AN ABSTRACT OF THE DISSERTATION OF

Mehmet Murat Monkul for the degree of Doctor of Philosophy in Civil Engineering presented on June 9, 2010.

Title: Influence of Silt Size and Content on Static Liquefaction Potential of Sand.

Abstract approved:

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Different specimen preparation methods such as moist tamping, dry funnel deposition, slurry deposition, dry air pluviation have been reported in the literature to investigate the undrained behavior of silty sands. Similarly, different means have been used to densify the soils prepared with such methods. However, the influence of the densification technique, utilized within a particular deposition method, on undrained behavior (e.g. change in initial peak deviator stress and instability angle) was not known. Therefore, a new densification technique is developed for the dry funnel deposition method, which avoids tamping, vibrating or mold tapping. This new method of densification is thought to create a much consistent soil fabric for different

amounts of densification than other specimen densification techniques. The experimental results show that the change in undrained behavior with increasing density produced by densification is much less pronounced when compared to the other densification methods reported in the literature.

Prior research efforts regarding the effect of non plastic silts on the liquefaction behavior of sands mainly focused on the influence of fines content, confining stress, and depositional techniques. However, there is no consensus in the literature regarding the influence of fines content on the undrained behavior of silty sands.

Strain-controlled monotonic undrained triaxial compression tests were performed on a single base sand mixed with three different essentially nonplastic silts. First, silt size effects are investigated while other factors like fines content (20%), confining stress (30kPa) and deposition method (dry funnel deposition) were kept the same. The results show that silt size is indeed an important factor which influences the liquefaction potential of silty sands. Different comparison bases for undrained behavior such as the loosest possible density after deposition, intergranular void ratio, void ratio and relative density were also evaluated. It was observed that as the mean grain diameter ratio (D_{50}/d_{50}) of the sand grains (D_{50}) to silt grains (d_{50}) decreases, liquefaction potential for a silty sand increases. This tendency is attributed to more metastable contacts with increasing silt size.

Finally, the influence of fines content on the static liquefaction potential of silty sand is investigated for different silt types. It was found that if the mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) is sufficiently small, the liquefaction potential of the sand increases steadily with increasing fines content for the studied range (0-20%). As mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) increases, the liquefaction potential of the sand first decreases then increases with fines content. For such cases, liquefaction potential of the silty sand might be less than the liquefaction potential of the clean sand. Differences in undrained behavior are explained based on the influence of mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) on the initial soil fabric.

Influence of Silt Size and Content on Static Liquefaction Potential of Sand

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Mehmet Murat Monkul, Author

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dedicated to my grandparents: Nazmiye Leman- Recep Monkul and

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INTRODUCTION

Liquefaction is a term used for cohesionless soils which suffers a drastic strength reduction when subjected to monotonic or cyclic loading so that it flows similar to a viscous liquid. Drained, strain controlled triaxial compression tests performed by Casagrande (1936) on initially loose and initially dense sands showed that all the specimens approached the same void ratio (called the critical void ratio, e_c) when sheared to large strains. Liquefaction was postulated to occur for sands that have initial void ratios above e_c. An analogous definition of steady state was given for undrained conditions as the state in which the soil mass is continuously deforming at constant normal effective stress, constant shear stress, constant volume, and constant velocity (Poulos, 1981). Steady state is assumed to ideally occur when the deviator stress becomes reasonably constant at a plateau in the stress-strain response. Verdugo and Ishihara (1996) mentioned that a condition of quasi steady state (QSS) exists in the midrange of strains, whereas the actual steady state is reached at quite large strains.

Instability

Sladen et al. (1985) defined a collapse surface based on the peak points of the undrained effective stress paths and stated that static liquefaction can occur if the soil state reached the collapse surface and the shear stress exceeded the (quasi) steady state shear strength. In their study, the steady state was assumed at the flat post-peak minimum value of the deviator stress at which the stress ratio (q/p') had reached a constant maximum value (even though a tendency of increasing deviator stress is observed at higher axial strains). Sands with stress states approaching or on the surface were stated to collapse if drainage is prevented. Sladen et. al. (1985) expressed the case as the initiation of the destruction of the metastable soil structure by static loading. Research has shown that only minimal excess pore pressure is adequate to trigger collapse if the soil state already is on the collapse surface. In other words, the loading may be drained up to the existing stress state until collapse is initiated by undrained conditions (Sladen et. al., 1985; Lade et al., 1988; Leong et al., 2000). Sladen et al. (1985) reported that the slope of the collapse line remains unchanged with a change in initial void ratio, but it is offset according to its steady state intercept.

