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Influence of gradation on shear strength and volume change behavior of silty sands

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Abstract. The results of an experimental program regarding the effects of gradation on shear strength and volume change behavior of silty sands are presented. Consolidated drained direct shear tests were performed on two clean base sands and twelve silty sands obtained by mixing those base sands with two different non-plastic silts at various fines contents (≤ 25%). Drained shear strengths were observed to be not significantly influenced by either base sand gradation or silt gradation or fines content for the studied range. Increasing fines content has increased the volumetric contraction of specimens at similar void ratio. However, the amount of increase in volumetric contraction of silty sands were found to be affected by silt gradation when other influencing factors such as fines content, base sand gradation and mineralogy were kept the same. Moreover, the amount of increase in volumetric contraction of silty sands were also found to be affected by base sand gradation when other influencing factors such as fines content, silt gradation and mineralogy were kept the same.

Keywords: sand; silt; gradation; volume change; shear strength; void ratio

1. Introduction

Drained and undrained engineering behaviors of cohesionless soils were usually investigated focusing on the response of clean sands. However, most sandy soils in situ contain certain amounts of fine grained fraction involving silt particles, clay particles or a mixture of both. Realizing this observation, stress-strain behavior of silty sands is under research for the last few decades especially focusing on the liquefaction perspective (Kuerbis *et al.* 1988, Pitman *et al.* 1994, Lade and Yamamuro 1997, Thevanayagam 1998, Thevanayagam *et al.* 2002, Murthy *et al.* 2007). These previous studies mostly concentrated on the influence of fines content (FC) on liquefaction potential of silty sands by mixing a single type of either non-plastic or plastic fines with a base sand at various percentages. Recently, Monkul and Yamamuro (2011) has shown that the mean size of the silt grains relative to the mean size of sand grains (i.e., $D_{50\text{-sand}} / d_{50\text{-silt}}$) is also an important factor influencing the liquefaction potential of the very same base sand (Nevada sand B) mixed with different non-plastic silts (Loch Raven, Potsdam and SilCoSil).

Carraro *et al.* (2009) investigated the drained behavior of Ottawa Sand mixed with different amounts of either plastic or non-plastic fines by triaxial compression tests. According to Carraro *et al.* (2009), increasing non-plastic fines content (btw. 0% and 15%) increases the shear strength and

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volumetric contractiveness at low relative densities (i.e., $D_r \approx 30\%$).

Koerner (1970) performed drained triaxial compression tests on clean quartz sand in both saturated and dry states to look at the influence of gradation on the internal friction angle. He found that varying the coefficient of uniformity (C_u) had negligible effect on the value of the drained friction angle for quartz sands at a given relative density. Kuerbis *et al*. (1988) compared two different gradations of clean Brenda mine tailings sand, and concluded that undrained triaxial compression behavior is similar for both well graded and uniform versions of Brenda mine tailings sands. In a later study, Pitman *et al*. (1994) added clean 70/140 silica sand to clean Ottawa sand in order to change the sand gradation. Similar to Kuerbis *et al*. (1988), Pitman *et al*. (1994) also concluded that monotonic undrained triaxial compression behavior of various samples prepared at similar initial void ratios are not influenced by the gradation of the sand (i.e., uniform or relatively well graded).

Vaid *et al*. (1990) conducted an experimental program of cyclic triaxial tests using clean Earls Creek River Sand, in which the sand gradation is varied by keeping the same mean grain diameter (D_{50}) but changing the coefficient of uniformity only. In that study, it was observed that cyclic liquefaction resistance of the loose Earls Creek River Sand has increased as the sand became well-graded at a given relative density. Kokusho *et al*. (2004) performed both monotonic and cyclic undrained triaxial tests on clean river sand of different gradations. Accordingly, influence of sand gradation had negligible effect on cyclic liquefaction resistance at a given relative density. However, static liquefaction (complete loss of shear strength under monotonic loading) resistance increased as the river sand became well graded (i.e., the coefficient of uniformity increased) at a given relative density (Kokusho *et al*. 2004). Igwe *et al*. (2007) conducted stress controlled undrained ring shear tests on clean industrial quartz sand with different gradations. Similar to Kokusho *et al*. (2004), Igwe *et al*. (2007) also concluded that as the sand gradation is changed so that the coefficient of uniformity is increased, its static liquefaction resistance is also increased at a given relative density.

It appears from the above mentioned studies that there is still no consensus regarding how gradational changes influence the stress-strain behavior of sands. Perhaps, this is no surprise considering the complexity of the problem, potential factors other than C_u influencing the initial soil fabric (particle shape, angularity etc.) and different comparison bases (e.g., similar void ratio vs. similar relative density etc.). Moreover, the previous studies focused on the effect of gradation on clean sand behavior, therefore very little is known about how gradation influences the stress-strain behavior of silty sands. The objective of the present study is to investigate the potential effects of gradation on the stress-strain and volume change behavior of silty sands. An experimental program is formulated so that two base sands with the same geological origin but different gradations were mixed with two different non-plastic silts with different gradations. Direct shear tests were performed on the resulting silty sands at various fines contents together with the clean sands.

2. Characterization of soils tested

Two clean sands with different gradations but same geologic origin were obtained from a sand quarry in the Sile region of Istanbul. Those sands are named Sile sand 20/30 and Sile Sand 80/100. Both sands are classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS). Two non-plastic silts, named TT silt and IZ silt are used in the experimental program. TT silt is produced by wet sieving of stone dust, which was obtained from a stone quarry in Sile region of Istanbul, through standard No 200 sieve (0.075 mm). IZ silt is a naturally formed soil and obtained from the city of Izmir. Characterization tests of soils such as sieve analysis, hydrometer, and specific gravity were conducted based on the relevant ASTM standards (ASTM, 2005). Sieve analysis and hydrometer tests are performed on the sands and silts respectively and the resulting grain size distribution is shown in Fig. 1. Accordingly, IZ silt has a natural fines content of 74%, which is considered in the planning of the experimental program. Some index properties of the sands and silts are given in Table 1.

