Investigation of the Effect of Fine-Grained and Its Plastic Properties on Liquefaction Resistance of Sand

S. A. Naeini, M. Mortezaee

***Abstract*—**The purpose of this paper is to investigate the effect of fine grain content in soil and its plastic properties on soil liquefaction potential. For this purpose, the conditions for considering the fine grains effect and percentage of plastic fine on the liquefaction resistance of saturated sand presented by researchers has been investigated. Then, some comprehensive results of all the issues raised by some researchers are stated. From these investigations it was observed that by increasing the percentage of cohesive fine grains in the sandy soil (up to 20%), the maximum shear strength decreases and by adding more fine- grained percentage, the maximum shear strength of the resulting soil increases but never reaches the amount of clean sand.

***Keywords*—**Fine-grained, liquefaction, plasticity, shear strength, sand.

I. Introduction

THE ground rupture is one of the main reasons for collapses during an earthquake. The ground rupture may occur due to cracks and gaps, abnormal or uneven ground movements, or strength loss. Increasing the pore water pressure in sandy soils may cause the strength loss of ground. This phenomenon, which may occur in loss, saturated sands, is called liquefaction. With the increase in pore water pressure, it may reduce the shear strength and discard the soil resistance completely [1]. Liquefaction is one of the most destructive events in which the assessment of its risks is recognized in each region, based on the liquefaction potential. After the 1964 Nigata earthquake in Japan, extensive research began on the liquefaction of clean sand, and it was thought that liquefaction occurred merely in clean sand, and the increase in fine grains increased the resistance of soil to liquefaction. Subsequent studies on fine-grained sandy soils [1]-[5] indicated that although conflicting results were obtained in some cases, reports show in most cases that the increase in fine-grained soil can raise liquefaction potential. Extensive studies are being conducted on fine-grained sandy soils to determine the effect of various parameters on undrainage behavior and the liquefaction of these soils. Georgiannou et al [2] also Shelly and Perez [3] examine the effect of different parameters on undrained clayey soil.

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II. Conditions for Considering the Fine-Grained Effect in Soil

In order to consider the fine-grained effect in soil, a series of boundary conditions must be controlled, and if they are correct, the fine-grained effect in the soil can be considered. Many researchers studied the boundary criteria for detecting the liquefaction potential of soils that have significant amounts of fine particles, and here some of these are introduced and compared with each other, and the conclusions are expressed.

Cassagrande presented one boundary criterion according to the particle size and the amount of plastic limit. Of course, he noted that it is impossible to use this boundary criterion (fine grain soil and LL[1] < 35) as an absolute standard and suitable criterion to investigate liquefaction [4].

For the first time, a severe assessment liquefaction potential in fine-grained soils was made based on information from sites where liquefaction had taken place. Accordingly, in 1979, Wang set the criterion for earthquakes in China, where liquefaction occurred subsequently. This method indicates that each fine-grain soil with following conditions has the liquefaction potential [5]: 1) The percentage of particles smaller than 0.005 mm or equal to 15%. 2) LL ≤ %35, 3) Wc[2] ≤ 0.9LL and 4) LI[3] ≤ 0.75

Youd called the Chinese standard a good prediction tool and concluded that the soils with LL < 35 and PI[4] < 7 (under A-line) are subjected to liquefaction [6]. Seed and Edris [8] proved that the soils with LL < 37, PI < 12 are susceptible to liquefaction, and soils with 25 < LL < 35 and 7 < PI < 10, should be tested using Sancio method [7].

With laboratory tests and the comparison of results with liquefaction soil criterion, Bray and Sancio [9] found out that the Chinese criterion could not be used as a suitable criterion for analyzing liquefaction in these soils because it could not indicate the conditions of fine-grained soil well. Also, the Chinese criterion for various earthquakes, such as the Turkish Kocaeli earthquake, could not provide the correct answer, and many lands that were recognized as low liquefaction potential sites according to the Chinese criterion, were subjected to liquefaction. On the other hand, a study of the Casagrande plastic diagram and its comparison with the Wang scale shows that he did not mention to the low ML liquid limit [9].

