Compressibility as an Indicator of Liquefaction Potential

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ABSTRACT: It is difficult to impossible to obtain intact samples of loose, silty sand from coastal and offshore sandy soil deposits, which could potentially liquefy. To evaluate the liquefaction potential for such soils, a quantity that may be used as an indicator and can be measured in-situ is the volume compressibility. The more compressible the easier the soil will liquefy. Presented here is a study of three clean sands with the same geologic origin: Sile Sand 20/30, Sile Sand 50/55 and Sile Sand 80/100. Sile Sand 80/100 is also mixed with two types of non-plastic silts: TT Silt and IZ Silt. Three different fines contents of 5%, 15% and 25% are used for each of the two combinations of silty sands. Isotropic compression tests and undrained triaxial compression tests have been performed on these soils to determine their liquefaction potential and their compressibilities, and these are correlated with each other. Experiments have shown that volumetric compressibilities increase with increasing fines content for both silt types, which is similar to the observation of increasing liquefaction potential with fines content. Approximate boundaries for stable response, transition stage, and liquefaction region are determined. Accordingly, specimens with volumetric compressibility values smaller than 0.17 (1/MPa) were stable, while all specimens with volumetric compressibility values greater than 0.23 (1/MPa) liquefied. Further laboratory and in-situ tests on different sand and silt types are still needed to verify and tune those boundaries, which could potentially serve as indicators of liquefaction potential via in-situ compressibility tests.

KEYWORDS: Compressibility, Fines, Instability, Silty sand, Static liquefaction, Triaxial tests

1. INTRODUCTION

Liquefaction of both coastal and offshore sandy soil deposits is one of the intriguing issues in geotechnical engineering. This is due to important economic and social consequences of liquefaction and resulting ground failures such as lateral spreading influencing harbour facilities, or submarine flow slides damaging offshore platforms and marine structures etc. Liquefaction and corresponding slides in the Nerlerk undersea berm during its construction in 1983 as part of the foundation system of a hydrocarbon exploration platform at Beaufort Sea is perhaps one of the best examples of such a case history (Sladen et al. 1985; Konrad 1991; Lade 1993; Monkul 2006). Lade and Yamamuro (2011) gave a good summary of reported cases of static and seismic liquefaction of submarine slopes, earth dams and various types of fills and embankments. From these liquefaction cases it may be observed that the predominant soil type that liquefies is fine sand with certain amounts of silt.

In parallel with this observation, experimental research on liquefaction has shifted towards silty sand behaviour in the past two decades, rather than focusing on clean sands studied during the initial period of liquefaction research. Previous research has shown that fines content (FC) (Pitman et al. 1994; Lade and Yamamuro, 1997; Polito and Martin, 2003; Murthy et al., 2007), confining stress (σ'_3) (Yamamuro and Lade, 1997; Thevanayagam, 1998), and many other possible factors including the silt size (Monkul and Yamamuro, 2011), specimen preparation technique (Høeg et al, 2000; Wood et. al., 2008) influence the undrained behaviour of silty sands, and therefore makes the liquefaction problem more complicated. Moreover, it is almost impossible to obtain so called "undisturbed" sandy soil samples to investigate their liquefaction characteristics for the design of offshore and coastal structures. To evaluate the liquefaction potential for such soils, a quantity that may substitute as indicator and can be measured in-situ is the volume compressibility. Yamamuro and Lade (1998) and Lade et al. (2009) suggested that the more compressible the easier the soil will liquefy.

Previous studies have shown that for fine Ottawa sand mixed with Loch Raven silt, compressibilities reported in the range from 0.012 to 0.016 (1/MPa) and higher may lead to liquefaction under undrained conditions (Lade et al., 2009). Limiting volumetric compressibilities for Nevada sand with different fines contents tested by Yamamuro and Lade (1997, 1998) and Lade and Yamamuro (1997) were reported in the approximate range from 0.014 to 0.022 (1/MPa), i.e. very similar to those determined for the fine Ottawa sand mixed with Loch Raven silt. It is now realized that these ranges were incorrectly calculated and they are too low by a factor of ten (10). Thus, the volumetric compressibility values should have been:

> 0.12 to 0.16 (1/MPa) for fine Ottawa sand mixed Loch Raven silt, and0.14 to 0.22 (1/MPa) for Nevada sand with different fines contents.

