INFLUENCE OF NON-PLASTIC FINES ON LIQUEFACTION POTENTIAL OF LOOSE SILTY SAND AT CONSTANT SKELETON VOID RATIO

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Abstract

After the occurrence of the earthquake in Alaska and Niigata Japan in 1964, the liquefaction of clean sand has been extensively studied. Generally, natural sand consists of fines particles and several well-documented earthquakes showed that, similar to clean sand, soils containing low-percentage non-plastic fines were equally sensitive to liquefaction. Hence, this paper aims to evaluate the influence of non-plastic silt content on the liquefaction resistance of silty sand by keeping the sand skeleton density index constant in undrained compression triaxial tests. The sand matrix is Hostun sand HN31, which is a uniform quartz reference sand; the fines particles are C500, which is a non-plastic fine silica powder. The monotonic tests were conducted in a very loose state I_{Dmat} = 0.00. The effect on loose specimens shows that the addition of non-plastic fines to the host sand matrix makes the specimens more resistant to liquefaction by inducing dilatancy and reducing the rapid buildup of the excess pore water pressure. The comparison of undrained response under two distinct confining pressures demonstrates that higher confining pressure enhances the positive role of non-plastic silt content. Also, a rotation of the instability line is observed as fines content increases with respect to the effective stress paths and the slope of this line approaches to that of the steady state line. This trend is non-linear and then becomes less remarkable after a certain threshold.

Keywords: silty sand, undrained triaxial tests, instability, soil liquefaction

1. Introduction

During an earthquake, much of serve damage to high dams and geotechnical structures constructed on sand layer has been attributed to soil liquefaction. Sandy soil behaves as a liquid due to a rapid development of excess pore water pressure within a short time. Sand boils, structure collapses, lateral spreadings of bridge piles are some examples of liquefaction damages. Since the last 50 years, especially following two destructive earthquakes in Alaska and Niigata in 1964, previous laboratory and field studies have focussed on uniform clean sand and its framework has been well established. However, natural sand is commonly found in nature under the form of a mixture of sand and fine particles. Abundant real field investigations indicated that sand containing fines particles were equally sensitive to liquefaction. Ishihara [1] observed considerable liquefaction of silty sand without previous treatments during the Miyagi earthquake, Japan in 1978. Ueng [2] observed a large amount of fines fraction in the liquefied soil during the 1999 Chi-Chi, Twiwan earthquake. Recently, young silty sand deposits were proved responsible for the widespread liquefaction in the 2010 New Zealand earthquake [3]. A systematic research [4] including 17 worldwide earthquakes concluded that 50% of liquefied soils had fines contents lower than 5%.

Despite the demand for a better understanding of silty sand mechanical behavior, extremely diverse views exist in the literature as to whether the effect of non-plastic fines is negative or positive for the occurrence of liquefaction. For example, almost all field investigations revealed a positive effect of non-plastic fines particles on silty sand ([5], [6]), which could be confirmed by some laboratory studies ([7]–[9]). Nevertheless, an opposite observation was repeatedly reported in more recent studies ([10]–[12]). Besides, Lade and Yamamuro [13] found that an increase in the fine content caused a dramatic reduction in liquefaction resistance for silty sand until a certain threshold was reached. Beyond this threshold value, further addition of fines particles made silty sand stronger. Later, Thevanayagam [14] and Ghalandarzadeh [15] arrived at similar conclusions. By keeping global void ratio constant and performing compression triaxial tests at various silt contents, Polito and Martin [16] indicated that there was no clear evidence to show a correlation between global void ratio and the cyclic resistance. However, based on their triaxial tests at same skeleton void ratio, cyclic resistance was almost independent of the increasing silt content.

Above controversial or even contradictory views reported in the literature suggest that the effect of fines remains an area of great uncertainty. The mechanical behavior of binary mixture is complex because both sand and fines are granular materials in nature. In particular, during shearing, the interact between each other is still an open question. Considering real liquefied sites that fines content was relatively low, it can be assumed that, in this case, the silty sand soil was dominated by coarse sand matrix but polluted by fines. As a consequence, the emphasis of this work is to explore how low-percentage non-plastic silt content affects overall response of silty sand.