Lade et al. (1988) also explained an instability approach considering the mechanics perspective. According to this approach, unstable behavior in undrained conditions may occur under decreasing stresses, which are accompanied by large plastic strains. The term failure is used when the maximum effective principle stress ratio, $(\sigma'_1/ \sigma'_3)_{max}$ is reached. In compression, the instability line passes through q_{max} $(\sigma_1- \sigma_3)_{max}$. These two conditions are reached simultaneously in drained tests. However, in undrained tests for loose soils $(\sigma_1- \sigma_3)_{max}$ can occur before $(\sigma'_1/ \sigma'_3)_{max}$. In this case instability might occur before reaching the failure surface since the geometry of the yield surface allows plastic strains to be produced under decreasing stresses. For the stress states on or above the instability line (where soil can deform plastically under decreasing stresses), the soil is found to be unstable in undrained condition. Lade (1993) concluded that the instability line goes through the origin of the stress diagram rather than the quasi steady state point and also observed that the slope of the instability line increases with a decrease in void ratio. Crossing the stress origin and change in the slope of the instability line with density are among the major differences between the collapse surface and current instability approaches.

Several other terminologies were used to refer the instability line, which passes through the top points of the undrained effective stress paths such as flow liquefaction surface (Kramer, 1996) or yield strength envelope (Olson and Stark, 2003). The name "instability line" will be used in this dissertation hereafter.

Undrained behavior of silty sands and influence of fines content

Field observations revealed granular soils often contain considerable amounts of silt. Consideration of this natural trend and questions regarding silt influence on engineering behavior of sandy soils have triggered the research on silty sands in the previous decade.

However, there are some discrepancies in the literature regarding the effect of silts on the undrained behavior of sands. Kuerbis et al. (1988) performed undrained triaxial tests on 20/200 Brenda mine tailings sand mixed with different fractions of Kamloops silt. They concluded that the silt content up to 20% slightly increases the dilatancy of the specimens under triaxial compression. In the same study, the intergranular void ratio (skeleton void ratio), which is essentially equivalent to the void ratio of the coarser grain matrix, is proposed as a basis for comparison of the shear strengths of silty sands with that of clean sands. Kuerbis et al. (1988) used slurry deposition method in the preparation of their samples. This method is intended to closely simulate the actual deposition process and to produce homogeneous specimens as compared with the water pluviation method (Kuerbis et al., 1988). However, as they also stated, the loosest void ratio following the slurry deposition method decreases substantially with fines content. On the other hand, the intergranular void ratio following the deposition remained in a fairly narrow range, which caused the increasing dilatancy with fines. The relative density of their specimens continued to increase with increasing fines.

Pitman et al. (1994) also expressed that the presence of fines decreases the instability potential of silty sands. They performed undrained triaxial compression tests on Ottawa sand mixed with different fractions of either kaolinite, crushed silica fines or 70/140 fine silica sand. Pitman et al. (1994) concluded that the base sand gradation (i.e. uniform or well graded) does not affect the undrained response significantly. Another interesting observation was that for a given fines content, the instability angles and steady state friction angles were approximately the same for different types of fines (i.e. $\phi'_i \approx 15°$, $\phi'_{ss} \approx 30°$ independent of the fines type at a given fines content, FC). A similar observation in terms of steady state friction angles was also reported by

Ni et al. (2004). Pitman et al. (1994) prepared their specimens by the moist tamping method, in which reconstituting homogeneous samples might be a problem. For kaolinite fines, consolidated void ratios (both global and intergranular) decreased up to a FC of 20% and then increased. However, for the crushed silica fines, the intergranular void ratio increased continuously, even though the void ratio showed a similar pattern as that of the kaolinite. In other words, type and gradation of fines in sandy soils seems to affect both the trend of intergranular contacts and the state of the finer grain matrix. For instance, when the void ratios are inspected, samples with kaolinite have much lower values than the samples with crushed silica fines at the same fines content. Pitman et al. (1994) attributed this to the different characteristics of the grain shapes. Accordingly, the flat elongated shapes of the kaolinite paricles resulted in lower void ratios as compared to the crushed silica fines. The relative density of their specimens both containing kaolinite and crushed silica fines increased with increasing fines up to 20%.