III. Comparison of Some Criteria

While various boundary criteria were presented to

[1] Liquid Limit
[2] Water Content
[3] Liquidity Index
[4] Plasticity Index

determine the liquefaction potential of fine-grained soils, most designers still use the Chinese criterion. However, as mentioned, this criterion considers fine-grained soils as not susceptible to liquefaction, while they are among the most susceptible to liquefaction. In the following section, a brief comparison is made between the Casagrande criterion with Wang criterion as well as Bray and Sancio criterion with Wang criterion.

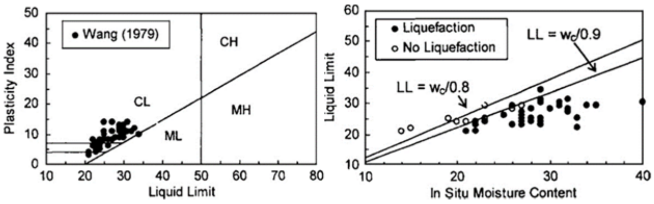
A. Comparison of Cassagrande and Wang Boundary Criteria

Wang's study [5] suggests that in order to detect the liquefaction potential for fine-grained soil, the location of that soil in the Cassagrande chart must first be determined. On the other hand, it is necessary to control the C index, which is a clayey soil parameter. For example, Fig. 1 shows the Wang study [5] and indicates that the ranges, which were subjected to liquefaction, follow a specific criterion, and this criterion is included in Fig. 1 (b). Since the stated standards by Wang [5] were all based on information from Chinese sites, this standard was known as the Chinese standard. Nevertheless, as mentioned above, the Chinese boundary criterion failed to show acceptable results in various earthquakes. For example, some Wang specimens had LL > 35 but showed susceptible to liquefaction behavior during laboratory tests. However, the condition W_c/LL showed more acceptable results, so that soils with (W_c/LL) < 0.85, were recognized as the susceptible to liquefaction soil with significant deformations [9].

B. Comparison between Bray and Sancio (2006) Boundary Criterion with Wang Criterion (Chinese Criterion) (1979)

Most of the soils studied in Wang's study [5] (Chinese criterion) met the standard had less than 15% clay content. Therefore, this criterion is not appropriate for soils with higher clay content. In 2006, Barry and Sankiw [9] achieved a new standard using laboratory tests based on the locations of earthquakes in several areas that liquefied despite compliance with Chinese standards. This criterion indicates that the liquefaction potential in unusual in fine grain soils with (Wc/LL) < 0.80 and instead, a group of soils with higher (Wc/LL) ratios (e.g., > 1.0) and low plastic index, would have the highest liquefaction potential. According to this theory, the PI criterion is an excellent way to express the liquefaction potential, but this criterion should not be considered an absolute index. We should expect a rapid change in fine-grain soil behavior for the plastic index in 11 to 13 range (e.g., more or less than 12). On the other hand, some soils, even with PI < 12, may not be susceptible to liquefaction because other factors are essential in liquefaction detection. For example, we can mention the minerals in the soil, porosity ratio, pre-consolidation ratio, age. In such cases, engineering judgment, along with laboratory tests, can be the criterion for decision making [9].

A comparison of these two criteria related to a project (new terminal of Lamerd Airport, Fars Province) was presented in Fig. 2 [10].



(a) (b)

Fig. 1 (a) Cassagrande Chart of fine grained soils studied Wang 1979, (b) Chinese fine-grained soil liquefaction criteria, based on the earthquake occurred in China [9]