The goal of the present study is to further investigate the relationship between the volume compressibility of sandy soils and their liquefaction potential. Isotropic compression tests and undrained triaxial compression tests have therefore been performed on three clean sands with the same geologic origin and on various silty sands obtained by using two non-plastic silts with different fines contents.

2. SOILS TESTED

Three clean sands from a sand quarry at the Sile region of Istanbul were obtained. These sands, which have the same geologic origin but different gradations, are named Sile Sand 20/30, Sile Sand 50/55 and Sile Sand 80/100. Their grain size distributions are shown in Figure 1. Two different non-plastic silts: IZ silt and TT silt were used in the experimental program.

TT silt was obtained from a stone quarry in the Sile region of Istanbul. It was produced by wet sieving of stone dust through the No 200 standard sieve (0.075mm). IZ silt is a naturally formed soil obtained from the city of Izmir. IZ silt has a natural fines content of 74%, but only the -No 200 portion (<0.075mm), obtained by wet sieving, was used in the experimental program. The grain size distribution curves of the two silts are also shown in Figure 1.

3. SPECIMEN PREPARATION AND TESTING PROCEDURE

All soils are deposited in a dry state into a cylindrical triaxial mold using the dry funnel deposition technique. The resulting specimens were about 7cm in diameter and 17cm in height in the dry stage (with height to diameter ratio about 2.4). It is well known that specimen preparation method can significantly influence the undrained response of sandy soils (Høeg et al., 2000; Wood et al., 2008). However, a discussion of the influence of the specimen preparation method is beyond the scope of this study, and the same method is consistently used for deposition through the entire testing programme. The details of the dry funnel deposition technique and a summary of common specimen preparation methods for sandy soils can be found in Monkul and Yamamuro (2010).

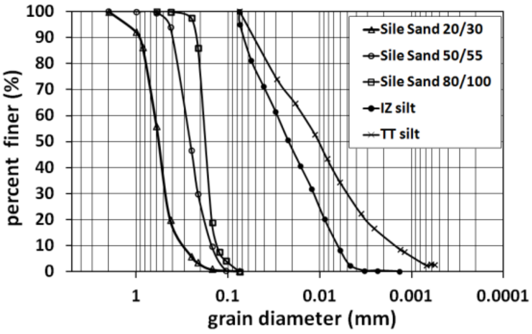

Figure 1 Grain size distributions of tested soils.

Once the specimens were deposited, CO_2 was flushed through the dry specimens from the bottom to the top for 20 min. Then, de-aired water was percolated in a similar fashion. Volume and height changes during saturation were monitored and considered in the calculations. A back pressure of 205kPa was applied prior to the B-value check to ensure saturation, and the resulting B-values were at least 0.99 for all tests in this study. Specimens were then isotropically consolidated to an effective confining stress of 30 kPa with computer controlled cell pressure increments less than 0.35 kPa, while maintaining zero excess pore pressure within the specimens. A computer controlled Geocomp triaxial testing system was used in the isotropic compression and triaxial compression tests. Once the consolidation stage ended, the strain controlled undrained triaxial shearing stage was started with an axial strain rate of 0.05%/min.

The triaxial test data were corrected for various factors including membrane stiffness, piston friction, piston uplift, buoyancy, and weights of piston with attached LVDT. Parabolic area correction for slightly barrelling specimen shapes was applied since lubricated ends were not used. Membrane penetration effect was negligible for the silty sands and was not considered in the corrections.

4. UNDRAINED TRIAXIAL COMPRESSION TESTS

At the end of dry funnel deposition, a given silty sand tends to have a "quasi-natural void ratio" provided that the same deposition energy is applied (Monkul and Yamamuro, 2011). However, different soils, such as the ones used in this study, would have different "quasi-natural void ratios" depending on their grain characteristics including grain size distribution, grain shape, fines content, etc. Thus, the "loosest possible density after deposition" is used as a common comparison basis in the literature for assessing the liquefaction potential of sandy soils (Zlatovic and Ishihara, 1995; Lade and Yamamuro, 1997; Georgiannou, 2006; Monkul and Yamamuro, 2011).