2. Test materials

The host sand used in this study is HN31, which is a uniform quartz (S_iO_2>99%) reference sand. The fines particles added to the host sand is C500, which is a non-plastic fines silica powder (I_p<10). Main properties of two materials are listed in Table 1. In this study, sand skeleton density index $I_{Dmat} = (e_{max}-e_{sand})/ (e_{max}-e_{min})$ was employed, where e_{max} and e_{min} are maximum and minimum void ratios of host sand. A very loose sand skeleton density index (I_{Dmat} = 0.00) was selected. The mass of the added non-plastic fines was calculated by dry clean sand mass and four low-percentage fines contents F_c=1%, 2.5%, 5%, 10% are targeted. Fig. 1 presents the grading curves of clean and mixed materials determined by laser diffraction method.

Table 1 – Main properties of clean materials

Material	D_{50} (μm)	D_{10} (μm)	C_u	e_{min}	e_{max}	ρ_s (g/cm^3)
HN31	350	250	1.57	0.656	1	2.65
C500	6	2	3.15	-	-	2.65

The minimum void ratios of the mixtures related to the densest soil structures were measured and are depicted in Fig. 2. It can be seen that it tends to decrease initially with the addition of fines particles up to a certain fines content and then to increase beyond this value. This critical state is called threshold fines content (TFC) signifying the transformation of granular structure from sand- to fines-dominance and the value of the tested soil was about 19%. Before this value, added fines particles can be supposed to be enclosed by the main skeleton formed by host sand. Thus, there was no sand matrix degradation in this study and all silty sand specimens tested were still sand-dominant since four fines contents were enough smaller than TFC [9].

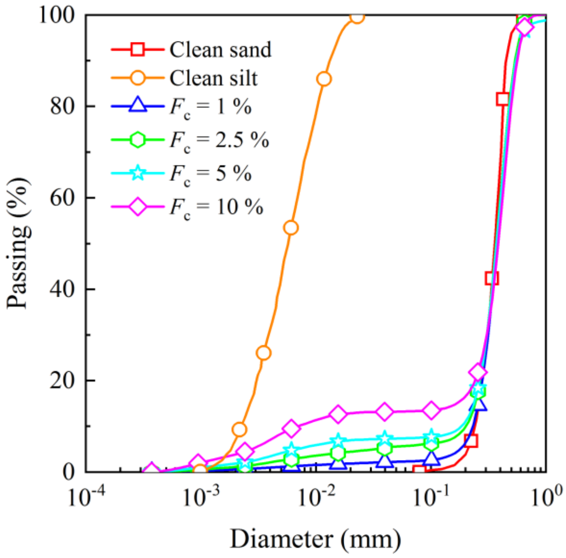

Fig. 1 – Grain size distribution curve of clean materials and silty sand of four fines contents

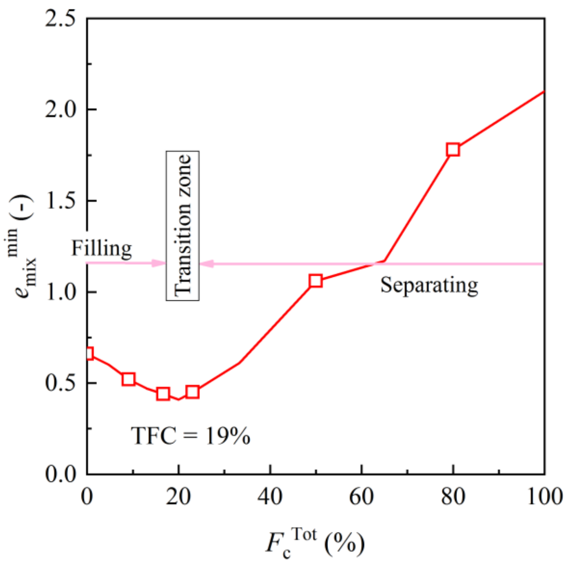

Fig. 2 – Evolution of minimum void ratios with the addition of non-plastic fines particles