	Bore number	Depth (m)														
		0-2			2-4			4-6			6-8			8-10		
		Soil type	Chinese criterion	Bray and Sancio criterion	Soil type	Chinese criterion	Bray and Sancio criterion	Soil type	Chinese criterion	Bray and Sancio criterion	Soil type	Chinese criterion	Bray and Sancio criterion	Soil type	Chinese criterion	Bray and Sancio criterion
Soil type	1	CL	NS**	NS	CL	NS	MS	CL	NS	NS	CL-ML	S*	S	CL-ML	NS	S
	2	CL	NS	NS	CL	NS	MS	CL-ML	NS	S	CL-ML	NS	S	CL-ML	NS	S
	3	CL-ML	NS	MS***	ML	NS	MS	ML	NS	NS	CL-ML	NS	S	CL-ML	S	MS
	4	CL	NS	NS	ML	NS	MS	ML	NS	NS	CL-ML	NS	S	CL-ML	NS	S
	5	ML	NS	NS	ML	NS	NS	ML	NS	MS	CL-ML	NS	S	CL-ML	NS	S

	Bore number	Depth (m)														
		10-12			12-14			14-16			16-18			18-20		
		Soil type	Chinese criterion	Bray and Sancio criterion	Soil type	Chinese criterion	Bray and Sancio criterion	Soil type	Chinese criterion	Bray and Sancio criterion	Soil type	Chinese criterion	Bray and Sancio criterion	Soil type	Chinese criterion	Bray and Sancio criterion
Soil type	1	CL-ML	S	S	CL-ML	S	S	CL-ML	NS	MS	CL-ML	S	S	CL-ML	NS	S
	2	ML	S	S	ML	S	S	CL-ML	S	S	CL-ML	NS	NS	CL-ML	NS	NS
	3	CL-ML	NS	S	CL-ML	NS	S	CL-ML	NS	MS	CL-ML	NS	S	CL-ML	NS	S
	4	CL-ML	NS	MS	CL-ML	NS	S	CL-ML	NS	S	CL-ML	NS	MS	CL-ML	NS	S
	5	CL-ML	S	S	CL-ML	S	S	CL-ML	S	S	CL-ML	NS	S	CL-ML	NS	MS

*S=Susceptible (For Liquefaction) **NS=Not Susceptible *** MS=Moderately Susceptible

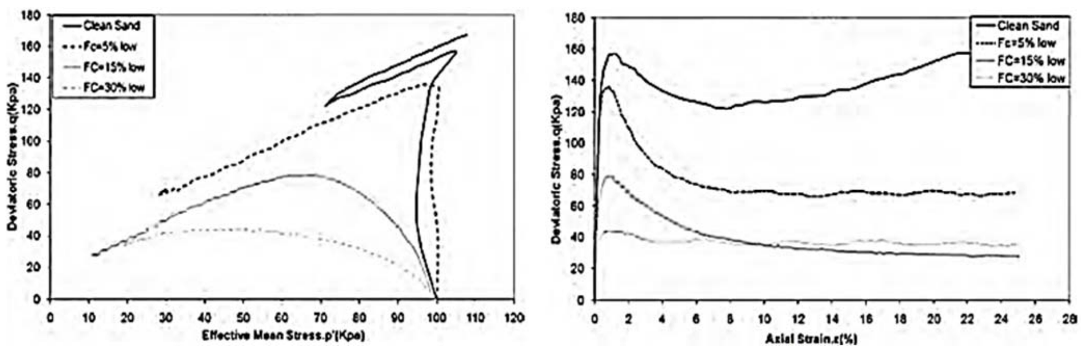
Fig. 2 Comparison between Bray and Sancio (2006) boundary criterion with Chinese criteria (Case Study) [10]

IV. Effect of PI and Clay Content on Monotonic Liquefaction Potential

For investigation of the effect of PI and clay content on monotonic liquefaction potential, a series of triaxial compressed undrained monotonic centrifugal experiments were performed on 161 standard sand with a fine grain percentage of 0 to 30%, for which two types of clay with different plasticity were used to investigate the effect of the plastic index on undrained behavior and sandy clay liquefaction [11]. Samples were made in two specific dry weights of 1.45 and 1.5 kg/cm^3, and two 100 and 400 kPa consolidation pressures were used to consolidate the samples. The wet compaction method was used for making samples. Analysis of the results shows the effect of clay percentage and plasticity on undrained behavior and liquefaction. After conducting the above experiments, the researcher concluded that with a slight increase in the percentage of clay, the sample had only shrinkage behavior and showed no tendency to dilatation behavior. The sample shows extensive dilatation behavior after the initial shrinkage behavior in clean sand and sand with high fine grains. It was also observed that the critical state line in the p'- e space moves downwards with increasing clay content. The following are the effects of various factors on soil behavior, which are:

A. Effect of Increasing the Clay Content on Undrained Behavior of Clayey Sand

In order to investigate the effect of clay content on undrained sand behavior containing fine grains, the results for samples with 0, 5%, 15% and 30% fine grains with low plasticity, confining pressure of 400 kPa and the initial density of 1.45 gr/cm^3 are shown in Figs. 3 (a) and (b). As can be seen, the clean sand specimen experiences semi-stable behavior, and the deviation stress increases again after a temporary drop and after peak state. With a slight increase in clay content of up to 5%, the behavior generally changes and the deviation stress does not increase after the initial peak, and only the softening behavior with strain is shown. As the percentage of clay increases further, the amount of drop decreases after peak and in the sample containing 30% clay, the slight semi-stable behavior is visible. As can be seen, the semi-stable state% is much more noticeable in the sample with 30% clay content. Fig. 3 (b) shows the stress path of these samples. The stress path of the clean sand sample shows that the sample indicates extensive dilatation behavior after the initial contraction behavior, which is due to the negative pore water pressure. As a result, the effective stress increases in the sample and the sample strength increases after the initial instability. With a small increase in grain size, the sample shows shrinkage behavior and does not have any tendency for dilatation. Deviation stress decreases after peak point, and since the sample cannot have constant deviation stress, the unstable state occurred. As the fine increases further, the sample continues to show only shrinkage behavior, but the sample's instability decreases. As in the sample with 30% clay, the sample tolerates very little instability.

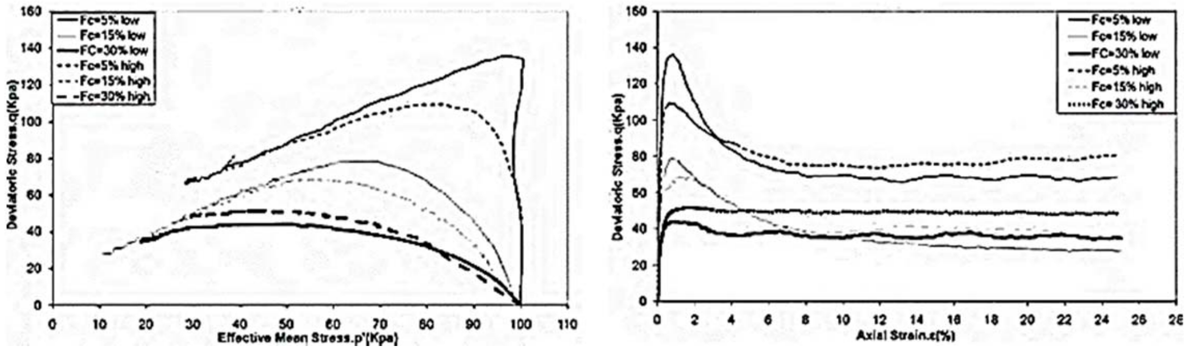


(b) (a)

Fig. 3 Effect of clay content enhancement on undrained behavior of clayey sand (a) stress-strain curve, (b) stress path [11]

B. Effect of Plasticity on Undrained Behavior of Clayey Sand

Fig. 4 shows strain-stress curve and the stress path of the specimens with 5%, 15%, 15%, 30% clay contents, in two groups with the same consolidation stress of 100 kPa and the same specific initial gravity of 1.5 g/cm^3 in clay with different PI index. According to this diagram, it can be seen that in low clay content, the sample with high PI has less peak deviation stress than the sample with low PI. This difference in peak deviation stress is small between two clay samples with different PI, and in some groups, this difference is very slight. The sample stress path with 5% clay content indicates that the reduction of effective stress is lower in the sample with high PI and shows shallow dilatation behavior in high strains. Therefore, the sample containing clay with high PI tolerates less instability and is more resistant to liquefaction and instability. With the increase in clay content, the difference in peak deviation stress between the two samples with different PIs decreases, and in the clay percentage, 30% of the samples with high PI tolerate the more peak deviation stress. In all clay contents, the drop in deviation stress is always lower in the high PI sample and is less stable than in the low PI sample. In the 30% of clay content, the sample with high PI was not subjected to any instability, while the sample with low PI tolerated little instability.