Each base sand is thoroughly mixed with each silt on dry weight basis to achieve 5%, 15% and 25% FC for the resulting silty sands, in which fines content refers to the percentage of soil grains finer than 0.075 mm in total dry weight of solids. Consequently two base sands and twelve silty sands with different fines contents are used in the experimental program.

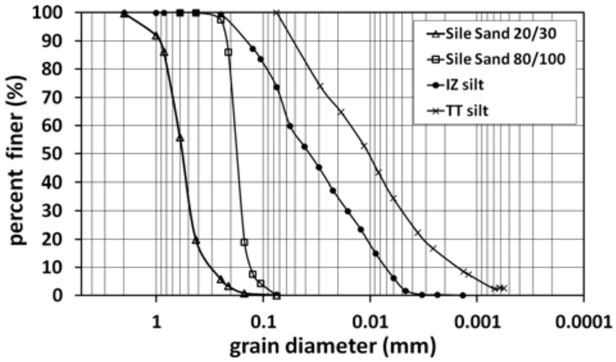


Fig. 1 Grain size distribution of sands and silts used in the experimental program

Table 1 Index properties of sands and silts used in experimental program

	Sile Sand 20/30	Sile Sand 80/100	TT silt	IZ silt
Grain diameter of sand at 50% passing: D_{50} (mm)	0.579	0.163	-	-
Grain diameter of silt at 50% passing: d_{50} (mm)	-	-	0.011	(1) 0.022
mean grain diameter ratio for TT silt: $D_{50}/d_{50\text{-TT}}$	52.6	14.8	-	-
mean grain diameter ratio for IZ silt: $D_{50}/d_{50\text{-IZ}}$	26.3	7.4	-	-
coefficient of uniformity C_u	1.8	1.1	10.1	(2) 4.3
USCS group symbol	SP	SP	ML	ML
maximum void ratio: $e_{\max}$	0.798	0.992	1.783	1.405
minimum void ratio: $e_{\min}$	0.508	0.666	0.529	0.849
specific gravity: G_s	2.65	2.64	2.75	2.70

(1) d_{50} for -No200 section of IZ silt; (2) C_u for -No200 section of IZ silt

Maximum (e_{max}) and minimum (e_{min}) void ratios of the soils were determined by the method proposed by Lade *et al*. (1998). Different methods of maximum and minimum void ratio determination (e.g., ASTM 2005 (D4253, D4254), Japanese standards etc.) could yield different e_{max} and e_{min} values, and also could involve their individual limitations (e.g., applicable up to a certain FC value). However, for this study the consistency and the repeatability of the procedure are important rather than the absolute values of e_{max} and e_{min}. Therefore, Lade *et al*. (1998) method is employed considering that it had been successfully adopted in various previous research studies involving silty sands (Yamamuro and Lade 1997, Yamamuro and Covert 2001, Monkul and Yamamuro 2011). The details and the technique of the method are well explained by Lade *et al*. (1998) and will not be repeated here.

3. Experimental program

Shear strength and volume change behavior of the two base sands and twelve silty sands are investigated by performing consolidated drained (CD) direct shear tests. It is well known that direct shear tests have some shortcomings such as forced failure surface in the horizontal plane; non-uniform shear stress distribution at the failure surface; inability to obtain strains, therefore representing the stress-volume change behavior in terms of displacements rather than the strains. On the other hand, as Lambe and Whitman (1969) mentioned: the general soil behavior observed in a direct shear test is identical to that observed during a triaxial compression test. Moreover, direct shear test is simple, easy to conduct, economical and consequently widely used in geotechnical engineering practice. Therefore, direct shear test is also used in various aspects of geotechnical research as well (Hideo *et al*. 1994, Kumar *et al*. 1999, Vallejo and Mawby 2000, Vallejo 2001, Monkul and Ozden 2007, Bareither *et al*. 2008, Iai and Luna 2011, Mesri and Huvaj-Sarihan 2012), where the influence of the above mentioned shortcomings are negligible on the observed behavior trends and resulting conclusions. In this study a fully automated computer controlled Geocomp direct shear apparatus is used.

Silty sand specimens are constituted by mixing the oven dried base sands with the oven dried silts to obtain soils with 5%, 15% and 25% FC. Once the sand constituent and silt constituent are put together, they are mixed manually in a dry state for a 10 to 15 min period with the help of a spatula, until the mixtures became visually homogenous. Later, resulting silty sands were transported to the cylindrical direct shear cell of 63.5 mm diameter by means of pouring the soil into the cell with an aluminum cup. Then, irregularities on the specimen surface are carefully and smoothly spread out by raking with a fork. Care was given so that raking is applied only to the irregular surfacial sections, not through the main body of the specimen. In the next stage, filter paper, porous stone, top cap and the bearing ball is positioned on the specimen to trigger the possible initial settlements due to weight of those parts. Then, the top cap and the bearing ball are removed temporarily and the specimen height is measured at four quadrants and averaged. During measurement, the porous stone of known thickness is still sitting on the specimen. By applying such a procedure, not only the initial height of the specimen is determined more precisely through a leveled top surface without the risk of calliper penetration into the loose dry soil, but also the uncertainty of possible initial settlement due to the weights of different parts (e.g., porous stone, top cap and bearing ball) is eliminated, since those parts are preseated and the measured height already includes the initial settlement. Consequently, the soils were deposited into the direct shear cell in a loose and dry state.

It is possible to test various types of sandy soils including sands (Skopek *et al*. 1994, Fannin *et al*. 2005), silty sands (Monkul *et al*. 2011), and clayey sands (Vallejo and Mawby 2000) in a dry state, especially when drained behavior is investigated. Soils in this study are also tested in a dry state in order to eliminate the influence of possible saturation differences between the specimens with different fines contents and possible partial drainage effects in the shearing stage of the direct shear testing. Once the specimens were deposited into the direct shear cell, they were consolidated to an effective normal stress of 100 kPa and sheared at a rate of 0.3 mm/min.

