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Effects of Plasticity and Fine Percentage on the Unstable Behaviors of Clayey Sands

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ABSTRACT: This paper covers the results of a comprehensive study on the unstable behaviors of clayey sands with special attention to the comparison of the fine content and its plasticity effects. Tri-axial tests were conducted by applying two different densities and confining pressures on sands mixed with 0% to 15% of low and high-plasticity clayey materials. The results showed that for some combinations of sand and clay, with only a 5% increase in high plasticity clays, the peak deviatoric strength decreased by about 31% compared to the original value, while this amount was about 18%, using low plasticity clays. The initial increase in clay content made a considerable loss in the steady-state strength values, while the reduction was less significant for a greater increase in the clay content. Adding only 5% of low plasticity clay has reduced the steady-state strength to about 60% compared to its initial value, while the continued increase in the percentage of clay up to 15% has sometimes caused the steady-state strength to increase again. The initial increase in the clay content significantly changed the clean sand structure to groups of clay and sandy particles with unstable connectors. Greater clay content increase gradually made these unstable structures steadier due to the increase in plasticity and therefore cohesion between particles. At low percentages of clay content, it is the fines content that dominates the type of behavior, while as the clay content increases the role of the plasticity of fines gradually becomes more crucial.

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1- Introduction

Different investigations have proposed that when subjected to undrained earthquake loading, loose saturated sands may exhibit strain-softening behaviors followed by a continual steady state [1-5]. The full strain-softening behavior described above is now recognized as flow liquefaction, which may produce the most devastating effects among all the liquefaction-related phenomena.

Ketabi *et al.* [6] indicate that the pore pressure generation and liquefaction resistance of sand are influenced by the relative densities and the type of irregular loadings. Also with the increasing duration of the records in the same PGA, the vibration waveform have more liquefaction potential than the shock waveform. Some researchers have examined the performance of building foundations against earthquakes. In 2022, for example, Zhang *et al.* [7] examined the effect of liquefaction and behavioral differences on piles and group piles.

Sladen [8] assumed the focus of peak points in the effective stress paths on a straight line, i.e., the collapse line, which passes through steady-state points (Fig. 1a). Also, some researchers, e.g., Vaid and Chern [9] and Lade [10] proposed a similar concept, i.e., the flow liquefaction line, whose end passes through the origin rather than the steady state points, as schematically shown in Fig. 1(b). Other researchers further discussed these instability lines; for example, Yang [11] defined a dependency of the flow liquefaction line slope upon a state parameter, while Been and Jefferies [12] offered an alternative interpretation that used the state parameter at peak strength rather than the initial state parameter used in Yang's proposal.

Using the concept of these instability lines, it would be possible to define an unstable zone between these lines and the steady-state line in the q-p' plane [13]. When the stress state (i.e., the combination of confining pressure and void ratio) is applied to this zone, the soil will become unstable. Instability has been considered one of the failure mechanisms that lead to flow slides or the collapse of granular soil slopes in several case studies [10, 14]. Yamamuro and Covert [15] showed that the stress condition required to initiate liquefaction under cyclic loading corresponded to the instability line established from the monotonic undrained tri-axial compression tests. This zone may therefore be accepted as the critical criterion indicating the potential for unstable and flow failure behaviors. Extensive investigations conducted on the earthquakes of Northridge (1994), Kokaeli (1999), and Chi Chi (1999) showed significant settlements for soils with even more than 15% clay content [16, 17], indicating the probability of unstable behaviors of clayey

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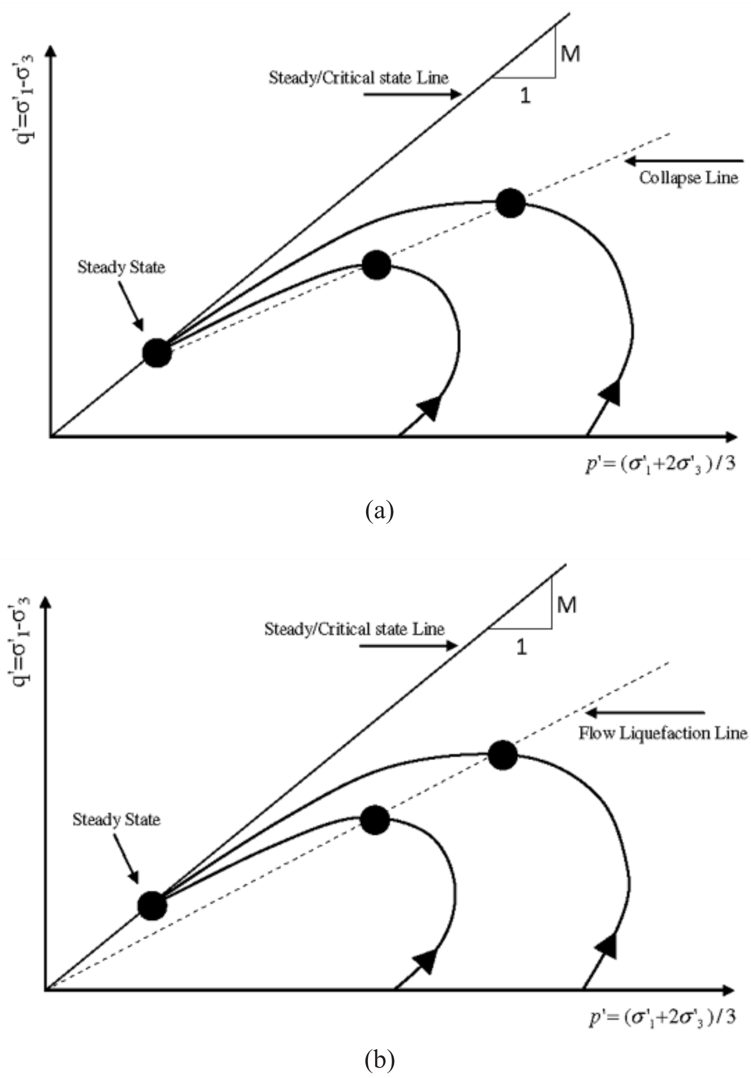


Fig. 1. Schematic diagram of (a) the collapse line concept and (b) the flow liquefaction line concept.

sands in addition to silty sands.

This research has continued in recent years. For example, subedi *et al.* [18] (2022) examined the potential of liquefaction in the Kathmandu Valley of Nepal. This area was selected based on its liquefaction records during the 2015 earthquake. According to research, the texture of the area contained a mixture of sand and silt as well as clay. Taslimian *et al.* [19] (2022) examined the effects of irregular topographic interfaces between porous layers. The results indicate that the irregularly embedded topographies play a role in assessing liquefaction, which can be useful in geotechnical earthquake engineering. Ghani *et al.* [20] investigated the liquefaction potential of fine-grained soil with medium to high plasticity using Artificial Intelligence-Based Hybridized Modeling.

Abedi [21] demonstrated an increasing instability in the sand behavior due to the elevation of clay content up to about 10% followed by a decreasing trend after 20%. However, he did not focus on the effect of the plasticity of the clay itself. Some other researchers have proved that the plasticity of clay has a crucial role in addition to the clay content and it can even be applied as a suitable criterion for assessing the liquefaction potential [22-23]. On the other hand, studies that have compared the effect of fines content and their plasticity report different results; some propose the clay content to be much more influential and others report the opposite findings [24, 25]. By summarizing the results of the previous research, it seems that despite conducting much research on the percentage of clay or on the plasticity of compounds, there is still no comprehensive summary regarding the comparison of the effect of clay percentage with its plasticity. In other words, it is not clear whether the percentage of clay plays a more key role in the behavior of the composites or its plasticity. Due to

Table 1. Sand 161, Toyoura, and Sengenyama sand properties.

Properties	Sand 161	Toyoura sand	Sengenyama sand
Specific gravity (Gs)	2.66	2.65	2.72
Maximum void ratio $(e_{\max})$	0.928	0.977	0.911
Minimum void ratio $(e_{\min})$	0.583	0.597	0.550
$D_{50}(mm)$	0.26	0.17	0.27
$D_{10}(mm)$	0.15	0.15	0.15
% Passing sieve No.200	0	0	2.3
Uniformity coefficient (C_U)	1.80	1.26	1.93
Curvature coefficient (C_C)	1.14	1.02	1.02

Table 2. Low (L) and high (H) plastic clay material properties (passed through No. 200 sieves).

Material	Gs	Liquid Limit (LL %)	Plastic Limit (PL %)	Plasticity Index (PI %)
Mashhad Clay (Low plastic)	2.64	28	17	11
Qazvin Clay (Highly plastic)	2.64	55	25	30

the existence of sand deposits with different percentages of clays with different plasticity, it seems necessary to investigate the liquefaction potential and determine their behavioral characteristics. In this research, an attempt will be made to obtain comprehensive results regarding their liquefaction potential by examining the critical state behavior of clayey sands with different plasticity. The unstable zone, steady-state lines, peak strength, and steady-state strength variations are properly investigated by applying two different densities and two different confining pressures. Using two distinct clayey materials with low and high plasticity properties and also employing microscopic images allowed us to efficiently compare the effect of the fines content and their plasticity on the unstable behaviors of clayey sands.

2- Experimental procedure

2- 1- Tested material

All basic geotechnical tests were performed under the American Standard Test Method (ASTM). In this study, standard crushed silica sand (sand 161) was used, which is similar in properties to known materials such as Toyoura or Sengenyama sands. The characteristics of the aforementioned sands are compared in Table 1.

Clayey material properties (passed through sieve No. 200) are presented in Table 2. High-plastic clayey material was obtained from a site near Gazvin City (latitude 35°46´19´´, longitude 50°3´46´´) while low-plastic clay was acquired from a site near Mashhad City (latitude 37°22´24´´, longitude 58°45´40´´). By mixing these two different clayey materials with sand 161, a proper investigation can be conducted on the effects of plasticity on the specimens' behaviors. The grain size distribution curves of used sand and clayey materials are presented in Fig. 2.