(b) (a)

Fig. 4 Effect of plasticity on undrained behavior of clayey sand: (a) stress-strain curve, (b) stress path [11]

Fig. 5 shows the results experiments by Chung et al. [12] to investigate the effect of fine-with low plasticity index (PI = 5) on the sand liquefaction potential. The figure shows that at a constant porosity ratio, with a fine grain increase of up to 10%, the soil strength to liquefaction decreases slightly and increases.

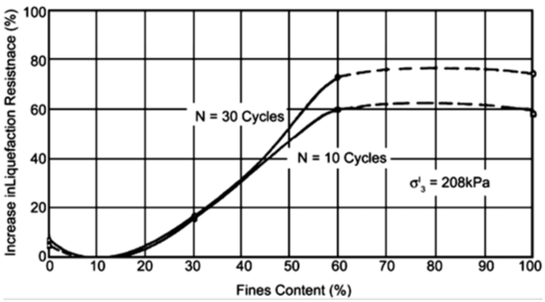


Fig. 5 Effect of low plasticity fine grains on sand liquefaction resistance [12]

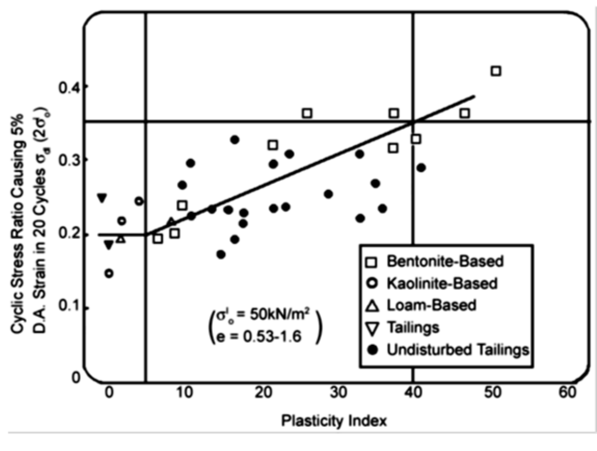


Fig. 6 Increased liquefaction resistance with increasing plasticity index [13]

C. *Effect of Plastic Fine Grains*

Ishihara and Koseki [13] conclude that there is no clear link between the clay content and the soil strength to liquefaction (Fig. 6). Nevertheless, Perla et al. [14] performed a simple tri-axial cyclic torsion test on samples with a constant porosity ratio and found that the clay content in the soil was more critical than its plasticity. Das et al. [15] found in experiments on silt and clay specimens that with increasing plasticity, the soil strength to liquefaction increases. Liang and Bai [16] also examined changes in the resistance of liquefaction by adding clay to fine sand and silt. They found that increasing the amount of clay by 9% reduced the resistance to liquefaction, and then it is increased. Clay plasticity was not included in this study.

1) Effect of Clay Percentage on the Cyclic Behavior of Sands

To determine the effect of plastic fine-grained percentage on sand cyclic behavior, Ghahremani et al. [17], by adding different amounts of clay by weight to Firoozkooh sand and applying cyclic load to it, examined the changes in soil liquefaction resistance.

