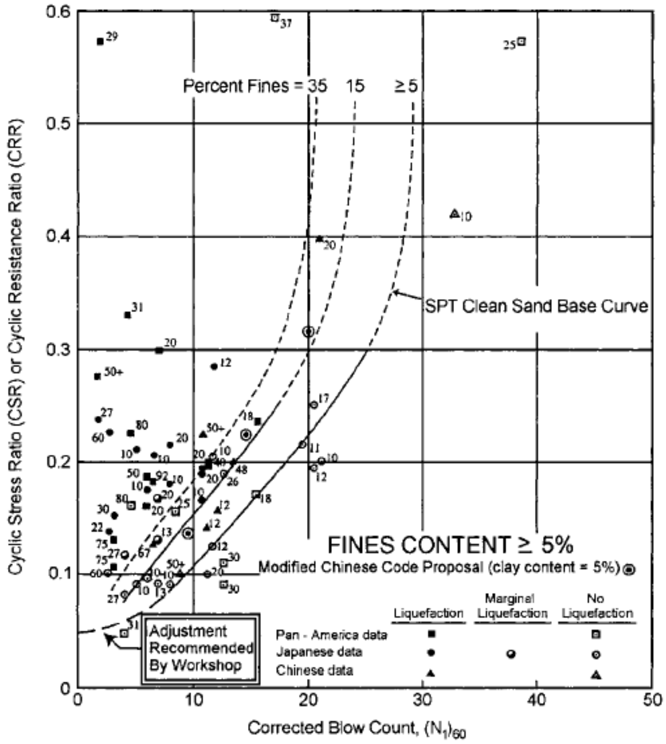

Figure 8: SPT clean-sand base curves with various fines content (Youd *et al.*, 2001)

5.0 Conclusion

Based on the experimental results, the following conclusions are achieved:

1. The concept of threshold fines content for sand-kaolin mixtures is 25% kaolin by weight. This makes a positive hyperbolic curve.
2. There is a positive hyperbolic relationship between fines content and liquefaction resistance (in term of undrained shear strength) of sand-kaolin mixtures.
3. The concept of threshold fines content has been proven to be a corresponding factor for the undrained shear strength for both of sand-non-plastic-fines mixtures and sand-plastic-fines mixtures.

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