2- 2- Test procedure

The device used for conducting tests was a Japanese tri-axial static apparatus. It features highly sensitive sensors and computer data logging. To conduct tests, the strain-controlled loading approach was adopted by a 0.5 mm/min loading rate. Specimens were prepared using the wet tamping method. In this method, first, sand and clay are mixed homogeneously with the desired percentage. The weight of sand and clay is selected in such a way that the specific dry weight of the mortar in the sample is provided. The resulting mixture is mixed completely homogeneously with 5% moisture and then poured into the mold in 6 different layers and each layer is compacted until it reaches the appropriate height. Since, in the usual case, densification of the upper layers causes densification of the lower layers, based on the modification technique of Ladd (1978) [26], the lower layers are compacted with less density. This causes the lower layers to reach the desired density while the upper layers are compacted, and the sample is finally compacted uniformly in the entire height.

The prepared specimens were 50 mm in diameter and 100 mm in height. It should be noted that all tests were conducted under consolidated undrained conditions (CU). To saturate the specimens, first, carbon dioxide gas was blown through the specimens followed by a slow desired water

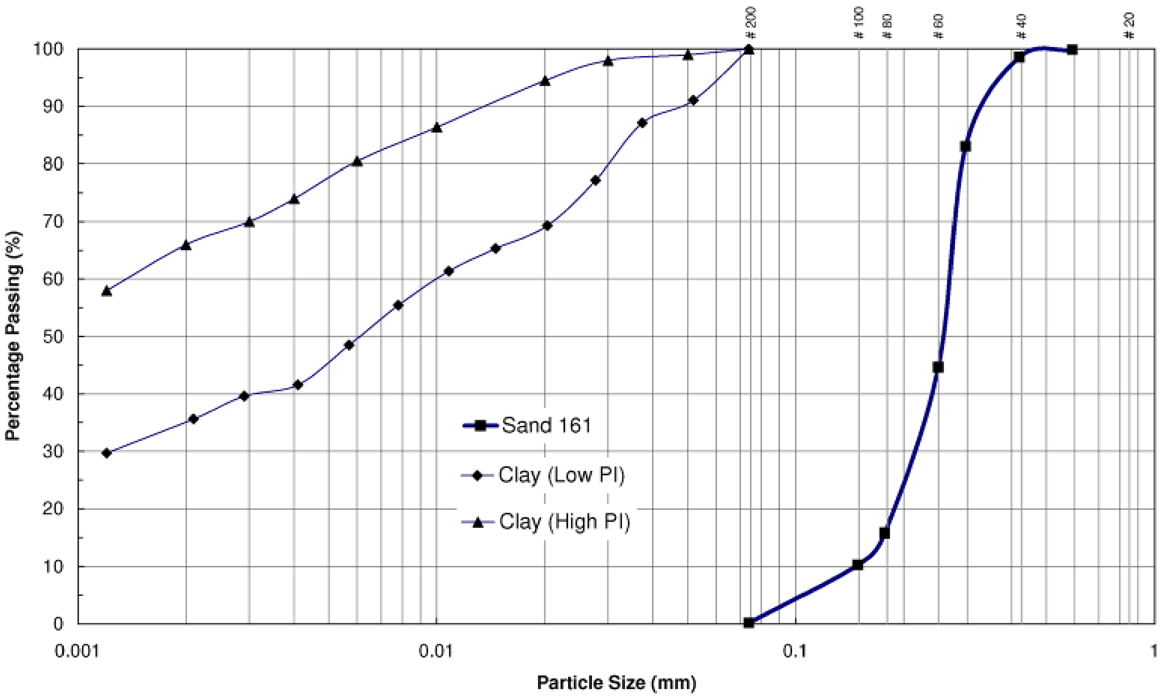


Fig. 2. The grain size analysis (Sand 161, Mashhad clay (Low PI), Gazvin clay (High PI)).

flow. Then, backpressure equal to 40 kPa was applied to reach complete saturation, while "B" values greater or equal to 0.98 were assumed to represent fully saturated conditions. Finally, specimens were consolidated by applying a suitable consolidation pressure and then subjected to shear.

2- 3- Test program

To investigate the fines content, plasticity, density, and confining pressure effects, the initial test conditions were adjusted especially, so it was possible to evaluate a parameter while others were kept constant during a test.

Two different density values, i.e., a) $\gamma_d = 1.45\, gr/cm^3\, (Dr = 27\%)$ and b) $\gamma_d = 1.5\, gr/cm^3\, (Dr = 45\%)$, were used for loose and medium-dense specimens, respectively. During this study, these densities showed two different liquefaction-associated behaviors in clean sand specimens: 1) complete strain-softening which led to a steady state and 2) limited strain-softening which led to a temporarily steady-state (quasi-steady-state).

For both density values, tests were conducted on specimens made of clean sand mixed with 0%, 5%, 10%, and 15% of clayey material for high- and low-plastic clayey materials. Furthermore, to investigate the influence of confining pressure on the test results, all the tests were conducted under two different confining pressures (100 and 400 kPa).

The used materials had virtually the same specific gravity (G_s) values, resulting in constant dry unit weights (γ_d) as well as constant void ratios. The void ratios for $\gamma_d = 1.45\, gr/cm^3$ and $\gamma_d = 1.5\, gr/cm^3$ were 0.828 and 0.767, respectively.

Every group of specimens was named in a sequence of A-B-C letters, where "A" represented the specimen density, "B" denoted the effective confining pressure applied in the test, and "C" indicated the clay type. For a high-plastic clayey material (PI = 30%) "H" and for a low-plastic clayey material (PI=11%) "L" was used as an abbreviation. Wherever it was necessary, the clay content of specimens was directly mentioned. For example, 1.45-400-H represents a specimen that is made by mixing and compacting sand with a suitable percentage of high-plastic clayey materials with a density equal to 1.45 g/cm^3 and consolidating to 400 kPa.

As tabulated in Tables 3 and 4, a total of 64 tests were conducted (considering the repetition of each test for more certainty). This classification of parameters provides an appropriate and independent evaluation of the effect of each parameter.

2- 4- Verification

To validate the results obtained in this research, the results of several experiments have been compared with the results obtained from the research of Shafiee *et al.* (2017) [27]. The reason for choosing the mentioned research was that the sand used and the conditions of the experiments were similar to the conditions of this research. In Fig. 3, the results of the two experiments conducted in this research are compared with the results of Shafiee *et al.* (2017) in similar conditions. It can be seen that there is a very good agreement between the results of the two studies. The figure related to the results of Shafiee

Table 3. The general classification of the tests for various mixtures of sand with low-plastic clay.

Group	Test No.	Combinations	Group	Test No.	Combinations
Group 1: 1.45-100-L	1	Clean sand	Group 3: 1.45-400-L	9	Clean sand
	2	Sand+5%clay		10	Sand+5%clay
	3	Sand+10%clay		11	Sand+10%clay
	4	Sand+15%clay		12	Sand+15%clay
Group 2: 1.5-100-L	5	Clean sand	Group 4: 1.5-400-L	13	Clean sand
	6	Sand+5%clay		14	Sand+5%clay
	7	Sand+10%clay		15	Sand+10%clay
	8	Sand+15%clay		16	Sand+15%clay

Table 4. The general classification of the tests for various mixtures of sand with high-plastic clay.

Group	Test No.	Combinations	Group	Test No.	Combinations
Group 5: 1.45-100-H	17	Clean sand	Group 7: 1.45-400-H	25	Clean sand
	18	Sand+5%clay		26	Sand+5%clay
	19	Sand+10%clay		27	Sand+10%clay
	20	Sand+15%clay		28	Sand+15%clay
Group 6: 1.5-100-H	21	Clean sand	Group 8: 1.5-400-H	29	Clean sand
	22	Sand+5%clay		30	Sand+5%clay
	23	Sand+10%clay		31	Sand+10%clay
	24	Sand+15%clay		32	Sand+15%clay

et al. is directly extracted from the relevant article.

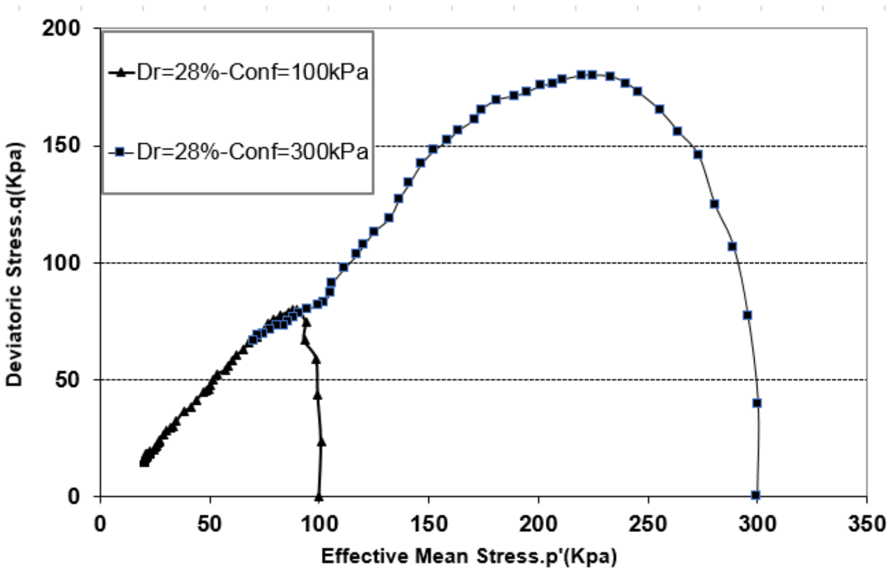
3- Results and Discussion

3- 1- Undrain stress paths

Stress paths for different group combinations, 1.45-100-L, and 1.45-100-H (containing different clay content values), are presented in Fig. 4. The clean sand showed a contractive behavior resulting in a continuous decrease in deviatoric stress after a peak value. An increase in clay content has considerably reduced the peak value similarly for two types of clay (Fig. 4a and 4b). MizanurRahman [28] and Shelley and Mesa [29] reported a similar reduction in peak strength values due to an increase in clay content up to 7%. Derakhshandi [30] observed a decrease in peak strength with a 20% increase in kaolinite clay (PI = 15%), while the trend was reversed for clay content which increased up to 30%. Naeemifar and Yasrobi [31] proved that the reduction of the peak strength value is related to the decrease in the height of the collapse surface in the three dimensional space.

To investigate the effect of the plasticity of clay, Fig. 4a and 4b can be compared. It can be seen that for the same clay content increase, the value of peak deviatoric strength has decreased more in high-plastic clay (Fig. 4b) compared with low-plastic clay mixtures (Fig. 4a).