4. Experimental results and discussion

Fourteen consolidated drained direct shear tests were performed, the details of which are given

Table 2 Specimen details and related parameters of the consolidated drained direct shear tests

Exp. No:	% and type of base sand	% FC and type of silt	Consolidated void ratio (e_c)	Cons. Relative density ($D_{r\text{-}c}$) (%)
1	100% Sile Sand 20/30	0	0.75	15.6
2	95% Sile Sand 20/30	5 TT silt	0.68	38.8
3	85% Sile Sand 20/30	15 TT silt	0.63	50.8
4	75% Sile Sand 20/30	25 TT silt	0.67	43.3
5	95% Sile Sand 20/30	5 IZ silt	0.66	27.3
6	85% Sile Sand 20/30	15 IZ silt	0.67	12.1
7	75% Sile Sand 20/30	25 IZ silt	0.62	39.5
8	100% Sile Sand 80/100	0	0.92	22.6
9	95% Sile Sand 80/100	5 TT silt	0.90	41.7
10	85% Sile Sand 80/100	15 TT silt	0.87	49.2
11	75% Sile Sand 80/100	25 TT silt	0.83	49.7
12	95% Sile Sand 80/100	5 IZ silt	0.90	29.8
13	85% Sile Sand 80/100	15 IZ silt	0.88	40.0
14	75% Sile Sand 80/100	25 IZ silt	0.87	45.4

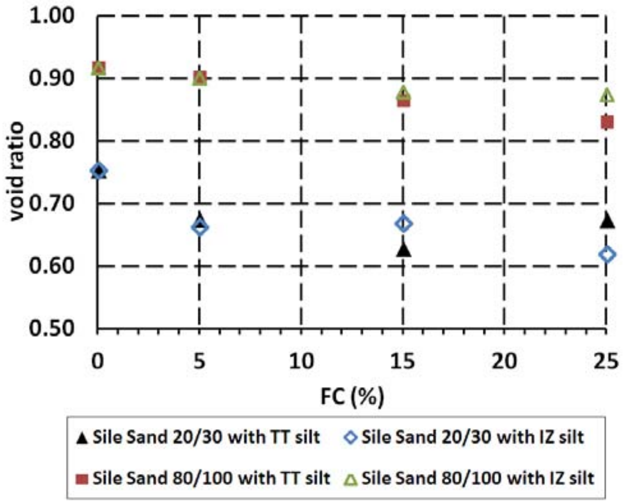


Fig. 2 Consolidated void ratio (e_c) values of the different specimens and their variation with fines content

in Table 2. As could be seen in Table 2; no special effort was made to prepare all the specimens at exactly the same void ratio or relative density. Soils in this study have various grain size distributions, grain shape characteristics and fines contents. Therefore, it is a very difficult task, if not impossible, to determine and target a unique void ratio or relative density value for all specimens, which could be achieved without significantly manipulating the specimen preparation procedure. In silty sands, initial specimen fabric and metastable grain contacts (relatively weaker silt grain contacts positioned between the sand grains) are known to be quite sensitive to such manipulations such as densification, which could eventually affect the resulting shearing behavior (Yamamuro and Wood 2004, Monkul and Yamamuro 2010). Moreover, even if such a target value of void ratio or relative density is achieved during specimen preparation, values after consolidation stage could be different, which would still influence the shearing response.

Consolidated void ratio (e_c) values of the tested specimens are plotted in Fig. 2. Accordingly, Sile Sand 80/100 and silty sands involving it as a base sand have a tendency of having greater void ratios before shearing compared to the ones with Sile Sand 20/30, even though the soils were deposited with the same method, consolidated under the same vertical stress (i.e., $\sigma'_v = 100$ kPa) and having the same fines type and content. Such a difference can be explained with the size and gradation difference between the two base sands. As seen in Fig. 1, Sile Sand 80/100 is a finer sand compared to the Sile Sand 20/30. For a basic comparison, mean grain size ($D_{50\text{-sand}}$) of Sile Sand 20/30 is approximately 3.5 times greater than that of Sile Sand 80/100 (Table 1). Also Sile Sand 80/100 is a relatively more uniform sand compared to Sile Sand 20/30 (see values of C_u in Table 1). As sand grains become smaller and more uniform, they tend be deposited at a higher void ratio when they are clean. Furthermore, when fines are added, it is easier for the silt grains to loosen the sand skeleton of Sile Sand 80/100 and increase the void ratio, as opposed to Sile Sand 20/30 which has a relatively larger D_{50} and is less uniform.

4.1 Influence of base sand, fines type and content on drained shear strength

Shear stress-shear displacement behavior of Sile Sand 20/30 mixed with TT silt and IZ silt at various fines contents are given in Fig. 3. Shear stress of soils involving Sile Sand 20/30 as base sand has increased smoothly with shear displacement in some cases with a small initial peak, where the amount of drop in shear stress is not large. This is a typical loose to medium dense soil behavior where the shear stress-shear displacement curve is ductile under drained conditions. Fig. 3 also shows that the shear response and shear strength of various silty sands involving Sile Sand 20/30 are quite similar. In fact, the drained shear strength is within a narrow range (i.e., between 83 and 90 kPa) for the soils in Fig. 3 (with the exception of one specimen with 25%TT silt) and is not significantly affected by the fines content and type. Drained shear strength is considered as the peak shear stress (τ_{max}) in this study, which usually occurred at relatively large shear displacements depending on the response of the soil.