3. Experimental program

The major challenge in experimental program is how to maintain good homogeneity of silty sand mixtures. Previous laboratory investigations revealed that moist tamping is pertinent for silty sand ([9]). It consisted of adding 5% water by mass to the total dry mixture. Two materials were then mixed for 15 min using a large blender. The mixture was divided into 10 parts to produce a cylindrical specimen of 100 mm in diameter and 200 mm in height, and each part was slightly compacted to 20 mm in a split mould. Once the specimen had been formed, the sample cap was placed and sealed with two O-rings, and a light vacuum of 15 kPa was applied to reduce possible disturbances. To ensure a good saturation, the specimens was saturated by first passing CO_2 under a low pressure during a period of 15 mins to evacuate air bubbles. De-aired water was then injected to saturate the specimens. A back pressure of at least 200 kPa was applied in steps of 20 kPa to improve the saturation degree and the Skempton's B value was equal or greater than 0.98 in all tests. The cell pressure was finally increased to achieve the desired confining pressure. All undrained tests were performed at a constant strain rate of 0.5% per minute. This value was slow enough allowing the equilibria of the pore water pressure change throughout the specimen, which was also verified by measuring the pore water pressure at the base and top of the specimens. Table 2 summarizes the test programs. In order to ensure the mixture homogeneity during all experimental steps, two very small samples were taken from two different positions of a post-shearing specimen at F_c=2.5%. Fig. 3 shows that their grain size distribution curves are almost coincident with that directly after mixing in the blender, confirming that the adopted experimental procedure is suitable in terms of the mixture homogeneity.

Table 2 – Summary of the test program

Reference	F_c (%)	I_{Dmat}	σ'_c (kPa)
TM01	1	0	100
TM02	2.5	0	100
TM03	5	0	100
TM04	10	0	100
TM05	1	0	400
TM06	2.5	0	400
TM07	5	0	400
TM08	10	0	400
TMC01	0	0	100
TMC02	0	0	400

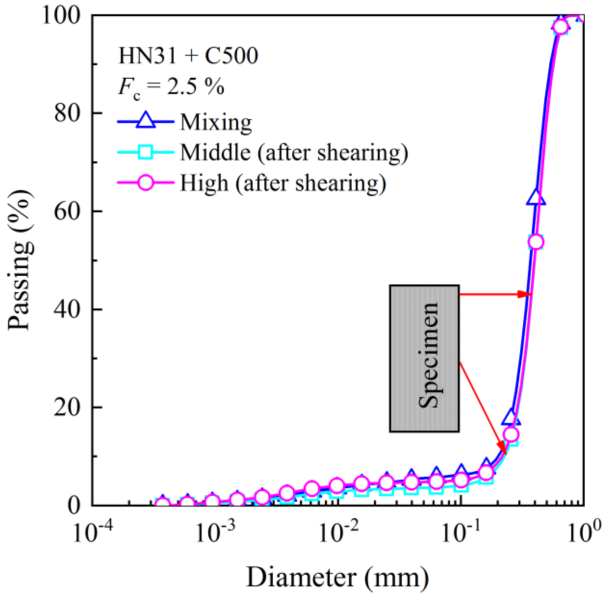

Fig. 3 – Comparison of grain size distribution curve after shearing and mixing

4. Results of undrained test of silty sand

Fig. 4 (a)-(b) displays the deviator stress/excess pore water pressure change versus axial strain under the same confining pressure of 100 kPa but at four different fines contents. In the small range of axial strain (ε_a<0.5%), both deviator stress/excess pore water pressure curves are almost coincident. With the further development of axial strain in Fig. 4(a): i) for clean sand and silty sand at F_c=1%, the deviator stress increases before reaching a peak resistance. It then decreases till the end of test (ε_a=20%); ii) by contrast, for higher fines content of F_c = 2.5%, 5% and 10%, the deviator stress could rise again. In addition, this trend becomes increasingly important with the increase in fines content, revealing a more dilatant behavior of tested soil. Under undrained conditions, the transformation state separating contraction and dilatancy ranges is defined as $d(\Delta u)$ = 0. The axial strain achieving this state is then the initiation of dilatant behavior. The results in Fig. 4(b) show that the excess pore water pressure generated in the contraction range is impeded with the addition of fines content. Afterwards, the increase in fines content results in more dissipation of excess pore water pressure in the dilatancy range. Moreover, the axial strain achieving the transformation state decreases as fines content increases.