4.1 Undrained triaxial compression tests on clean sands

The change in deviator stress ($q = \sigma_1 - \sigma_3$) with axial strain is shown in Figure 2(a) for the three clean sands used in this study. Corresponding Cambridge *p'-q* diagrams are presented in Figure 2(b), in which *p'* shows the effective mean normal stress [i.e. $p' = (\sigma_1' + 2\sigma_3')/3$]. Note that all three clean sands have the same geologic origin, as explained in Section 2. The stress paths in Figure 2(b) demonstrate that as the sands becomes finer (Figure 1) and at the same time slightly more uniform (Table 1), their liquefaction resistance decreases. Accordingly, Sile Sand 80/100 has the lowest liquefaction resistance, while Sile Sand 20/30 has the highest. Also note that this conclusion is based on the "loosest possible density after deposition" as comparison basis. The consolidated void ratios of the specimens, given in Figure 2(a), increase as the sands become finer. Hence, it is unclear what the trend would be if they had been tested at exactly the same void ratio. However, it can reasonably be assumed that the consolidated relative densities given in Figure 2(a) are similar, i.e. practically in a narrow range of $D_r = 30 \pm 3\%$. Therefore, the liquefaction resistance of the sands in this study, when tested at similar relative densities, decreases as they become finer and more uniform. Consequently, Sile Sand 80/100 was found to have the least liquefaction resistance among the three sands tested.

Table 1 Index Properties of Soils Used in This Study

	Sile Sand 80/100	Sile Sand 50/55	Sile Sand 20/30	TT Silt	IZ Silt
CU	1.4	1.9	2.0	10.6	4.3
USCS symbol	SP	SP	SP	ML	ML
e_{max}	0.992	0.901	0.798	1.783	1.405
e_{min}	0.667	0.596	0.506	0.538	0.851
G_s	2.65	2.65	2.64	2.75	2.70

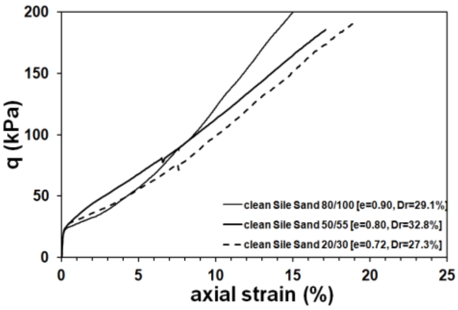

Figure 2(a) Undrained stress-strain relations for clean sands.

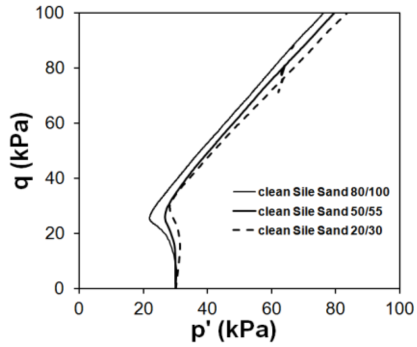

Figure 2(b) Effective stress paths on Cambridge p'-q diagram for clean sands.

4.2 Undrained triaxial compression tests on Sile Sand 80/100 with TT Silt

Figure 3(a) shows the change of deviator stress with axial strain when TT silt is added to the Sile Sand 80/100. Corresponding stress paths are given in Figure 3(b). Accordingly, liquefaction potential consistently increases with increasing fines content (FC) for the studied range (FC≤ 25%). In fact, specimens involving 15% and 25% TT Silt have both shown static liquefaction, i.e. the deviator stress is reduced to zero with progressing axial strain due to excess pore pressure generation. The conclusion of increasing liquefaction potential with increasing fines content is valid whether the "loosest possible density after deposition" or the same relative density is used as a comparison basis. One can compare the results at D_r =

35%, at which the curves for clean sand and sand with 5% TT Silt would become even stiffer than shown in Figure 3, i.e. show increasing liquefaction resistance. The void ratios of the tested specimens shown in Figure 3 indicates a slightly increasing trend with increasing FC, meaning that the base sand matrix has become looser with the addition of fines.