Fig. 4 shows drained shearing behavior of Sile Sand 80/100 mixed with TT silt and IZ silt at various fines contents. Similar to the soils in Fig. 3, the shear stress-shear displacement curves are generally ductile under drained conditions for the soils involving Sile Sand 80/100 as base sand. The drained shear strength of soils in Fig. 4 is also in a relatively narrow range (i.e., between 83

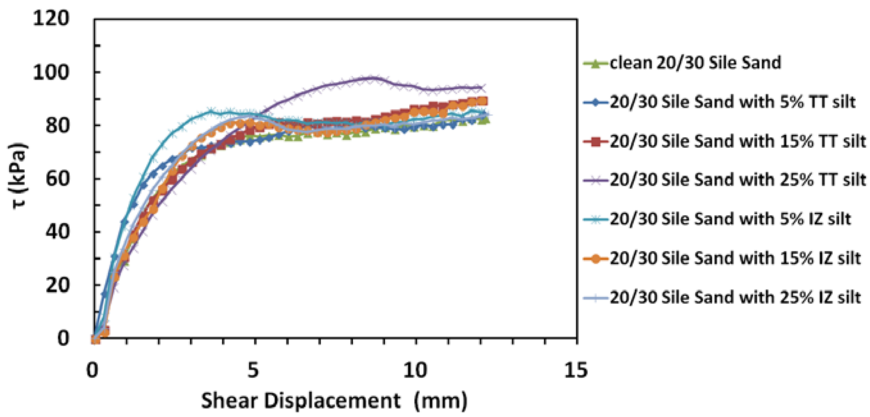


Fig. 3 Shear stress-shear displacement behavior of Sile Sand 20/30 mixed with TT Silt and IZ Silt at various fines contents

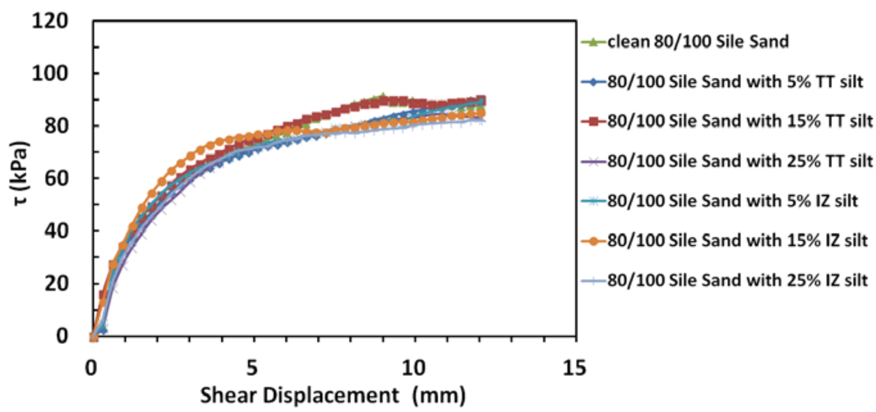


Fig. 4 Shear stress-shear displacement behavior of Sile Sand 80/100 mixed with TT Silt and IZ Silt at various fines contents

and 91 kPa), and the shear stress-shear displacement curves are quite close to each other. Based on the observations from Figs. 3 and 4, it was found that, the value of drained shear strength of sandy soils used in this study is not significantly influenced by either different base sand gradations or different silt gradations or different fines contents (i.e., FC ≤ 25%). Thus, the inclusion of silt has only a small influence on the measured friction angle, which is consistent with published results from other studies (e.g., Bobei *et al*. 2009).

Secant internal friction angles (ϕ'), calculated by Eq. (1), for the silty sands with different base sands, silts and fines contents are plotted in Fig. 5. The values are mostly scattered between 39.5° and 42.5° (with the exception of one specimen mentioned in Fig. 3). These numbers might seem high for loose to medium dense soils, however it should be noted that those are drained secant friction angles obtained by direct shear tests, which are also within the range of previously reported values for silty sands obtained by direct shear tests. As an example Iai and Luna (2011) performed direct shear tests with dry JSC-1A lunar regolith simulant, which was a silty sand and they reported an internal friction angle value of 46.2° for dry medium dense (i.e., D_r between 43% and 51%) samples. Fannin *et al*. (2005) conducted direct shear tests on three different well graded sands including some gravel and silt fraction under low normal stresses (between 5 kPa and 20 kPa). Accordingly, in-situ moist block samples gave internal friction angles between 58° and 64°, while critical state friction angles were reported to be between 46° and 48°.

$$\phi' = \tan^{-1}\left(\frac{\tau_{peak}}{\sigma'_v}\right) \tag{1}$$

4.2 Influence of fines content on volume change behavior of soils with Sile Sand 20/30

Results have shown that drained shear strength of sandy soils used in this study is not significantly influenced by base sand gradation, silt gradation, or fines content (i.e., FC ≤ 25%) (Figs. 3 and 4). However, the influence of the very same factors on the volume change response is quite important for both the constitutive deformation behavior and liquefaction potential characteristics of the soils. It is well known that liquefaction of sandy soils occur when significant amount of excess pore water pressure is generated during undrained loading, so that the effective

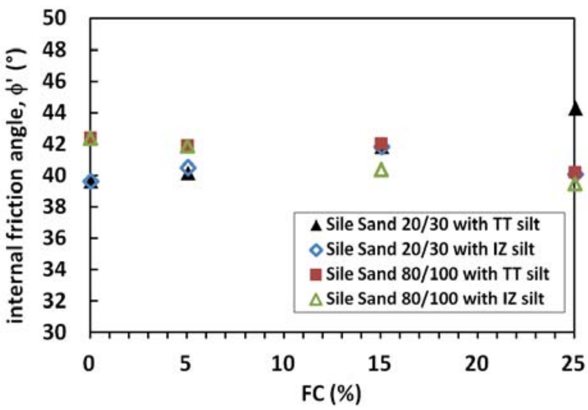


Fig. 5 Secant internal friction angle values obtained from CD direct shear tests under 100 kPa vertical effective stress for soils with different base sands, silts and fines contents in this study

stress between the soil grains approaches to zero. One of the fundamental triggering mechanisms of liquefaction is the volumetric contractive tendency of a soil mass under the specific stress conditions it is experiencing.