Salgado et al. (2000) also noted that silt content increases the dilatancy of the silty sands compared to clean sands based on drained triaxial compression tests on isotropically consolidated Ottawa sand (SP) with 0 to 20% Sil-Co-Sil #106 fraction. Their comparison basis was also relative density. However, especially for loose samples, the reported relative density range was quite high, i.e. between 24.3% and 46.1% for σ'_3=400kPa. For dense samples, a narrower range of relative densities were reported between 74.1% and 80.3% for σ'_3=100kPa. Salgado et al. (2000) prepared their specimens by slurry deposition method. They also stated that the critical state friction angle of a silty sand increases with increasing fines content.

Georgiannou (2006) performed anisotropically consolidated undrained triaxial compression tests on two different sands (Jumana Sand and Ham River Sand) as well as those sands mixed with 2.5% HPF4 silt. Tests on clean sands showed that relatively well graded and coarser Jumana Sand was more liquefiable than the Ham River Sand. Similar to Lade and Yamamuro (1997), Georgiannou(2006) used the loosest possible density after deposition as a comparison basis for different soil specimens. The basic idea is that the soil would tend to fall into a “quasi-natural” void ratio, provided that the depositional method is the same. The “quasi-natural” void ratio represents the loosest possible density when deposited in exactly the same manner for different soils. This ensures the same amount of energy of deposition (Lade and Yamamuro, 1997). Georgiannou (2006) concluded that the presence of silt increased the liquefaction resistance of both sands.

Yamamuro and Lade (1997) had shown that very loose silty sands might show a decreasing contractiveness with increasing confining pressure in a relatively low pressure range where particle rearrangement is the primary mechanism. Compared to loose clean sands, which show increasing contractiveness with increasing confining pressure, this kind of loose silty sand behavior is quite abnormal. This so-called reverse behavior of silty sands was also observed by other researchers (Ng et al., 2004). The reverse behavior was hypothesized on the basis of a metastable structure. Accordingly, silt particles were located at the contact points of the sand grains after deposition, which were then pushed into the intergranular voids when the specimen was isotropically consolidated and/or sheared (Yamamuro and Lade, 1997). The type of depositional method with a low energy input seems to be important in order to obtain the metastable structure, in which the load sustaining sand grains was initially held apart by the silt grains.

Unlike the previously reviewed literature, Lade and Yamamuro (1997) found that the static liquefaction potential increased with increasing fines content. They prepared their specimens by the dry funnel deposition method and used the loosest possible density as their comparison basis. In their study two different base gradations of Nevada sand were produced (No 50/80 and No 50/200). Also two different gradations of Ottawa sand were utilized (50/200 and 60/200 Ottawa F-95 sand). All base gradations were reported as having angular sand grains, except the Ottawa F-95, which was subrounded. Undrained triaxial compression tests were conducted at relatively low initial confining pressures (i.e. 25 kPa) because static liquefaction of loose silty sands is more prevalent at low confining pressures up to a certain relative density (31% for that particular sand) at which the mentioned reverse behavior disappears (Yamamuro and Lade, 1997). This is possibly because more metastable contacts are preserved at low initial confining pressures.

Lade and Yamamuro (1997) showed that as the fines content increased, the effective stress paths were depressed with a lower maximum value of deviator stress and the soil liquefied at lower values of axial strain. It was also observed that the potential for static liquefaction increased with fines content for all base sands (Nevada sand 50/80 and 50/200, Ottawa sand 50/200 and Ottawa F-95 sand), even though the relative and absolute densities generally increased with increasing fines content. The effect of base sand also seems to be an important factor. For instance without any fines, Nevada sand 50/200 showed a more contractive tendency than Nevada 50/80 sand. This finding shows some contrast to the study by Pitman et al. (1994), who stated that the base sand gradation (i.e. uniform or well graded) does not affect the undrained response significantly. As also expressed by Lade and Yamamuro (1997), it might be that grains between the No.80 and No.200 sieves helped the relatively larger grain matrix to be arranged in a looser structure. Ottawa sand was reported to be more resistant to liquefaction than the Nevada sand (Lade and Yamamuro, 1997). In the same study, void ratios of specimens after deposition decreased with increasing silt content up to 20%. However, intergranular void ratios continued to increase, which might have increased the contractive tendency with increasing fines content.