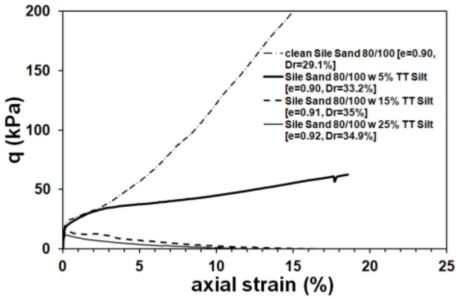

Figure 3(a) Stress-strain relations for Sile Sand 80/100 with TT Silt.

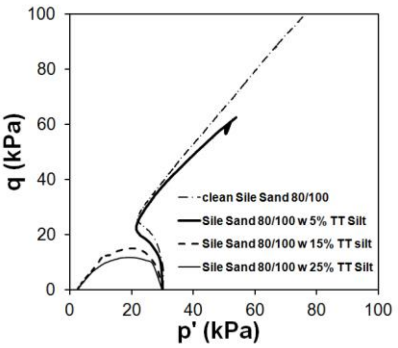

Figure 3(b) Effective stress paths on Cambridge *p'-q* diagram for Sile Sand 80/100 with TT Silt.

4.3 Undrained triaxial compression tests on Sile Sand 80/100 with IZ Silt

In this part of the investigation IZ Silt is added to the Sile Sand 80/100 instead of TT Silt in order to check the validity of the trends observed in the previous section with a different non-plastic silt. Figure 4(a) shows the change of deviator stress with axial strain, while Figure 4(b) shows the corresponding stress paths. Similar to TT Silt, adding IZ Silt to Sile Sand 80/100 consistently increased the liquefaction potential. Specimens involving 15% and 25% IZ Silt both showed static liquefaction. The conclusion of increasing liquefaction potential with increasing fines content is valid whether the "loosest possible density after deposition" or the same relative density is used as a comparison basis. One can project and compare the results at a relative density of 36%, since the D_r of the most liquefiable specimen, namely sand with 25% IZ Silt, in Figure 4 is 36%. This time the consolidated void ratios of the tested specimens are also in a relatively narrow range (i.e. e=0.895±0.006), hence the liquefaction potential of the Sile Sand 80/100 increased with increasing fines content of IZ silt at similar void ratios as well.

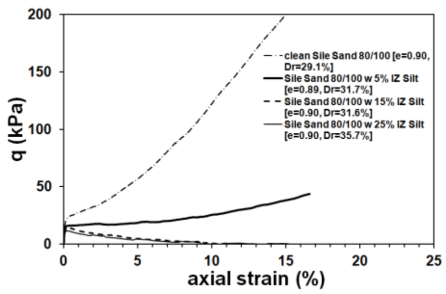

Figure 4(a) Stress-strain relations for Sile Sand 80/100 with IZ Silt.

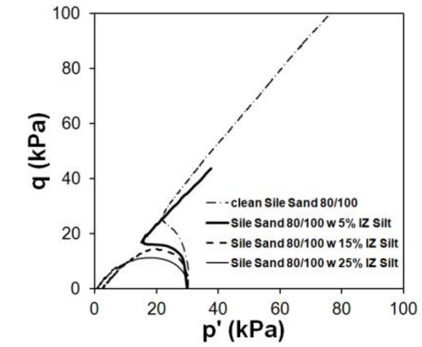

Figure 4(b) Effective stress paths on Cambridge *p'-q* diagram for Sile Sand 80/100 with IZ Silt.

5. ISOTROPIC COMPRESSION TESTS

The results of the undrained triaxial tests revealed a consistent increase in liquefaction potential of Sile Sand 80/100 with increasing non-plastic fines content. The volumetric strains (ε_v) plotted versus effective confining stresses (σ'_{3c}) during isotropic compression are given in Figures 5(a) and 5(b) for sand with TT and IZ Silts, respectively. Note that those are the same specimens used in the undrained triaxial compression tests.

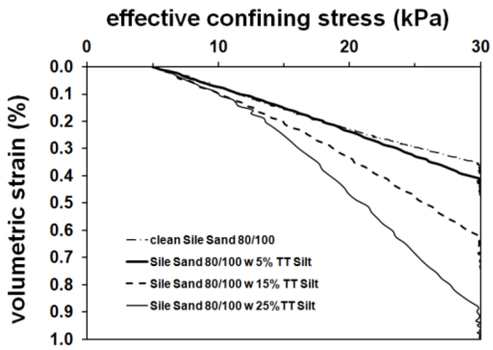

Figure 5(a) Volumetric strain variation with effective confining stress for Sile Sand 80/100 with TT Silt.