For example, with only a 5% increase in high plasticity clays, the peak deviatoric strength decreased by about 31% compared to the original value, while this amount of low plasticity clay in similar conditions was about 18%. As the percentage of clay content increases to 15%, the difference in the amount of reduction for different clays decreases. So that the peak deviatoric strength of compounds with 15% of low and high plasticity clays show about 68 and 60%



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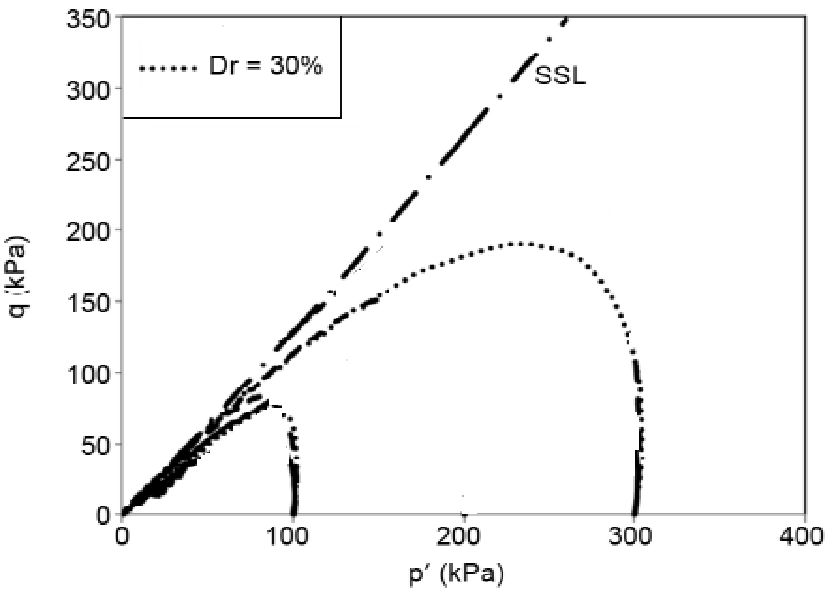
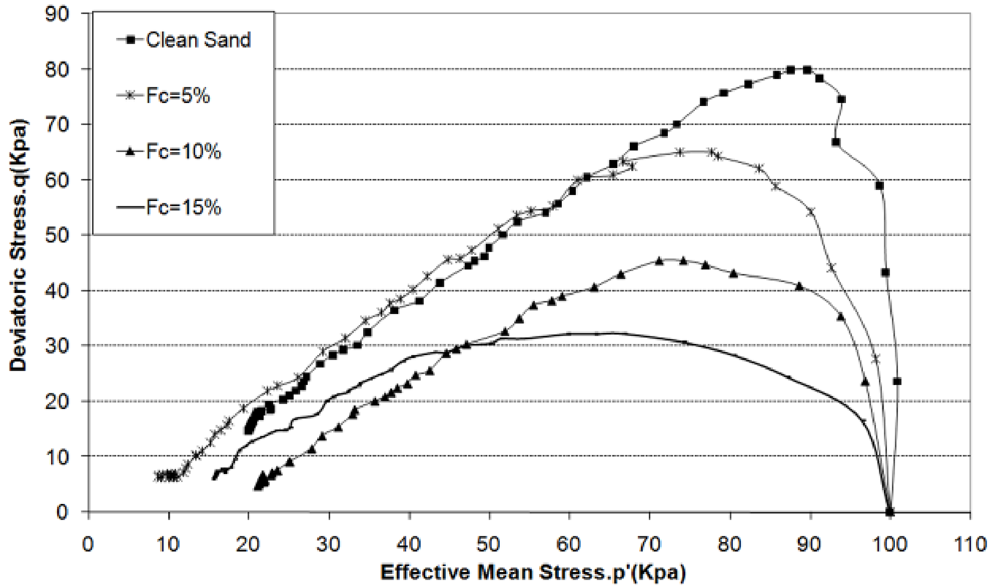


(b)

Fig. 3. Comparing the results of the experiments of this paper with the results of the experiments conducted under similar conditions. a) The results of experiments related to this research. b) The results of the experiments related to the research of Shafiee et al. (2017) [27]



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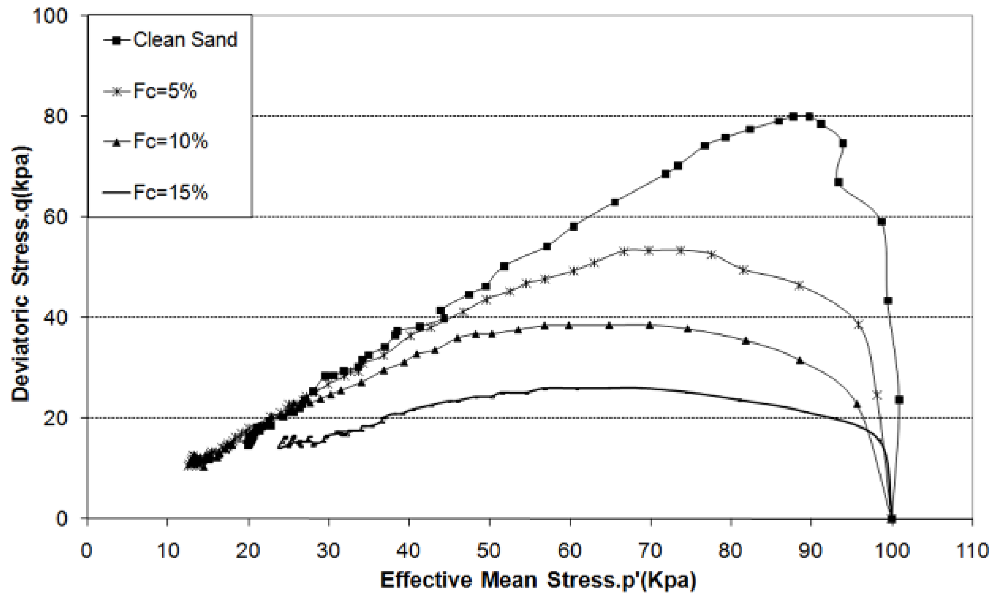


(b)

Fig. 4. Plot of the stress paths for different mixtures of sand and clay. a) 1.45-100-L. b) 1.45-100-H

reduction compared to the initial value, respectively. For better comparison, the stress-strain and pore water pressure variations are presented in Figs. 5 and 6.

Fig. 7 presents the effect of clay content increase for different mixtures of sand with low- (Fig. 7a) and high- (Fig. 7b) plasticity clays. These mixtures belong to groups of 1.5-100-L and 1.5-100-H with dilatant behaviors in clean sand specimens. The results showed a transition from dilatant to contractive behaviors with a small increase in the clay content. Such a transition was reported by Chakrabortty and Nilay [32] and Drakhshandi [30] for increasing the clay content up to 15% and 20%, respectively. Comparing Fig. 7a and 7b, it can be concluded that the trends are similar for both low- and high-plasticity clay mixtures, but the drop in the peak value of deviatoric stress is more significant for mixtures of sand with higher plasticity clays. It can be seen that with only a 5% increase in high plasticity clays, the peak deviatoric strength decreased by about 37% compared to the original value, while this amount of low plasticity clay in similar conditions was only about 17%. As the percentage of clay continues to increase up to 15%, the reduction rate for clays with different plasticity properties becomes closer to each other, so that the peak deviatoric stress for clays with high and low plasticity properties is reduced by ca. 75% and 65%, respectively, compared to the initial value. Similarly, Boulanger and Idriss [22] showed a decline in peak strength with an increase in the plasticity of fines. Previous studies [33] have shown that peak strength variations are associated with the initiation of flow liquefaction or flow deformation, so these results demonstrate that a more unstable structure is created in mixtures with higher clay content, especially for high plasticity clays. It should be noted that these results are valid for clay content increases of less than 15%. For better comparison, the stress strain and pore water pressure variations are presented in Figs. 8 and 9.

3- 2- Instability zone

As it was mentioned, the area between the steady-state line and the instability line can be supposed as an instability zone; therefore, it would be possible to investigate the potential for unstable behaviors under different conditions. Figs. 10a and 10b indicate slope variations of the abovementioned lines where:

M: Slope of the steady-state line in the q-p' plane

M_L: Slope of the collapse line in the q-p' plane

It is clear that the area between the lines of M and M_L variations presents the unstable zone in Fig. 10, while Fig. 11 presents the distance between these lines in a differential form for better understanding. According to Fig. 10 (a & b) and 11, it can be observed that an initial increase in the clay content makes the instability zone considerably larger and more significant for high-plasticity clays. From Fig. 11, it can be seen that the maximum instability occurs in clay percentages of about 5 and 8 for low- and high-plastic clays, respectively, while the largest unstable zone occurs on a wider range of clay content for sand mixtures with high-plasticity clays compared with low-plasticity clays.

Microscopic images were used to interpret the mentioned results. These images (Figs. 12a and 12b) indicate that adding clay particles causes some sandy particles to stick together, forming an unstable structure consisting of groups of particles and large void spaces between them. In this structure, some particles act as unsteady connectors between the mentioned particle groups. When the load is applied, these structures fail and collapse into the existing voids, resulting in a dramatic reduction in the stress value required to initiate the collapse (peak deviatoric stress). Higher clay plasticity will intensify these unstable structures, leading to more reduction in the peak deviatoric stress and a higher potential for unstable behaviors. It is of great importance to note that the abovementioned results are valid only for low clay content increases. According to Figs. 10 and 11, greater clay content increase making the unstable zone smaller. It seems that in mixtures of sand with higher clay contents, the plasticity of mixtures leads to a considerable cohesion between particles, forming more stable structures and preventing sudden failures. Therefore, it may be predicted that increasing the clay content by more than 15% will result in more stable behaviors.