Fig. 6 shows the change of vertical displacement with increasing shear displacement for different silty sands having Sile Sand 20/30 as the base sand and mixed with 5%, 15% and 25 % TT silt. Vertical displacements measured in direct shear tests essentially correspond to the volume change behavior of the tested specimens. The direction of volumetric contraction is also shown in the figure. Clean Sile Sand 20/30 has started to contract with the initiation of shearing. Soon after 2.5 mm shear displacement is passed, the initial contraction diminishes until about 9 mm shear displacement, after which the amount of contraction increases again, however with a much slower rate compared to the initial contraction section. When 5% TT silt is added to the Sile Sand 20/30, the specimen contracted with the initiation of shearing, then showed a temporary dilation which is followed by contraction until failure.

When 15% TT silt is added to the Sile Sand 20/30, the amount of contractiveness has significantly increased compared to both the clean sand and sand with 5% TT silt, as the volume change curve is shifted downwards (Fig. 6). The volume change behavior is also changed compared to that of the clean Sile Sand 20/30 and sand with 5% TT silt. For this silty sand (with 15% TT silt), the amount of initial contraction is larger (i.e. close to one and a half times that of the clean sand and sand with 5% TT silt). Also the specimen continued to contract until the end of shearing with no intermediate dilation. These observations are also quite important if undrained loading conditions had prevailed, because the specimen would have more chance to generate progressive excess pore water pressures at the initial stages of shearing, which would inevitably influence its liquefaction potential.

As further TT silt is added to the Sile Sand 20/30 so that the fines content is increased to 25%, the volumetric contractiveness of the specimen has significantly increased compared to the sand with lower fines contents (Fig. 6). The amount of initial contraction is much larger (i.e. triple of the clean sand and sand with 5% TT silt, double of the sand with 15% TT silt) and this initial contraction continued until reaching greater shear displacements compared to other specimens (almost double of the other specimens). Also the specimen continued to contract until the end of shearing with no intermediate dilation.

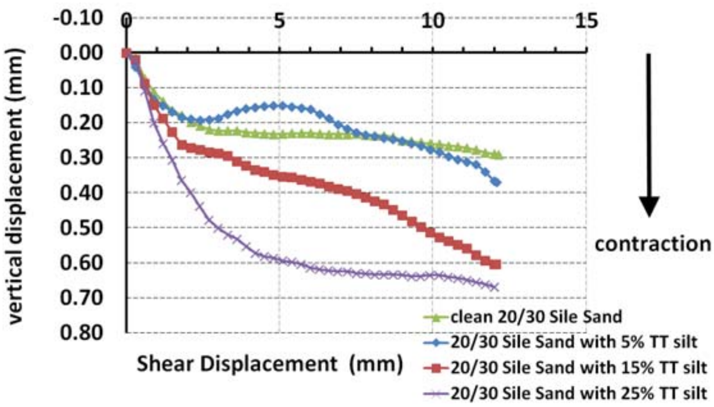


Fig. 6 Change of vertical displacement with increasing shear displacement for Sile Sand 20/30 as the base sand mixed with 5%, 15% and 25 % TT silt

Note that the consolidated void ratio of the clean Sile Sand 20/30 is significantly greater than the other silty sands shown in Fig. 6 (Table 2). Hence, had the clean sand been tested at a smaller void ratio similar to the other soils, its volume change curve would shift upwards, possibly above the 5% TT silt curve. Based on the experimental results, it could be stated that addition of TT silt to Sile Sand 20/30 steadily increased its volumetric contractiveness at similar void ratio.

Fig. 7 shows the change of vertical displacement with increasing shear displacement for specimens having Sile Sand 20/30 as the base sand but this time mixed with 5%, 15% and 25 % IZ silt. When 5% IZ silt is added to the Sile Sand 20/30, the amount of contractiveness decreased significantly compared to the clean sand. The specimen contracted with the initiation of shearing, after which the specimen has shown a temporary dilation, and finally the specimen has started to contract again until failure.

When 15% IZ silt is added to the Sile Sand 20/30, the amount of contractiveness has considerably increased compared to the sand with 5% IZ silt (Fig. 7). Even though the clean sand curve in Fig. 7 and curve for sand with 15% IZ silt is close to each other, it should be noted that the clean Sile Sand 20/30 specimen has a considerably greater void ratio compared to the other specimens shown in Fig. 7 (Table 2). Therefore, had the clean sand been tested at a smaller void ratio similar to the other soils, its volume change curve would shift upwards. But whether it would be above the 5% IZ silt curve is unknown.

When 25% IZ silt is added to the Sile Sand 20/30 volumetric contractiveness continues to increase compared to the sand with lower fines contents (Fig. 7). Also note that the void ratio of the specimen with 25% IZ silt is lower than the other specimens, hence had they been tested at the same void ratio, its curve would further shift downwards.

When Sile Sand 20/30 is mixed with IZ silt, the amount of initial contraction increases and the amount of intermediate dilation decreases with increasing fines content (Fig. 7). As discussed previously, the amount of initial contraction and intermediate dilation is also important for the excess pore water pressure generation capability of specimens. In general, similar to the TT silt, the addition of IZ silt to Sile Sand 20/30 increased its volumetric contractiveness at similar void ratio. Thus, inclusion of silt increases the shear contractancy considerably and this is consistent with findings in other studies (e.g., Bobei *et al*. 2009).