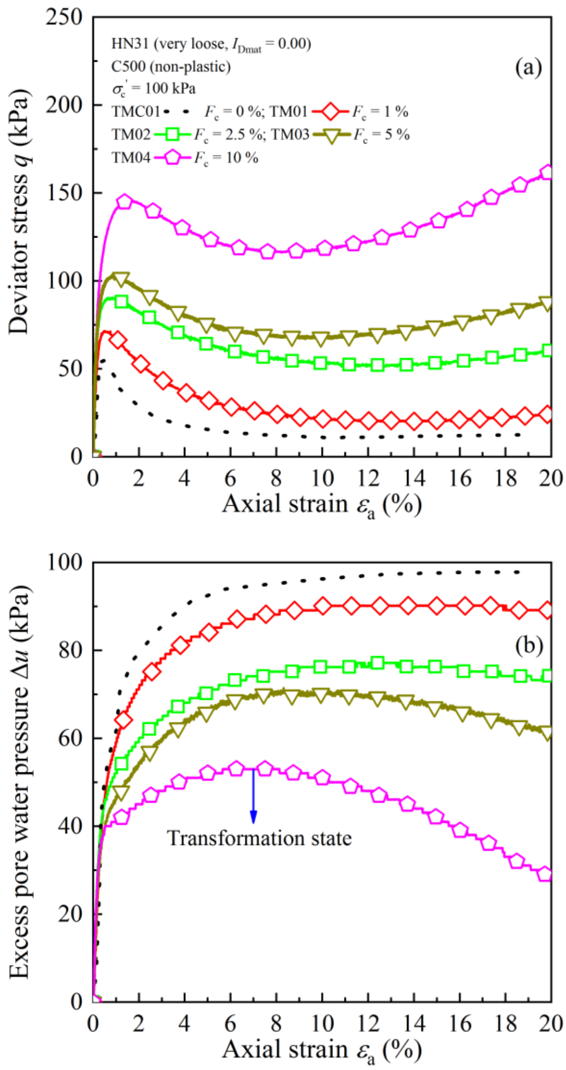

Fig. 4 – Effect of fines content on undrained behavior of silty sand under confining pressure of 100 kPa (a) q - ε_a; (b) Δu - ε_a

Fig. 5(a)-(b) presents the deviator stress/excess pore water pressure change versus axial strain under the confining pressure of 400 kPa. In terms of stress-strain curve in Fig. 5(a), all curves are almost coincident in the very small range of axial strain. Subsequently, the deviator stress increases as the fines content increases. As regards excess pore water pressure curves shown in Fig. 5(b), the positive generation of Δu from contraction is limited by the addition of fines content. Meanwhile, The axial strain achieving transformation state decreases with the increase in fines content, which is in good agreement of the results under 100 kPa. Afterwards, the excess pore water pressure decreases with the further axial strain development. However, this decreasing tendency become much less obvious compared to that of 100 kPa. This can be attributed to that, under higher confining pressure, silty sand specimens are difficult to expand in volume.

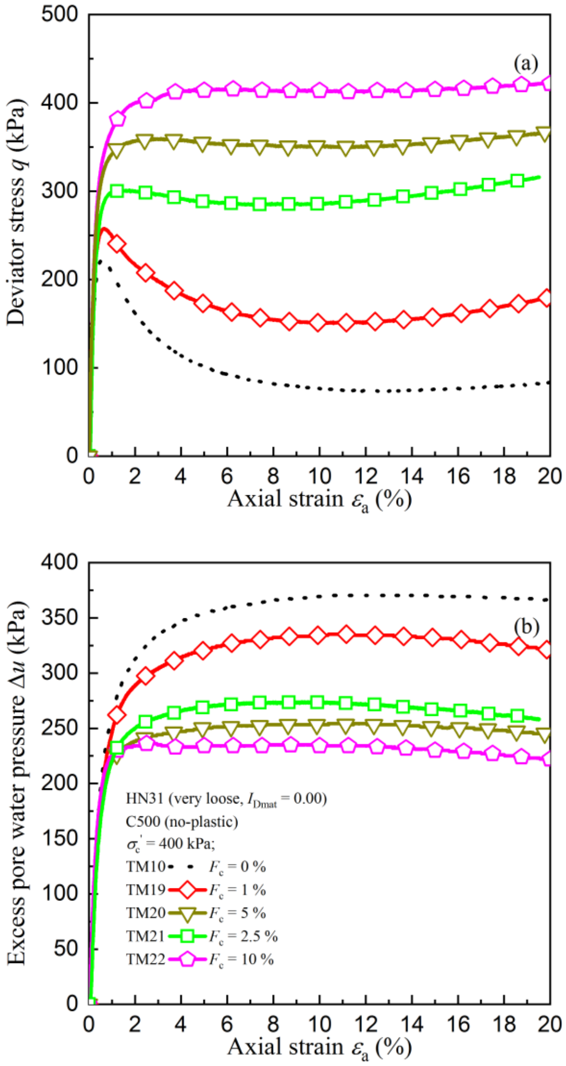

Fig. 5 – Effect of fines content on undrained behavior of silty sand under confining pressure of 400 kPa (a) q - ε_a; (b) Δu - ε_a