3- 3- Steady-state strength

In Fig. 13, the effect of clay content increase on the steady-state strength variations is discussed in a new manner. The vertical axis presents the reduction percentage in the steady-state strength values compared with clean sand strength values under the same conditions using the following equation:

$$\Delta q_{ss}(\%) = [(q_{ss_{cs}} - q_{ss}) / q_{ss_{cs}}] \times 100 \tag{1}$$

where:

$\Delta q_{ss}(\%)$: Percentage of reduction in the steady-state strength

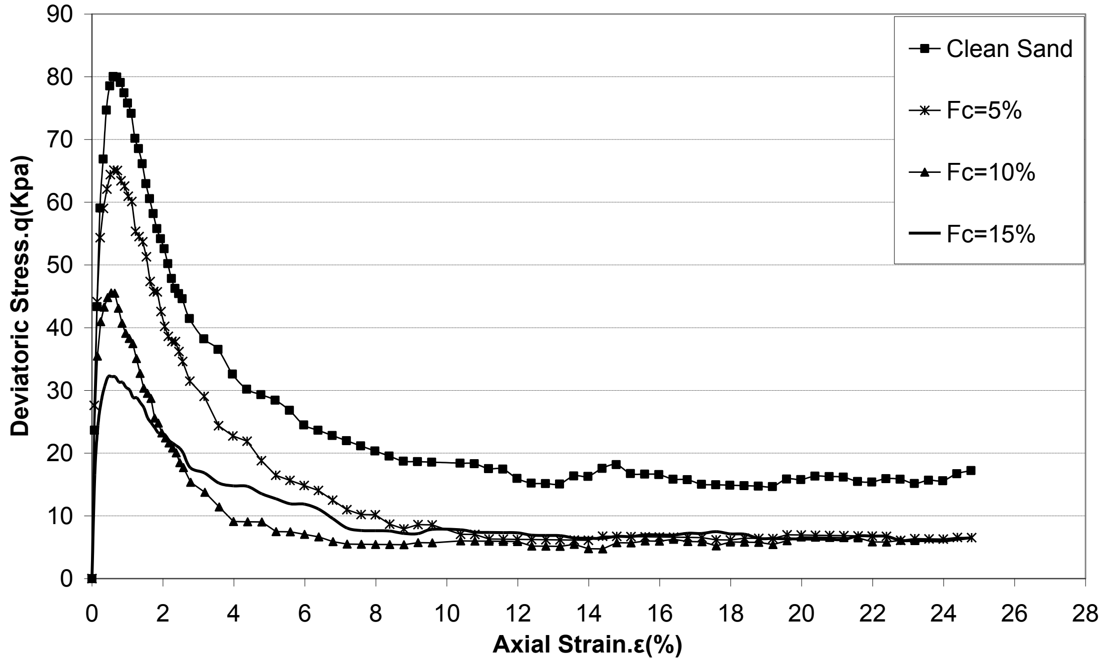
q_{ss} : Steady-state strength values for any optional mixture containing fines

$q_{ss\,cs}$: Steady-state strength value of clean sand

A general study of Figs. 13a and 13b reveal that most of the losses in the steady-state strength values are up to about 5% clay content, at which point this decreasing trend gradually diminishes and in some cases turns into an increasing trend. In combinations of sand with clays with low plasticity, while only adding 5% of clay has reduced the steady-state strength to about 60% compared to its initial value, the continued increase in the percentage of clay up to 15% has sometimes caused the steady-state strength to increase again.

Georgiannou [34] reported similar results regarding the reduction in the steady-state strength for a 7% increase in the clay content of sand mixtures with kaolin clay (PI = 30%). The same behavior was observed by Mizanur Rahman [28] for fines with a plasticity index of about 10%.

Moreover, other researchers reported a reduction in the



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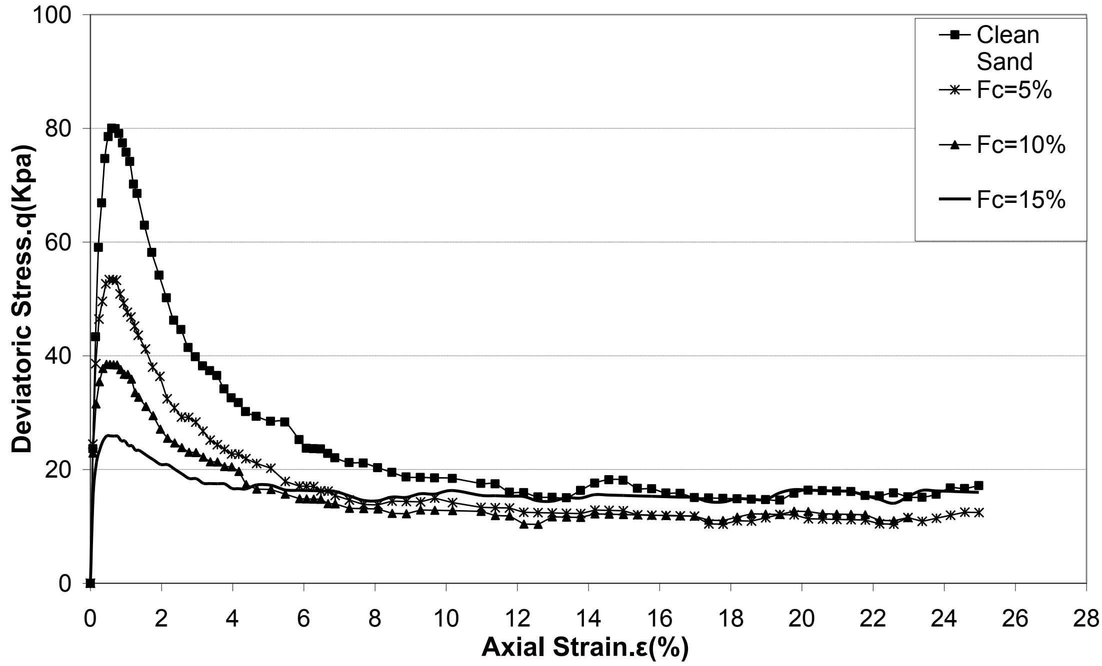

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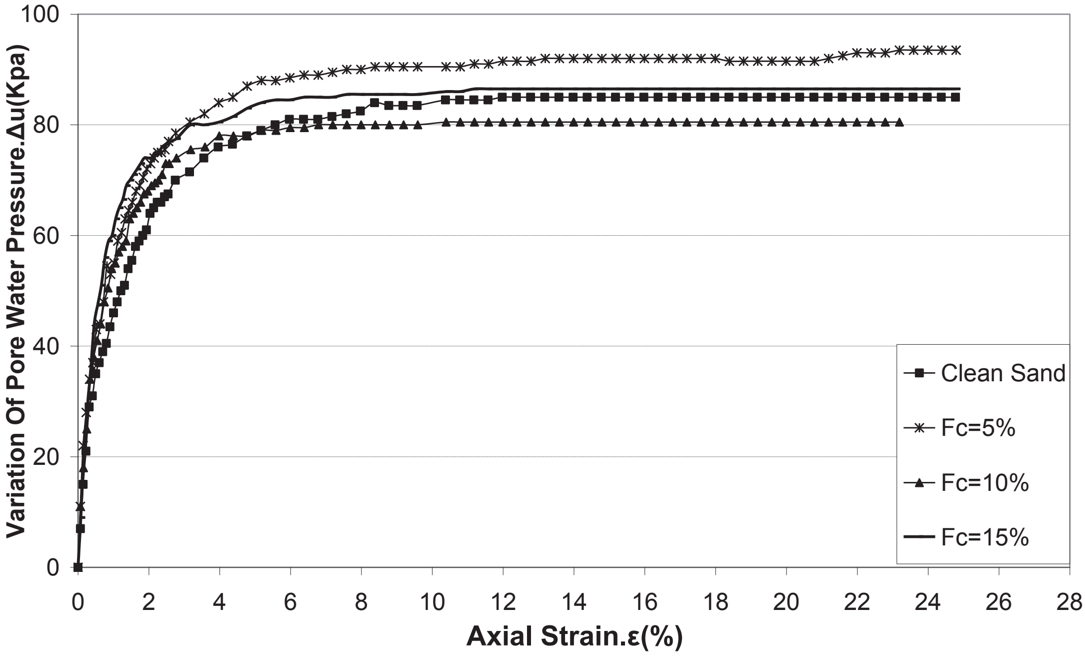
Fig. 5. Stress-strain variations for different mixtures of sand and clay. a) 1.45-100-L. b) 1.45-100-H



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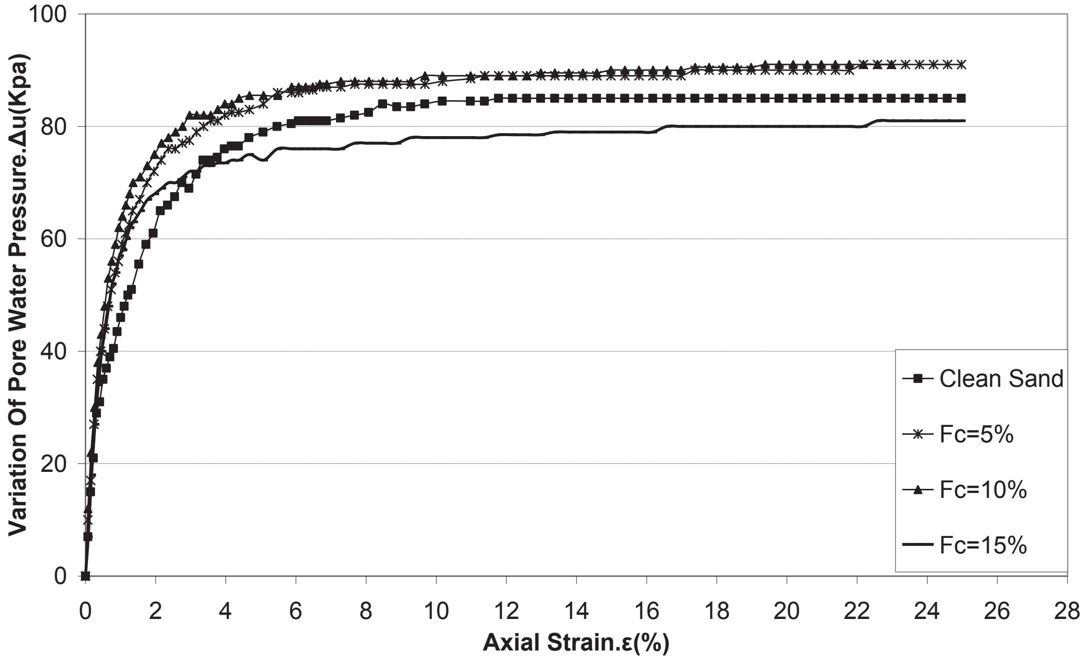