Fig. 7 shows a diagram of the change in soil strength to liquefaction through different clay content for a cyclic stress ratio equal to 15 loading cycles (earthquake with magnitude M = 7.5). As can be seen, with increasing the percentage of clay to %30, the soil strength to liquefaction decreases, but after 30%, the soil strength to liquefaction begins to increase. According to Tuana Yagam's proposed model, it can be concluded that with the increase of clay up to 16%, most of the clay particles are in the space between the grains of sand and less part between the sand grains. As the clay content increases to 30%, clay particles, in addition to filling the space between the grains of sand, also cause the grains of sand to separate from each other. In this case, the behavior of the sample is controlled by clay. As the clay content rises to 30%, the soil strength to liquefaction also begins to increase. The exact amount of fine grain limit requires more testing in the range of 25 to 30% clay. Fig. 8 shows the latter process. This figure shows the porosity ratio of the sand grains and the porosity ratio between the clay particles as can be seen, with the fine-grain escalation, the porosity ratio between sand grains increases in quantities less than the limit value. In other words, most of the fine-grained particles only fill the space between the sand grains without any role in the load-bearing capacity, and the smaller part is placed between the sand grains. So the soil is loosened, and soil strength to liquefaction of the sample is reduced. However, in amounts more significant than the limit, clay particles completely "encompass" the sand grains and prevent them from contacting each other. In this case, the clay particles control the soil behavior, and as the amount of fine grains increases, the porosity ratio between the clay particles also decreases. That leads to an increase in liquefaction resistance.

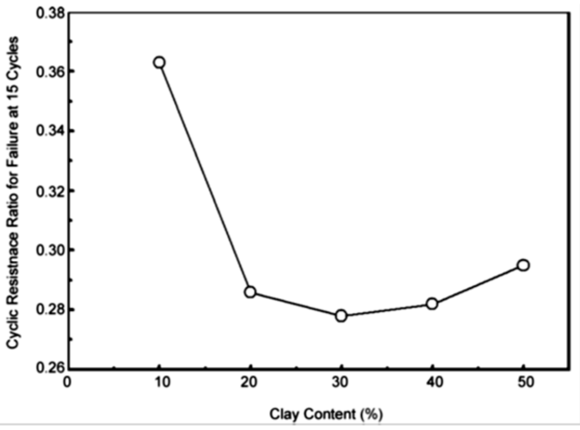


Fig. 7 Change the equivalent periodic resistance for an earthquake with a magnitude of 7.5 in terms of clay percentage [17]

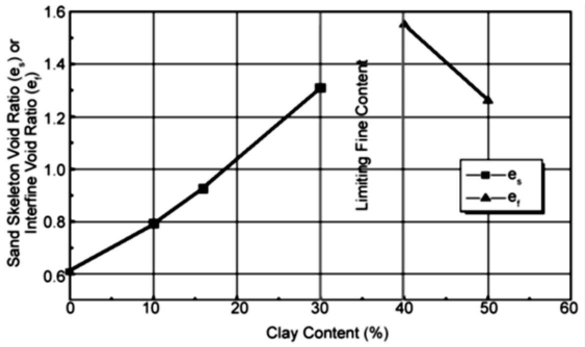


Fig. 8 Changes in Porosity ratio between sand grains and porosity ratio between clay grains based on clay content [17]

V. CONCLUSION

- A comparison of the criteria in the first section and the relevant tables suggests that silts and low-plasticity clays may be susceptible to liquefaction if they become loose and saturated.
- The high PI soils are more resistant to liquefaction than the low PI soils.
- With the increase in clay content, the peak deviation stress decreases, but after the %20 of clay content, the decline rate of the peak deviation stress is reduced.
- As the plasticity of the clay particles increases, an increase in soil liquefaction resistance is observed.
- To investigate the effect of plastic fine grains on the soil strength to liquefaction of sands, two separate phenomena must be considered:

a) The fine particles in the sand can cause a change in the tendency of the soil to dilatation and shrinkage due to shear stress. It results in an increase in water pore pressure and, therefore, liquefaction resistance.

b) Due to the cohesive nature, clay in the sample can transfer some of this cohesion to the surrounding sand grains and increase the resistance to liquefaction.

Cohesion will be more effective in cases where the fine-grained clay has excellent plasticity. For this, it is concluded according to both (a) and (b) in above cases that two factors affect the liquefaction, and in fact, their interaction determines the increase or decrease of the soil strength to liquefaction of the sand.

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