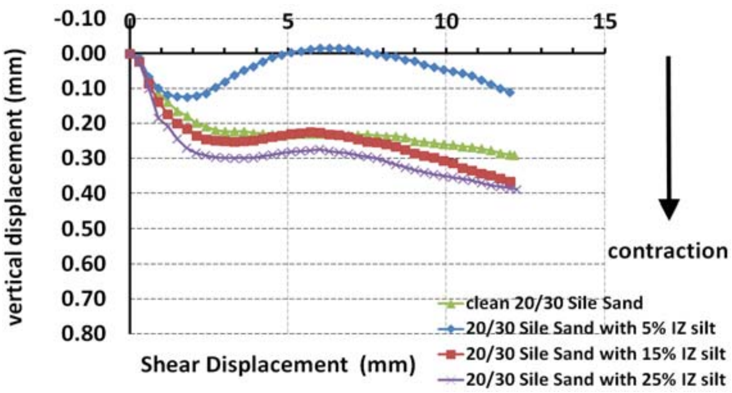


Fig. 7 Change of vertical displacement with increasing shear displacement for Sile Sand 20/30 as the base sand mixed with 5%, 15% and 25 % IZ silt

4.3 Influence of fines content on volume change behavior of soils with Sile Sand 80/100

Fig. 8 shows the change of vertical displacement with increasing shear displacement for different silty sands having Sile Sand 80/100 as the base sand and mixed with 5%, 15% and 25 % TT silt. Clean Sile Sand 80/100 has started to contract with the initiation of shearing. Soon after 2 mm shear displacement is passed, the rate of initial contraction decreased until about 5 mm shear displacement, after which it increased again.

When 5% TT silt is added to the Sile Sand 80/100, the volume change curve shifted downwards with increasing amount of initial contraction. The specimen contracted with the initiation of shearing until about 2.7 mm of shear displacement, after which the specimen has shown a very small amount of temporary dilation until about 6 mm of shear displacement. Then the specimen has started to contract again until failure. At high shear displacements (greater than 9 mm), the volume change curve for sand with 5% TT silt crosses the clean sand curve, however note that the specimen with 5% TT silt has a lower void ratio compared to the clean sand specimen (Table 2).

When 15% TT silt is added to the Sile Sand 80/100, the amount of contractiveness has significantly increased compared to both the clean sand and sand with 5% TT silt, as the volume change curve is considerably shifted downwards (Fig. 8). The volume change behavior is also changed compared to that of the sand with 5% TT silt. For this silty sand (with 15% TT silt), the amount of initial contraction is larger (i.e., close to triple of the clean sand and close to the double of the sand with 5% TT silt). Also the specimen continued to contract until the end of shearing with no intermediate dilation.

As further TT silt is added to the Sile Sand 80/100 so that the fines content is increased to 25%, the volumetric contractiveness of the specimen continued to increase compared to the sand with lower fines contents (Fig. 8). The amount of initial contraction is larger and this initial contraction continued until reaching greater shear displacements compared to other specimens. Similar to the sand with 15% TT silt, the specimen continued to contract until the end of shearing with no intermediate dilation.

Note that the consolidated void ratio of the specimens shown in Fig. 8 decreased with increasing

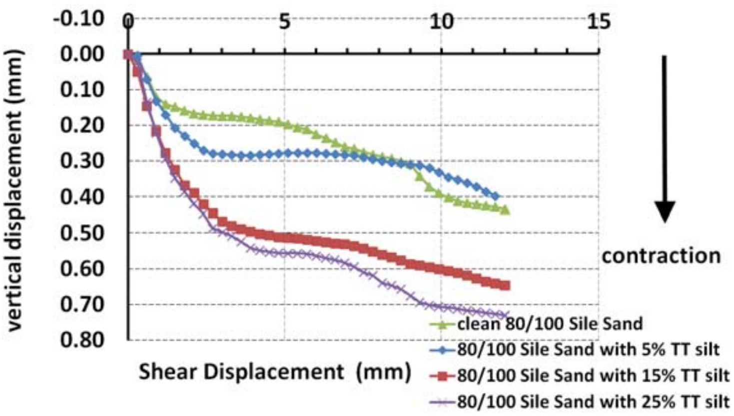


Fig. 8 Change of vertical displacement with increasing shear displacement for Sile Sand 80/100 as the base sand mixed with 5%, 15% and 25 % TT silt

fines content (Table 2). Hence, had they all been tested at the same void ratio, for example the void ratio of the clean sand the volume change curves of silty sands would shift further increasingly downwards with increasing fines contents. Based on the experimental results, it could be stated that addition of TT silt to Sile Sand 80/100 steadily increased its volumetric contractiveness at similar void ratio.

Fig. 9 shows the change of vertical displacement with increasing shear displacement for specimens having Sile Sand 80/100 as the base sand but this time mixed with 5%, 15% and 25 % IZ silt. When 5% IZ silt is added to the Sile Sand 80/100, the volume change curve shifted downwards with increasing amount of initial contraction. The specimen contracted with the initiation of shearing until about 2.4 mm of shear displacement, after which the specimen has shown a very small amount of temporary dilation until about 5.5 mm of shear displacement. Then the specimen has started to contract again until failure. At high shear displacements (greater than 6 mm), the volume change curve for sand with 5% IZ silt crosses the clean sand curve, however note that the specimen has a lower void ratio compared to the clean sand specimen (Table 2).

When 15% IZ silt is added to the Sile Sand 80/100 the volume change curve is shifted downwards compared to both the clean sand and sand with 5% IZ silt, indicating an increase in the amount of volumetric contractiveness (Fig. 9). For this silty sand (with 15% IZ silt), the amount of initial contraction is larger than the specimens with lower fines contents.

As further IZ silt is added to the Sile Sand 80/100 so that the fines content is increased to 25%, the volumetric contractiveness of the specimen continued to increase compared to the sand with lower fines contents (Fig. 9). The amount of initial contraction is larger and this initial contraction continued until reaching greater shear displacements compared to other specimens. Note that all the specimens except the clean sand in Fig. 9 have shown intermediate dilation. The least amount of intermediate dilation is observed for specimen with 25% IZ silt.

The consolidated void ratio of the specimens shown in Fig. 9 decreased with increasing fines content (Table 2). Hence, had they all been tested at the same void ratio, for example the void ratio of the clean sand the volume change curves of silty sands would shift further increasingly downwards with increasing fines contents. Based on the experimental results, it could be stated that addition of IZ silt to Sile Sand 80/100 steadily increased its volumetric contractiveness at similar void ratio.