(b)

Fig. 6. Pore pressure variations for different mixtures of sand and clay. a) 1.45-100-L. b) 1.45-100-H

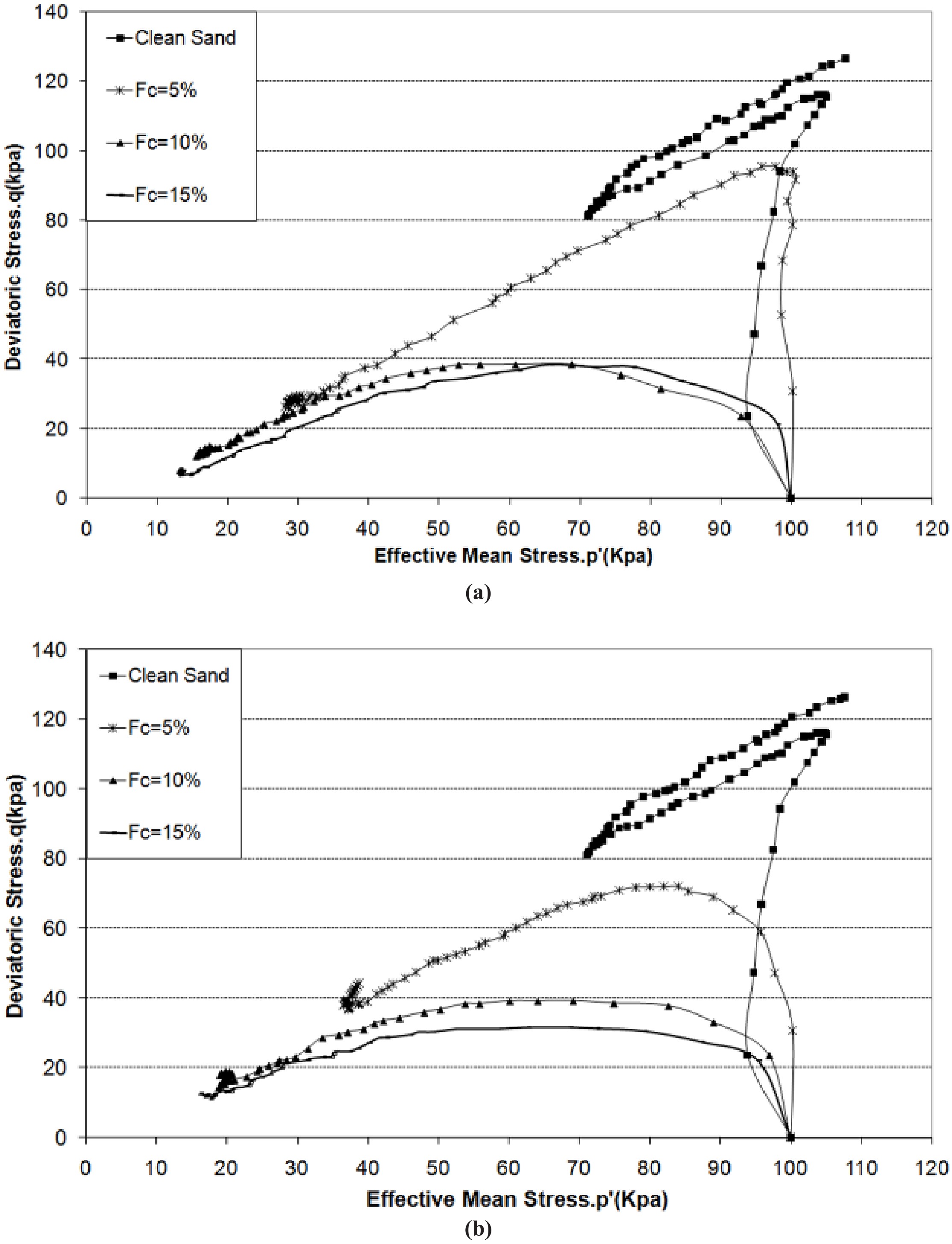
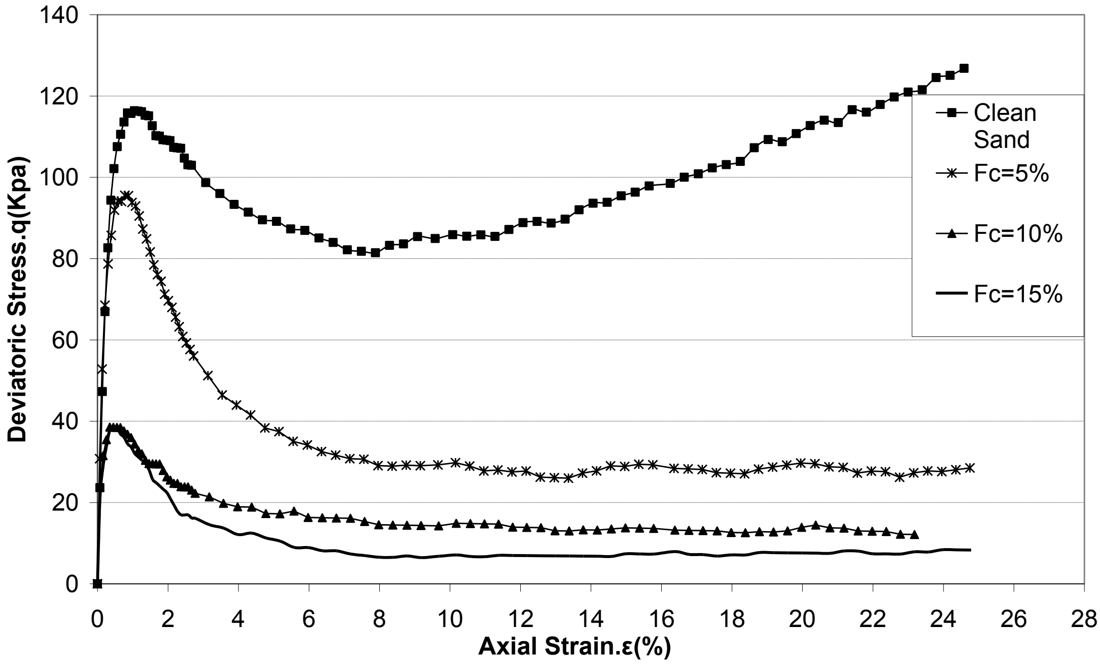


Fig. 7. Plot of the stress paths for different mixtures of sand and clay. a) 1.5-100-L. b) 1.5-100-H



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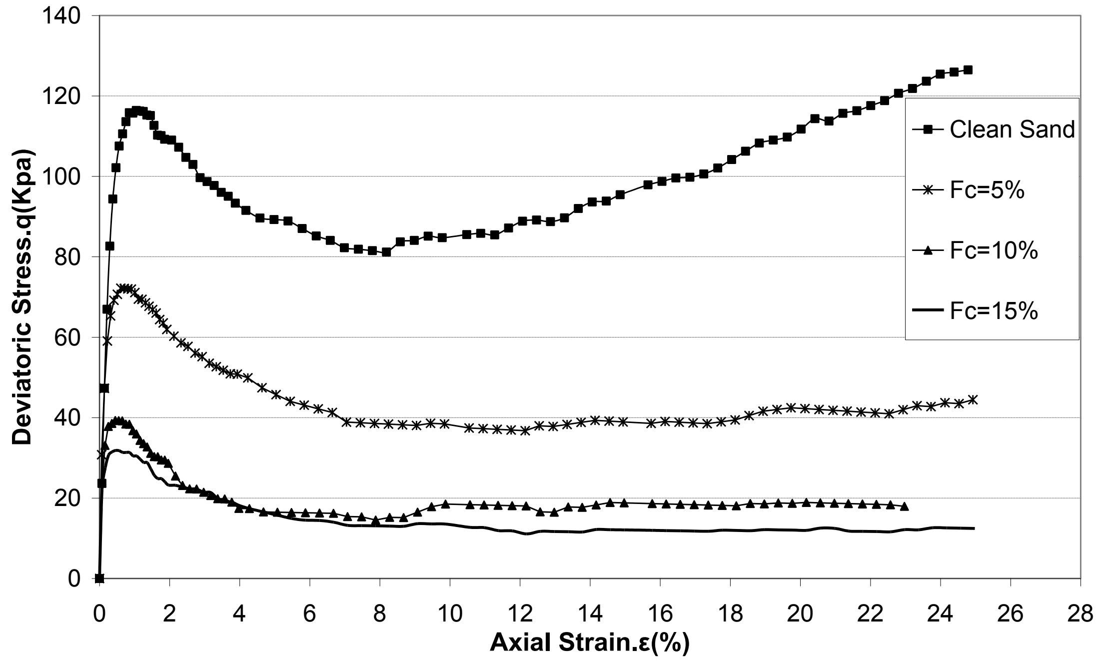
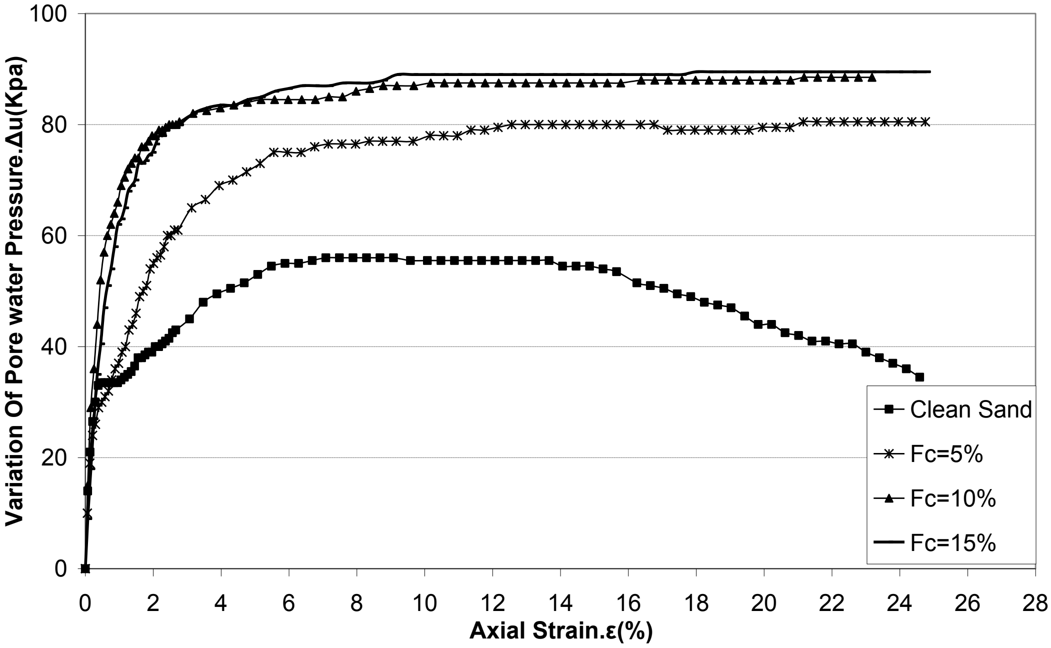