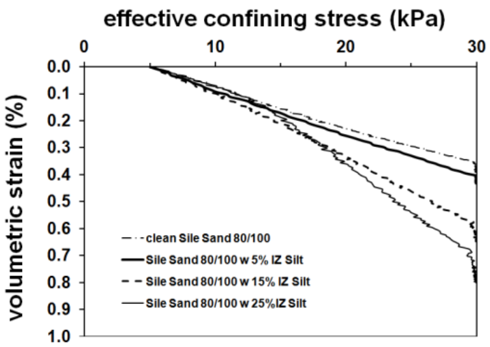

Figure 5(b) Volumetric strain variation with effective confining stress for Sile Sand 80/100 with IZ Silt.

It may be observed from Figure 5 that the volumetric strains increase almost linearly with increasing confining stress, and the amount of volumetric strain at the end of isotropic compression increases with increasing fines content for both silts. Volumetric compressibility, m_v, sometimes called the coefficient of volume change, is a parameter mostly used in analysing consolidation of soils. Eq. (1) shows that m_v is the increment of volumetric strain, $\varepsilon_v = \Delta V/V_{sat}$ divided by the increment of effective confining pressure:

$$m_v = \frac{d\varepsilon_v}{d\sigma'_{3c}} = \frac{\Delta\varepsilon_v}{\Delta\sigma'_{3c}} \tag{1}$$

The change of volumetric compressibility of Sile Sand 80/100 obtained by Eq. (1) with fines content is plotted in Figure 6. This figure clearly demonstrates that volumetric compressibility of a sand increases with fines content. This observation is parallel to the trend found in the undrained shearing stage, where liquefaction potential of Sile Sand 80/100 increased with fines content. In other words, volumetric compressibility could be an indicator for liquefaction potential.

Figure 6 also shows that the m_v-values for both silt types are close to each other and increasing in an almost parallel fashion until 15% FC, and then started to deviate considerably towards 25% FC. Based on the results shown in Figures 3 and 4, approximate boundaries for stable response and static liquefaction are also drawn in Figure 6, and the region in between is named the transition zone between stable behaviour and liquefaction. Accordingly, sandy specimens with volumetric compressibility values smaller than 0.17 (1/MPa) were stable, while all specimens with volumetric compressibility values greater than 0.23 (1/MPa) liquefied. It should be noted that these boundaries are approximate based on the specimens prepared at "quasi-natural void ratios" explained before, and the precise transition zone could be slightly narrower. However, it may be expected that somewhere in the transition zone, shown in Figure 6, the behavior of Sile Sand 80/100 would change from stable to temporary liquefaction, and then the behavior would gradually transform towards static liquefaction. Temporary liquefaction occurs when the deviator stress reaches an initial peak (q_{peak}) and then temporarily drops before it increases again until reaching steady state.

Nevertheless, Figure 6 shows that Sile Sand liquefies for $m_v \geq$ 0.23 (1/MPa) for both types of non-plastic silts. This value is interestingly of the same order of magnitude as the values reported by Lade et al. (2009), who performed undrained triaxial tests on fine Ottawa Sand with Loch Raven fines, and by Yamamuro and Lade (1998), who performed tests on Nevada sand with different fines contents.

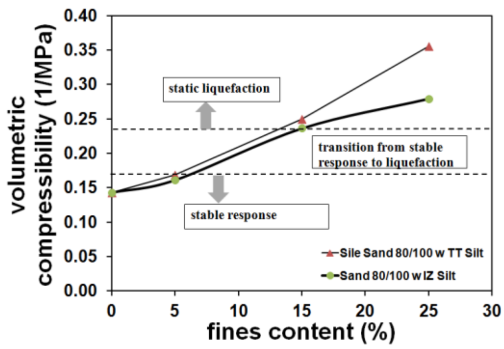

Figure 6 Volumetric compressibility versus liquefaction potential of Sile Sand 80/100 with fines content for two different non-plastic silts.