By keeping host sand matrix unchanged and adding silt grains, above experimental results under two confining pressures and of various fines contents reveal that dilatant behavior is clearly induced with the increase in fines content of non-plastic silt, which i) impedes the rapid buildup of excess pore water from soil contraction; ii) encourages the dissipation of excess pore water pressure in the dilatant domain; iii) makes the contraction range of silty sand much smaller.

5. Discussion

As mentioned previously, the role of non-plastic silt inside a sand matrix is to induce the dilatant behavior and to impede the rapid buildup of excess pore water pressure in the contraction range, resulting in lower liquefaction potential. Following this logic, in order to clarify this positive impact of fines content under different confining pressures, the peak deviator stress q_{max} and the axial strain achieving transformation state ε_a^{tra} could be considered as comparison bases, as schematized in Fig. 6(a)-(b). It can be observed from Fig. 6(a) that the undrained shear strength of silty sand is much stronger under 400 than 100 kPa. Furthermore, the increasing tendency of undrained shear strengths becomes more remarkable under higher confining pressure, justified by the increasing slope value from 8.7 to 19.2. The results identified in Fig. 6(b) shows that the axial deformation entering the dilatant domain is earlier achieved for 400 kPa and a more remarkable decrease is found for higher confining pressure. This analysis proves that high confining pressure makes the positive role of non-plastic silt content more efficient.

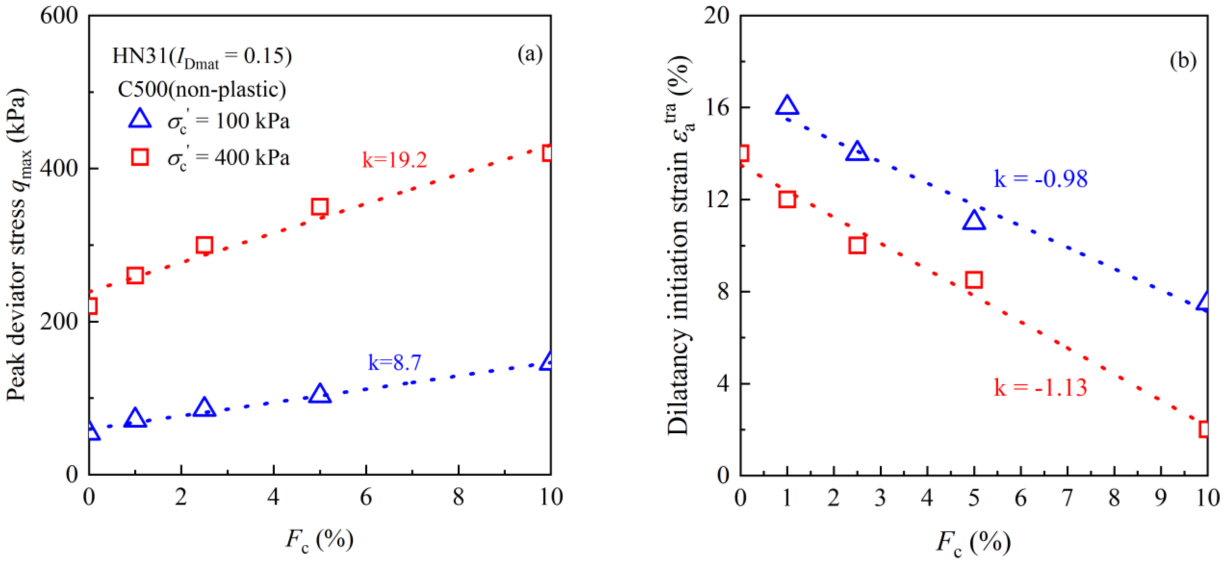

Fig. 6 – Effect of confining pressure on undrained shear strength and dilatancy initiation strain