(b)

Fig. 8. Stress-strain variations for different mixtures of sand and clay. a) 1.5-100-L. b) 1.5-100-H



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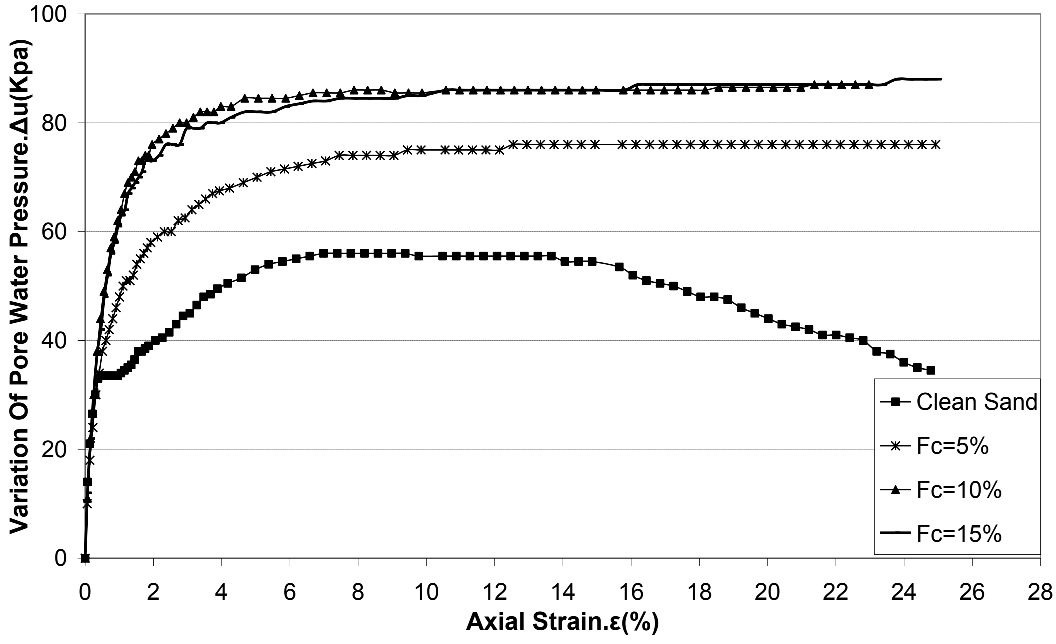

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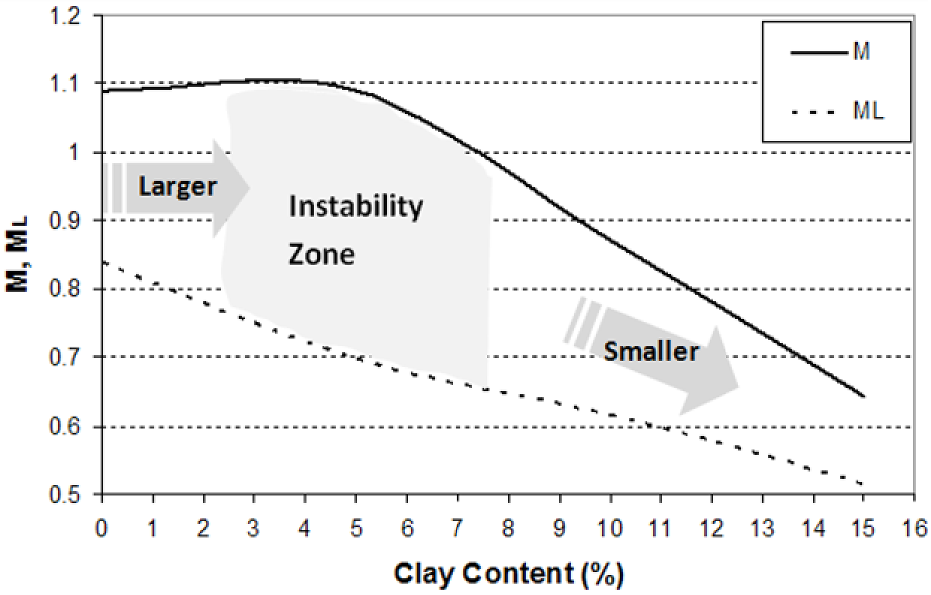
Fig. 9. Pore pressure variations for different mixtures of sand and clay. a) 1.5-100-L. b) 1.5-100-H



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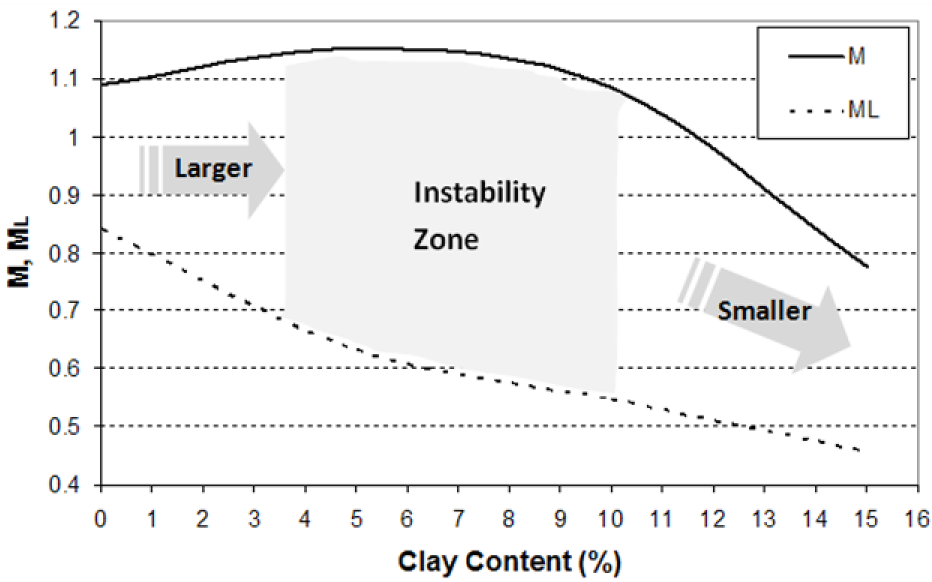


(b)

Fig. 10. Variations of M and ML parameters for the different mixtures of sand with low and high plasticity clays. a) low-plasticity clays. b) high-plasticity clays

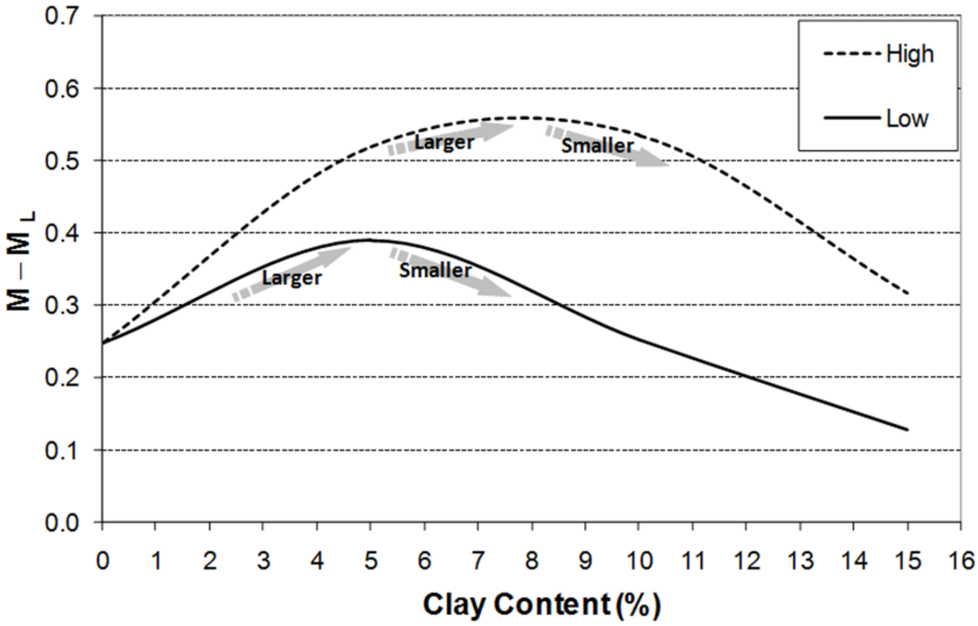


Fig. 11. Variation of instability zone for mixtures of sand with low- and high-plasticity clays.

steady-state strength by increasing the clay content up to 15%, while the trend was reversed by a greater clay content increase [32].

Considering all the abovementioned results, it seems that in low clay contents, the clay percentage has a crucial role and the occupation of spaces among sand grains by clayey particles leads to a significant decrease in the inter-particle friction, which results in a great drop in the strength value. On the other hand, when the clay content increases after about 5%, the mixture's plasticity plays a more crucial role than the clay particles. It means that in high clay contents, mixture plasticity and the cohesion between particles reach a considerable value, preventing a significant loss in strength and even leading to regaining strength in some cases.

3- 4- Steady-state lines

Fig. 14 presents the steady-state lines for clean sand mixed with 0-15% low- and high-plasticity clays. It is observed that as the clay content increases from 0% to 15%, the steady-state lines move downward. Three main conclusions can be extracted from Fig. 14.

- Based on previous studies, the downward movement of steady-state lines is an index of the development of liquefaction potential [3, 35]. As all the tests were conducted under constant void ratios and dry unit weights, it can be concluded that for constant latter parameters, clay content increases (from 0% to 15%) lead to the development of liquefaction potential. Similar results were reported by other researchers [25, 32, 36-39].