Figure 6 also shows that the numerical values of m_v do not enable a direct comparison of liquefaction potential of a sand at specific FC but with different silts. For example at FC=5%, m_v for sand with TT Silt is slightly greater than m_v for sand with IZ Silt, but sand with IZ Silt was more liquefiable than sand with TT Silt (see Figures 3 and 4). Similarly at FC=25%, m_v for sand with TT Silt is considerably greater than m_v for sand with IZ Silt, but their liquefaction potentials were almost the same (see Figures 3 and 4). In fact, these comparisons confirm the complexity of the liquefaction problem. Even though the same base sand is used, adding different silts while keeping plasticity and fines content the same may still change the soil fabric, which is critical for the resulting liquefaction behavior (Monkul and Yamamuro, 2011; Monkul 2012). There could be many factors influencing the fabric of sandy soils including but not limited to fines gradation, size, plasticity, content, angularity, mineralogy etc.

The change of volumetric strain of clean sands with confining stress is given in Figure 7. Once again numerical values of m_v do not enable a direct comparison of liquefaction potential of different sands even with same geologic origin. As observed in Figure 2, the liquefaction resistance of the clean sands in this study have decreased as they become finer and more uniform. Hence, Sile Sand 20/30 was the least liquefiable among the three clean sands, yet its volumetric compressibility was greater than the m_v-values of the other two clean sands as shown in Figure 7. However, it is important to note that m_v-values of clean sands are all in the range of the "stable response" zone discussed in Figure 6, which correlates well with the observed undrained behaviour.

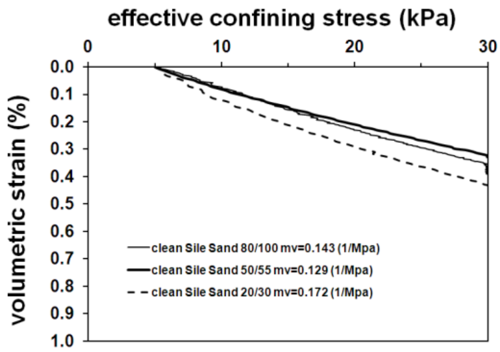

Figure 7 Variation in volumetric strain with effective confining stress and corresponding volumetric compressibilities for clean sands.

6. CONCLUSIONS AND SUGGESTIONS

In this study, an experimental investigation is conducted to investigate the possibility of considering volumetric compressibility (m_v) as an indicator of liquefaction potential for sands and silty sands, typically encountered in both offshore and coastal deposits. Isotropic compression tests and undrained triaxial compression tests were performed on three clean sands with the same geologic origin and six silty sands with two different non-plastic silt types at three different fines contents each.

Undrained triaxial compression tests revealed that the liquefaction resistance of clean sands used in this study have decreased as they become finer and more uniform when they are tested at similar relative densities. Consequently, Sile Sand 80/100 was found to be the most liquefiable among the three sands tested.

When silt is added to Sile Sand 80/100, the liquefaction potential of the resulting silty sands consistently increased with increasing fines content for the studied range (FC≤ 25%). This conclusion is verified for various comparison bases such as "loosest possible density after deposition," similar relative density and similar void ratio.

Isotropic compression tests on the same specimens suggest that there is a strong relationship between volumetric compressibility and liquefaction potential of sandy soils with different fines contents. The numerical values of m_v appear to enable a general comparison between soils involving different sand and silt types. The approximate boundaries for stable response, transition stage, and liquefaction region are determined. Accordingly, specimens with volumetric compression values smaller than 0.17 (1/MPa) were stable, while all specimens with volumetric compression values greater than 0.23 (1/MPa) liquefied.

Even though different sands and silts were used in this study, further laboratory and in-situ tests on different sand and silt types are still needed to verify and somewhat tune those volumetric compression boundaries for the benefit of geotechnical engineering practice. If such a verification is successful and approximate boundaries are established, perhaps including categories of different sandy soils, the necessity of the challenging task of obtaining undisturbed samples in sandy soils could be avoided. Instead, field tests such as screw plate, pressuremeter and flat dilatometer tests could be used to obtain equivalent volumetric compressibilities in-situ. This would also have the benefit of testing the soil at its original fabric, thus avoiding the problem of appropriate specimen preparation.

7. ACKNOWLEDGEMENT

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