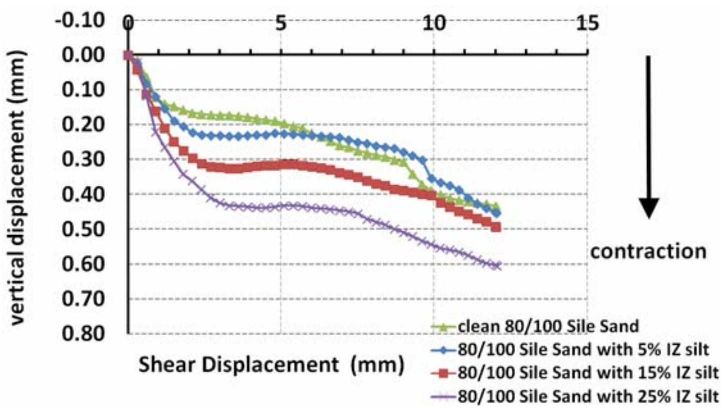


Fig. 9 Change of vertical displacement with increasing shear displacement for Sile Sand 80/100 as the base sand mixed with 5%, 15% and 25 % IZ silt

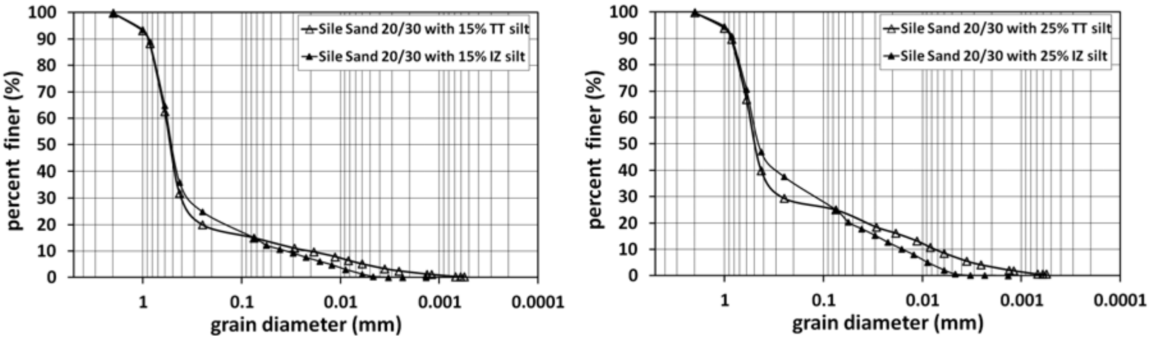
5. Effects of base sand and silt gradations on volume change behavior

5.1 Influence silt gradation on volume change behavior

Experimental results discussed in the previous section have shown that increasing fines content increased the volumetric contraction of silty sands for the tested range (i.e., FC $\leq$ 25%). On the other hand, analyses indicated that two different non-plastic silts could influence the amount of volume change of the same base sand differently. As an example, the increase in volumetric contraction of Sile Sand 20/30 due to FC was considerably lower when IZ silt used (Fig. 7) compared to when TT silt is used (Fig. 6) as fine grain matrix. Similarly, the increase in volumetric contraction of Sile Sand 80/100 due to FC was considerably lower when IZ silt used (Fig. 9) compared to when TT silt is used (Fig. 8) as fine grain matrix. It should be noted that, with a few exceptions consolidated void ratio values for specimens involving IZ silt were generally either similar or greater than that of their counterparts with TT silt (Table 2). Moreover, the consolidated relative densities for specimens involving IZ silt are consistently lower than their counterparts with TT silt (Table 2). Hence, if relative density was chosen as a comparison basis (i.e., if the results were compared at the same relative density and fines content), the difference in the amount of volumetric contractiveness would even increase. Consequently, TT silt made both of the base sands more contractive compared to the IZ silt at the same fines content.

This is an interesting finding, because one might expect that the smaller TT silt would more easily fit into the intergranular void space in-between the sand grains and could make base sands less contractive compared to the relatively larger IZ silt especially at low fines contents. In other words, the smaller TT silt has a greater chance to considerably fill up the intergranular void space, which could have caused a less contractive response. Moreover, the coefficient of uniformity of below No 200 portion of IZ silt is less than half of the C_u of TT silt (Table 1) indicating that the silt fraction of the IZ silt is not only bigger but also relatively more uniform than TT silt. At its natural state, IZ silt is still more uniform ($C_u = 7.9$) compared to the TT silt (Fig. 1). Therefore, one might expect that IZ silt with smaller mean grain diameter ratio ($D_{50\text{-sand}} / d_{50\text{-silt}}$) and coefficient of uniformity (Table 1) would make base sands more contractive compared to TT silt at the same FC. However, the experimental results indicated the opposite for the soils tested in this study. This implies that other factors are also influential on the volume change behavior of silty sands.

One of the reasons could be that the silty sands become relatively gap graded when TT silt was added, compared to the ones when IZ silt was added. As shown in Fig. 1, natural IZ silt has a fine sand percentage of 26%, and the base sands were mixed with silts in such a proportion that their fines contents (percent weight of grains smaller than 0.075 mm) with different silts were exactly the same. This influenced the lower section of the base sand gradation curve to a certain extent. Fig. 10(a) shows the gradation curves for Sile Sand 20/30 having 15% of different fines. Even though both silty sands had exactly the same fines content, sand involving TT silt was more gap graded compared to the sand involving IZ silt. This effect became more pronounced when the fines content is increased to 25% as shown in Fig. 10(b). Previous research has shown that gap gradation considerably decreases the undrained shear strength (i.e., increases the volumetric contractive tendency) for sands (Igwe *et al*. 2012). Therefore, it is possible that the differences in gap gradation of soils in this study caused by the silt gradation could have influenced their contractiveness in such a way that the more gap graded silty sand involving TT silt became more contractive compared to the silty sand involving IZ silt. This is consistent with recent findings that the effectiveness of the silt particles in transmitting forces in the solid skeleton is dependent on the



(a) (b)

Fig. 10 (a) Gradation curves for Sile Sand 20/30 at 15% FC with different silts; (b) Gradation curves for Sile Sand 20/30 at 25% FC with different silts

mean grain diameter ratio, $D_{50\text{-sand}} / d_{50\text{-silt}}$ (e.g., Rahman *et al*. 2008).