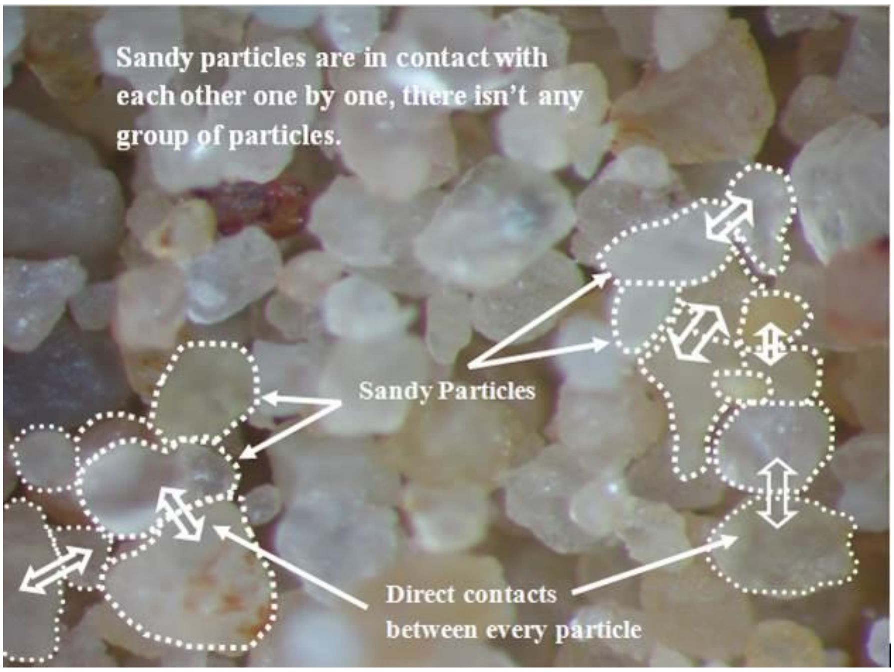
- The steady-state lines for high-plasticity clays were lower than their counterparts for low-plastic clays. This means that for the initial increase of the clay content, the more the plasticity is, the more the increase of liquefaction potential will be, which is because more unstable structures are created in the sand mixtures with high-plasticity clays with low percentages of clay content.

- As the clay content increases, the diversity between the lines of two different types of clay (with the same clay content) increases considerably. Again it can be concluded that for low clay contents (less than 5%), it is the fine content that dominates the behavior not the plasticity; however, when the clay content exceeds 5% and continues to increase, the plasticity gradually gains more importance. Thus, the diversity between the lines of two different types of clay develops, and it can be concluded that for higher clay contents, it is the plasticity that significantly governs the behavioral properties.

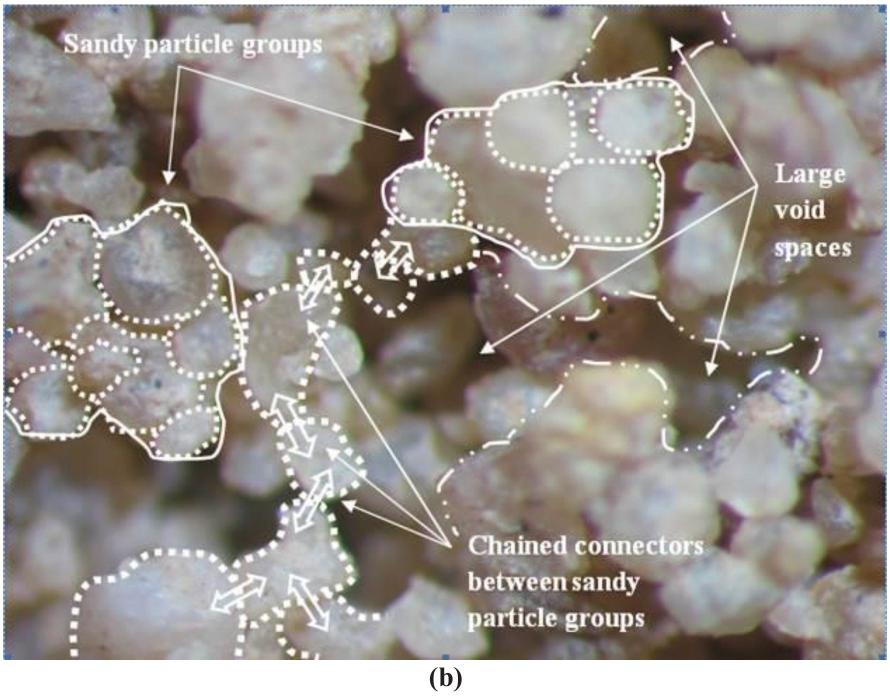
4- Conclusion

To compare the fines content and their plasticity effects on the unstable behaviors of clayey sands, about 64 consolidated undrained tri-axial tests were performed. Variations of the peak deviatoric stress, steady-state strength, instability zone, and steady-state lines were investigated. The most important results are as follows:

The initial clay content increase significantly changed the clean sand structure, from individual sand particles (with direct contact between them) to groups of clay and sandy particles with unstable connectors between them. A greater

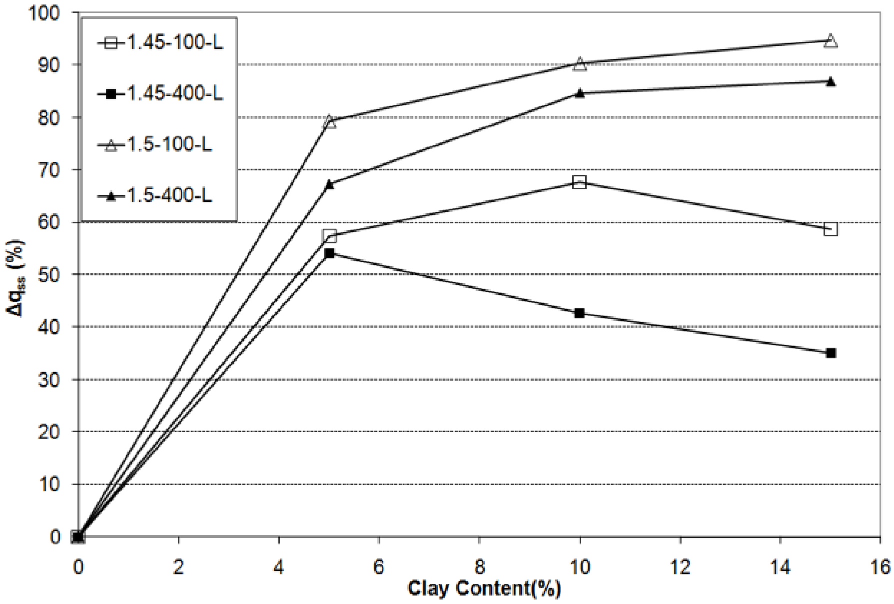


(a)

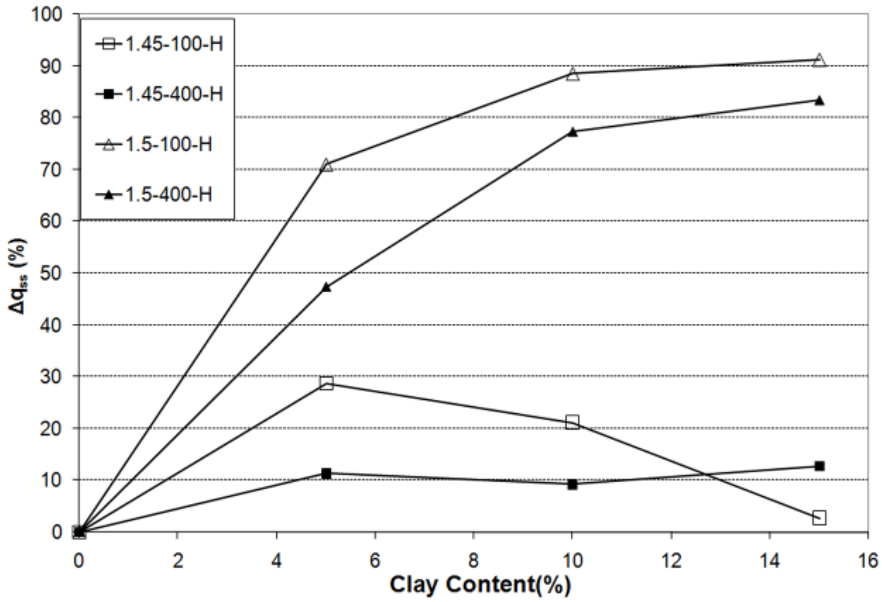


(b)

Fig. 12. . Microscopic images. a) Clean sand. b) Sand with 15% high-plasticity clay



(a)



(b)

Fig. 13. The steady-state strength reduction (in percentage) versus the clay content increase. a) mixtures of sand with low-plasticity clay. b) mixtures of sand with high-plasticity clay

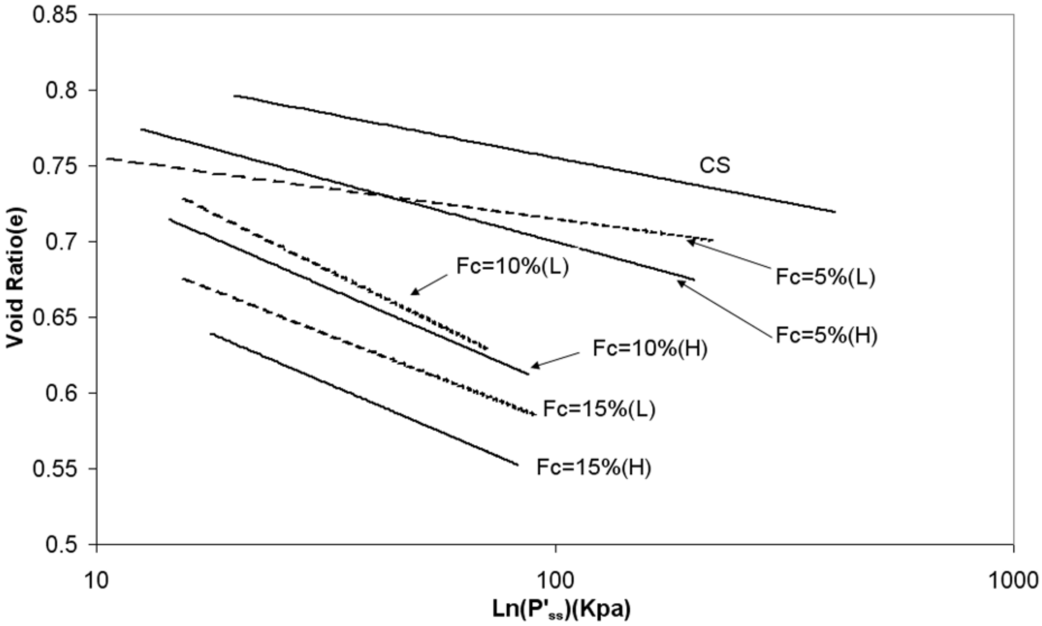


Fig. 14. Steady-state lines for sand mixtures with different types of clayey materials.

increase in the clay content gradually makes these unstable structures steadier due to the increase in plasticity and consequently the cohesion between particles.