For loose sandy soil, the peak point of effective stress path can be joined to the origin of the axes by a straight line, which is called the instability line [17]. It is of great importance to recall that this line for loose soil is not unique and it can rotate as a function of density index. The smaller the later, the lower slope value of the former becomes, triggering more easily liquefaction behavior. Thus, the slope of this line is a very important parameter to evaluate the liquefaction potential of loose sandy soils. The effective stress paths of the confining pressure equal to 100 kPa are depicted in Fig. 7(a). In cases of clean sand and silty sand at F_c=1%, a move toward the origin of the axes of zero effective stress state is observed, meaning a significant contractive tendency. On the contrary, as for silty sand of fines content higher than 2.5%, this tendency is largely limited with the increase in fines content. In particular, at F_c=10%, a totally reversed phenomenon is found that the effective stress path moves away from the origin of the axes after a very short-live contraction stage, exhibiting a strong dilatant behavior, leading to the increase in mean effective stress. The similar observations are also identified for the results under confining pressure of 400 kPa. In Fig. 7(b), the corresponding instability line of each mixture of 400 kPa are marked as the same color of effective stress path. It can be seen that, with the increase in fines content, a rotation of instability line is observed in q-p' space. Meanwhile, these lines gradually approach to the steady state line.

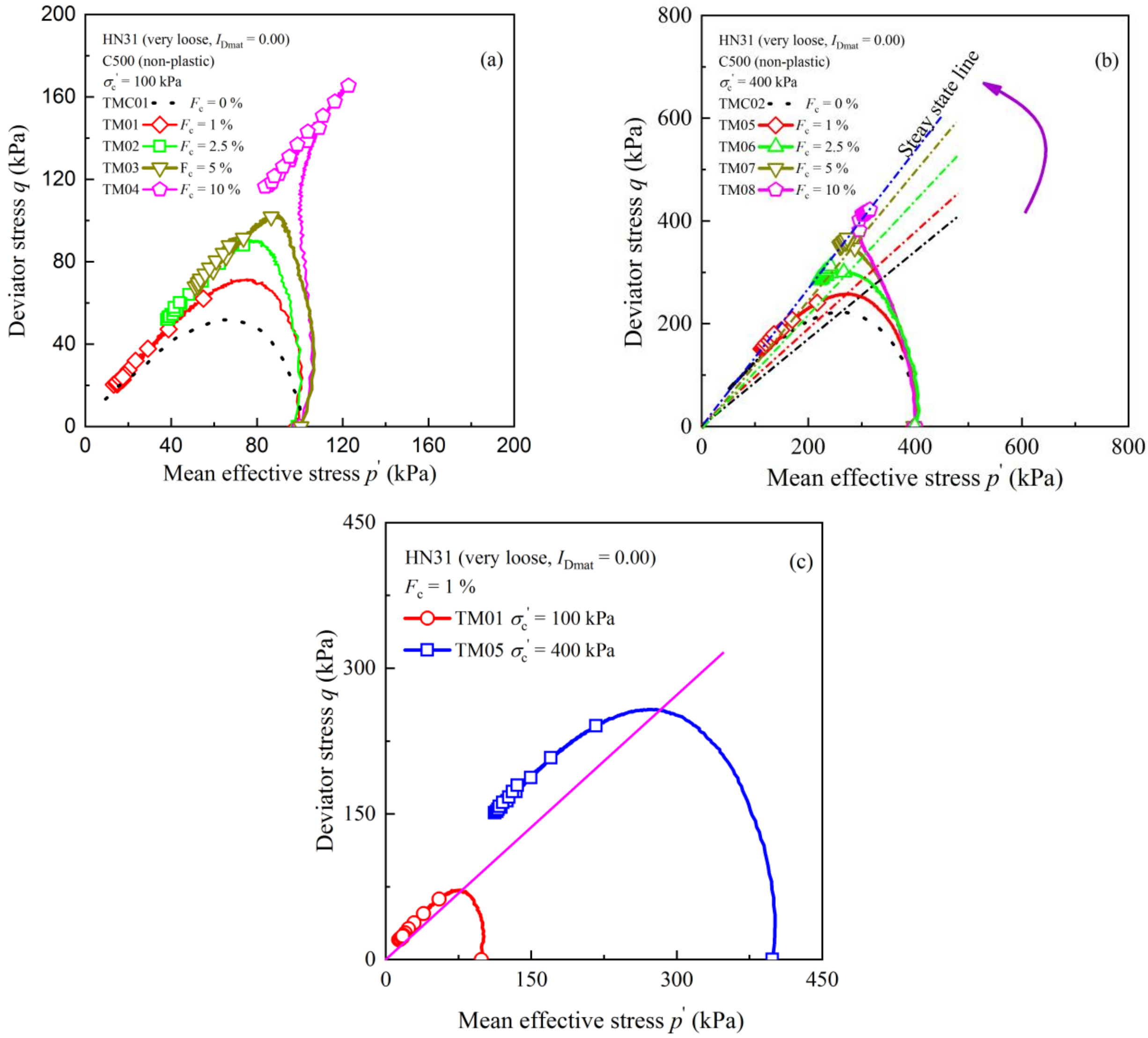

Fig. 7 – Effective stress paths of silty sand (a) under confining pressure of 100 kPa; (b) under confining pressure of 400 kPa; (c) comparison of same fines content under different confining pressures

For a clear exposition, Fig. 7(c) describes the effective stress paths of the same specimen but under two different confining pressures. It can be seen that two peaks of effective stress paths fell almost at the same straight line passing through the origin of the axes. This observation confirms that, similar to clean sand, the instability line of silty sand is still irrespective of the confining pressure and initial density index dependent. Note that same conclusion can also be drawn on three another fines contents (F_c = 2.5%, 5% and 10%). Thereby, the mobilized angle at the instability state calculated by the following equation would be identical for distinct confining pressures:

$$\phi_{inst} = \arcsin\left(3\eta_{inst} / (6 + \eta_{inst})\right) \tag{1}$$

where η_{inst} is the stress ratio at the instability state. In order to quantity the rotation of the instability line, Fig. 8 describes the evolution of the mobilized angle at the instability state with the variation in fines content. It can be noticed that the increasing trend elevates sharply until the fines content is equal to 2.5% and this trend becomes then less significant for higher fines content values. This finding indicates that the role of non-plastic silt on host sand matrix is not linear with the fines content. The beginning addition of fines content up to F_c=2.5% is more efficient to lower the silty sand liquefaction potential and this effect becomes then very limited with further addition.

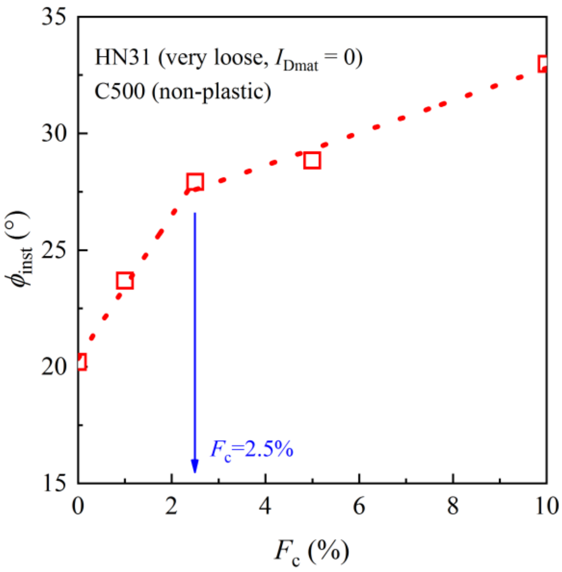

Fig. 8 – Variation in the mobilized angle at instability state with different fines contents

6. Conclusion

This paper presents briefly a laboratory investigation of the effect of low-percentage silt content on loose sand matrix. For comparison, undrained triaxial tests were performed both on the clean and silty sand specimens at various fines contents under two distinct confining pressures. All studied fines contents were far removed from the TFC to avoid degradation of the host sand skeleton. The reconstitution method was moist tamping and the homogeneity of the silty sand mixtures was checked by comparing the grain size distribution curve between a post-shearing specimen and the mixture in the blender. The principal findings can be as follows:

1. The experimental results demonstrate that, at the very beginning of the tests, the role of non-plastic content is inactive. With the further development of axial strain, the positive role of non-plastic fines on the host sand matrix is identified by two aspects. The positive excess pore water pressure is largely reduced as fines content increases. Afterwards, non-plastic silt content facilitates the dissipation of excess pore water pressure in the dilatant range.

2. The comparison between same specimens under different confining pressures illustrates that the positive effect of non-plastic silt becomes more efficient under higher level of confining pressure. The variation in the slope of the instability line in terms of fines content indicates that the effect of non-plastic silt is more notable at a lower fines content.

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8. References

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