Fig. 10 also shows that coefficient of uniformity (C_u) alone is not a sufficient parameter for the assessment of volumetric contractiveness even for the same base sand mixed with different silts (i.e., an increase in C_u does not necessarily imply a decrease in volumetric contractiveness or vice versa). As observed in Fig. 10, C_u for silty sands with TT silt were greater than the C_u for silty sands with IZ silt, however silty sand specimens with TT silt were consistently more contractive than their counterparts with IZ silt as discussed before. A secondary factor influencing the volumetric contractiveness could be the shape effect of silt grains, however investigating such an effect is beyond the scope of this study.

5.2 Influence base sand gradation on volume change behavior

Experimental results in this study have also implied that base sand gradation (i.e., having same geologic origin but different size and gradation in this study) could influence the volume change behavior differently, even though soils involve same silt type, fines content and sand mineralogy. Therefore, the influence of fines content on volume change response of sand could also be affected by the base sand gradation as well.

When Figs. 6 and 8 are investigated, it is seen that for the same fines content and type (TT silt), soils involving Sile Sand 80/100 as a base sand showed a more contractive response especially at the initial stages of shearing (i.e., shear displacement values < 3 mm) compared to the soils involving Sile Sand 20/30 as a base sand. Though, this difference in the amount of contraction diminished towards the end of shearing. When Figs. 7 and 9 are investigated, it is seen that for the same fines content and type (IZ silt), soils involving Sile Sand 80/100 as a base sand once again showed a more contractive response especially at the initial stages of shearing (i.e., shear displacement values < 3 mm) compared to the soils involving Sile Sand 20/30 as a base sand. But this time, the difference in the amount of contraction continued towards the end of shearing. It should be noted that, specimens involving Sile Sand 80/100 have greater void ratios after consolidation compared to their counterparts involving Sile Sand 20/30 (Fig. 2), which inevitably affected the observed difference in the amount of contraction. Nevertheless, as explained in the "Experimental Results and Discussions" section, this difference in void ratio is also due to the intrinsic properties of the base sands such as size and gradation, since the same depositional method is used in the specimen preparation.

However, the consolidated relative densities for specimens involving Sile Sand 20/30 as a base sand were either very close or mostly smaller than their counterparts involving Sile Sand 80/100 for the same fines content and type (Table 2). Hence, if relative density was chosen as a comparison basis (i.e., if the results were compared at the same relative density and fines content), it can be stated that Sile Sand 80/100 makes the silty sand more contractive compared to the Sile Sand 20/30. In other words, at the same relative density, fines content, fines type and sand mineralogy, silty sands in this study become more contractive as the mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) and C_u of the silty sands decreases simultaneously due to base sand gradation (Table 1, Fig. 1). It should be noted that even though the C_u for Sile Sand 20/30 is almost double of the C_u for Sile Sand 80/100, both base sands can still be considered quite uniform. Therefore, for this case the influence of C_u on the observed contractiveness could be less compared to the influence of mean grain diameter ratio.

6. Conclusions

In this study, influence of soil gradation on shear strength and volume change behavior of silty sands was investigated. Two base sands (Sile Sand 20/30 and Sile Sand 80/100) of same geologic origin but different gradations and two different non-plastic silts (TT silt and IZ silt) with different gradations were mixed at different proportions such that two base sands and twelve different silty sands were obtained and utilized in a series of consolidated drained direct shear tests. Main findings are summarized as follows:

(1) Drained shear strengths of all sandy soils used in the experimental program were observed to be in a relatively narrow range (i.e., 83 to 91 kPa) and therefore drained shear strengths were not significantly influenced by either base sand gradation or silt gradation or fines content for the studied range ($\leq$ 25%).

(2) Increasing fines content was observed to increase the volumetric contraction of specimens at the same void ratio for the studied range (i.e., FC $\leq$ 25%). This trend was valid for both base sands mixed with different non-plastic silts.

(3) The amount of volumetric contraction of silty sands was found to be influenced by the non-plastic silt type and gradation, even though specimens involve same base sand and fines content. Interestingly, the smaller and less uniform TT silt consistently made both base sands more contractive compared to the larger and more uniform IZ silt at the same FC. One of the possible reasons was hypothesized to be the changes in the overall gradation of soils caused by the gradation of silts. Sands involving TT silt became gap graded compared to sands involving IZ silt, as IZ silt naturally contains 26% of fine sand sized grains and its mean grain size (d_{50}) is larger compared to TT silt. This difference in the gradation of two non-plastic silts influenced the amount of volumetric contraction of resulting silty sands.

(4) Coefficient of uniformity (C_u) was shown to be not a sufficient parameter alone as an indicator for volumetric contractiveness of the same base sand at the same fines content but with different non-plastic silts (i.e., an increase in C_u does not necessarily imply a decrease in volumetric contractiveness or vice versa).

(5) Base sand gradation was found to influence the volume change behavior of silty sands, even though soils involve same silt type, fines content and sand mineralogy. Therefore, the

influence of fines content on volume change response of a sand is also affected by the base sand gradation as well. As an example, at the same relative density, fines content, silt gradation and sand mineralogy, silty sands in this study became more contractive as the mean grain diameter ratio ($D_{50\text{-sand}}$ / $d_{50\text{-silt}}$) and C_u of the silty sands decreased simultaneously due to base sand gradation.

The findings of this study are important and promising in order to better understand the stress-deformation behavior of silty sands not only under drained conditions but also under undrained conditions as well. Considering the fact that the undrained behavior and excess pore water pressure generation of such soils are strongly proportional to their volume change tendencies, further research is still needed to extend the findings listed above and to figure out the importance of grain size distribution on the engineering behavior of silty sands. Indeed, this paper is a preliminary study of a much larger, ongoing research project on liquefaction of silty sands involving undrained monotonic and cyclic triaxial tests on further extended sand and silt types.

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