For a low percentage of fines, the plasticity of fines intensified the unsteady connections between the particle groups, leading to more unstable structures. For greater clay content increases, using fines with higher plasticity resulted in more cohesion between the particle groups and therefore more stable structures.

Clay content increase resulted in a considerable drop in peak deviatoric stress, which was more significant for high-plastic clays due to the creation of more unstable structures. The initial increase of the clay content led to a considerable loss in the steady-state strength values, while the reduction was less significant for more clay content increases due to the gradual increase of cohesion between particles.

The instability zone became larger with the initial increase in the clay content and then gradually became smaller due to the effect of plasticity in creating more stable structures. The downward movement of the steady-state lines and the latter conclusion mean more collapse and liquefaction potential due to the initial increase in the clay content, but a reverse trend may be expected for greater clay content increases.

The fines content mainly dominated the type of behavior at a low percentage of fines. When the fines content increased and the plasticity of the mixture grew, the role of plasticity gradually became more important and fines with various plasticity values led to very different behaviors.

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References

[1] G. Castro, Liquefaction of sands, Harvard soil mechanics series, Harvard Univ., 81 (1969).

[2] M. Geyin, B.W. Maurer, B.A. Bradley, R.A. Green, S. van Ballegooy, CPT-based liquefaction case histories compiled from three earthquakes in Canterbury, New Zealand, Earthquake Spectra, (2021) 8755293021998755-8755293021992930

[3] S.L. Kramer, H.B. Seed, Initiation of soil liquefaction under static loading conditions, Journal of Geotechnical Engineering, 114(4) (1988) 0733-9410.

[4] R.W. Boulanger, M. Khosravi, B.R. Cox, J.T. DeJong, Liquefaction evaluation for an interbedded soil deposit: St. Teresa's School, Christchurch, New Zealand, in: IACGE 2018: Geotechnical and Seismic Research and Practices for Sustainability, American Society of Civil Engineers Reston, VA, 2019, pp. 686-704.

[5] S.J. Poulos, The steady state of deformation, Journal of the Geotechnical Engineering Division, 107(5) (1981) 0093-6405.

[6] bahareh katebi, abas ghalandarzadeh, Mehdi Derakhshandi and Navid Ganjian" Experimental investigation of the effect of relative densities and type of loading on sand liquefaction under irregular earthquake

loading, Amirkabir journal of civil engineering, Volume 54, Issue 1, April 2022.

[7] Cong Zhang, Zhongju Feng, Yunhui Guan, Huiyun Chen, Fuchun Wang, and Boxi Xu, Study on Liquefaction Resistance of Pile Group by Shaking Table Test, Advances in Civil Engineering Journal, 2022

[8] J.A. Sladen, R.D. D'Hollander, J. Krahn, The liquefaction of sands, a collapse surface approach, Canadian geotechnical journal, 22(4) (1985) 0008-3674

[9] Y.P. Vaid, J.C. Chern, Cyclic and monotonic undrained response of saturated sands, in, ASCE, 1985, pp. 120-147.

[10] P.V. Lade, Initiation of static instability in the submarine Nerlerk berm, Canadian Geotechnical Journal, 30(6) (1993) 0008-3674.

[11] J. Yang, Non-uniqueness of flow liquefaction line for loose sand, GÃ©otechnique, 52(10) (2002) 0016-8505.

[12] J. Yang, M. Jefferies, K. Been, Discussion: Non-uniqueness of flow liquefaction line for loose, Geotechnique, 54(1) (2004) 66-68.

[13] S.L. Yang, R. Sandven, L. Grande, Instability of sandâ€“silt mixtures, Soil dynamics and earthquake engineering, 26(2-4) (2006) 0267-7261.

[14] L. Feng, S. Zhang, Z. Jin, M. Zhang, S. Pingping, J. Jia, G. Chu, W. Hu, The critical mechanics of the initiation of loess flow failure and implications for landslides, Engineering Geology, (2021) 100013-107952.

[15] J.A. Yamamuro, K.M. Covert, Monotonic and cyclic liquefaction of very loose sands with high silt content, Journal of geotechnical and geoenvironmental engineering, 127(4) (2001) 1090-0241

[16] B.A. Bradley, Strong ground motion characteristics observed in the 13 June 2011 Mw6. 0 Christchurch, New Zealand earthquake, Soil Dynamics and Earthquake Engineering, 91 (2016) 0267-7261.

[17] D.B. Chu, J.P. Stewart, S. Lee, J.-S. Tsai, P.S. Lin, B.L. Chu, R.B. Seed, S.C. Hsu, M.S. Yu, M.C.H. Wang, Documentation of soil conditions at liquefaction and non-liquefaction sites from 1999 Chiâ€“Chi (Taiwan) earthquake, Soil Dynamics and Earthquake Engineering, 24(9-10) (2004) 0267-7261.

[18] Subedi, M., Acharya, I.P. Liquefaction hazard assessment and ground failure probability analysis in the Kathmandu Valley of Nepal. Geoenviron Disasters journal, Vol 9, 1 (2022).

[19] Rohollah Taslimian, Ali Noorzad & Mohammad Reza Maleki Javan, Numerical analysis of liquefaction phenomenon considering irregular topographic interfaces between porous layers, Feb 2022

[20] Ghani, S., Kumari, S. & Ahmad, S. Prediction of the Seismic Effect on Liquefaction Behavior of Fine-Grained Soils Using Artificial Intelligence-Based Hybridized Modeling. Arab J Sci Eng 47, 5411–5441 (2022). https://doi.org/10.1007/s13369-022-06697-6

[21] M. Abedi, S.S. Yasrobi, Effects of plastic fines on the instability of sand, Soil Dynamics and Earthquake Engineering, 30(3) (2010) 0267-7261.

[22] R.W. Boulanger, I.M. Idriss, Liquefaction susceptibility criteria for silts and clays, Journal of geotechnical and geoenvironmental engineering, 132(11) (2006) 1090-0241.

[23] S.J. Brandenberg, P. Zimmaro, J.P. Stewart, D.Y. Kwak, K.W. Franke, R.E.S. Moss, K.Ã.n. Ã‡etin, G. Can, M. Ilgac, J. Stamatakos, Next-generation liquefaction database, Earthquake Spectra, 36(2) (2020) 8755-2930.

[24] R. Romeo, Emilia (Italy) M5. 9 Earthquake on 20 May 2012: An unusual pattern of liquefaction, (2012).

[25] S.A. Naeini, M. Mortezaee, Investigation of the Effect of Fine-Grained and Its Plastic Properties on Liquefaction Resistance of Sand, International Journal of Geotechnical and Geological Engineering, 15(2) (2021) 92-96.

[26] R.S. Ladd, Preparing test specimens using under compaction, Geotechnical testing journal, 1(1) (1978) 0149-6115.

[27] Ali Shafiee, Rouzbeh Dabiri and Faradjollah Askari, Dynamic Properties of Firoozkooh Sand-Silt Mixtures, JSEE Journal, Vol. 19, No. 4, 2017

[28] M.M. Rahman, T.G. Sitharam, Cyclic liquefaction screening of sand with non-plastic fines: Critical state approach, Geoscience Frontiers, 11(2) (2020) 1674-9871.

[29] Y. Huang, L. Zhao, The effects of small particles on soil seismic liquefaction resistance: current findings and future challenges, Natural hazards, 92(1) (2018) 1573-0840.

[30] M. Derakhshandi, E.M. Rathje, K. Hazirbaba, S.M. Mirhosseini, The effect of plastic fines on the pore pressure generation characteristics of saturated sands, Soil Dynamics and Earthquake Engineering, 28(5) (2008) 0267-7261.

[31] O. Naeemifar, S.S. Yasrobi, Collapse surface characteristics of clayey sands, Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, 165(6) (2012) 1353-2618.

[32] P. Chakrabortty, N. Nilay, A. Das, Effect of silt content on liquefaction susceptibility of fine saturated river bed sands, International Journal of Civil Engineering, 19(5) (2021) 2383-3874.

[33] T.G. Murthy, D. Loukidis, J.A.H. Carraro, M. Prezzi, R. Salgado, Undrained monotonic response of clean and silty sands, GÃ©otechnique, 57(3) (2007) 0016-8505.

[34] V.N. Georgiannou, J.B. Burland, D.W. Hight, The undrained behavior of clayey sands in triaxial compression and extension, Geotechnique, 40(3) (1990) 0016-8505.

[35] D. Manzanal, S. Bertelli, S. Lopez-Querol, T. Rossetto, P. Mira, Influence of fines content on liquefaction from a critical state framework: the Christchurch earthquake case study, Bulletin of Engineering Geology and the Environment, (2021) 1435-9537.

[36] K.T. Law, Y.H. Ling, Liquefaction of granular soils with non-cohesive and cohesive fines, in, 1992, pp. 1491-1496.

[37] A.S. Thakur, S. Pandya, A. Sachan, Dynamic behavior and characteristic failure response of low plasticity cohesive soil, International Journal of Civil Engineering, 19(2) (2021) 2383-3874

[38] Z. Zhu, F. Zhang, J.-C. Dupla, J. Canou, E. Foerster, Investigation on the undrained shear strength of loose sand with added materials at various mean diameter ratios, Soil Dynamics and Earthquake Engineering, 137 (2020) 100267-107261.

[39] J. Liu, Influence of fines contents on soil liquefaction resistance in cyclic triaxial test, Geotechnical and Geological Engineering, 38(5) (2020) 4735-4751.

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