Thevanayagam (1998) examined effects of fines and confining stress on the large strain undrained strength of silty sands (steady state strength) prepared by the dry air pluviation method. He performed undrained triaxial compression tests on a sand (including 2% natural fines) mixed with two types of non-plastic fines (Sil-Co-Sil #40 and kaolin silt fines, KS). Tests were performed using 10% and 25% of KS, as well as using 10% of Sil-Co-Sil #40. Thevanayagam (1998) investigated the behavior with constant low fines content (FC) within various cases: Case 1) high densities, when $e_s < e_{max\text{-Host Sand}}$, resulting in low to no influence of fines on shear strength, Case 2) intermediate densities, when e_s is close to $e_{max\text{-Host Sand}}$, Case 3) low densities, when $e_s > e_{max\text{-Host Sand}}$, resulting in low shear strength. In order to obtain Case 3, fines should form a metastable structure as explained by Yamamuro and Lade (1997). Therefore, as mentioned by Thevanayagam(1998), if one moves from Case 1 to Case 3, the intergranular contacts decrease progressively, but the sensitivity of the active contacts to confining stress increases. More explicitly when $e_s < e_{max\text{-Host Sand}}$ the effect of confining stress was not observed significantly for the specimens consolidated to same e_s. However, when $e_s \geq e_{max\text{-Host Sand}}$, the effect of confining stress was observed clearly (Thevanayagam, 1998). Even though not explicitly discussed by Thevanayagam himself, one can comment based on the test data that for similar relative densities, increasing amount of fines decreased the undrained shear strength.

Murthy et al. (2007) conducted undrained triaxial tests on clean Ottawa sand and Ottawa sand mixed with SilCoSil106. They reported that increasing silt content increased the instability potential of silty sands.

Other factors influencing undrained silty sand behavior

Consolidation history, strain rate and depositional technique are among the other factors influencing the undrained response of silty sands. Unlike the effect of fines, there is consensus in literature on the influence of these factors on soil behavior.

Anisotropic consolidation does not influence the instability friction angle of soils significantly unless the consolidation path is steeper than the slope of the instability line (Vaid et al., 1989; Doanh et al., 1997; Imam et al., 2004).

Previous research reported that increasing strain rate influences the undrained behavior of sands such as increasing q_{max} and decreasing ϕ' (Whitman and Healy, 1962; Yamamuro and Lade, 1993). Increasing strain rate was reported to decrease the volumetric contractiveness of silty sands. Therefore, slow deformation control is suggested in order to be on the conservative side of the undrained silty sand analyses (Yamamuro and Lade, 1998).

Depositional technique is known to be very influential for the stress-strain behavior of soils observed in laboratory tests. Various depositional techniques were used in the literature for depositing silty sand specimens such as dry funnel deposition (Ishihara, 1993; Zlatovic and Ishihara, 1995; Lade and Yamamuro, 1997; Yamamuro and Wood, 2004; Bahadori et al., 2008; Sitharam and Dash 2008), dry air pluviation (Thevanayagam and Mohan, 2000), moist tamping (Shen et al., 1977; Pitman et al., 1994; Erten and Maher, 1995; Zlatovic and Ishihara, 1995; Ni et al., 2004; Hazirbaba and Rathje, 2009; Polito and Martin II, 2003; Papadopoulou and Tika, 2008), water sedimentation (Zlatovic and Ishihara, 1997; Vaid at al., 1999; Yamamuro and Wood, 2004), slurry deposition (Kuerbis et al., 1988; Salgado et al., 2000; Murthy et al., 2007; Carraro and Prezzi, 2008). Dry deposition techniques were shown to produce more contractive specimens compared to the wet deposition techniques (Yamamuro and Wood, 2004).

Several researchers suggested different specimen preparation methods in order to resemble the natural deposition process, to simulate the soil fabric formed during construction of earth structures, or to simply eliminate the disadvantages of other specimen preparation methods. For instance, slurry deposition was proposed to simulate the fabric of hydraulic fills and to eliminate the non-uniformities of void ratio compared to moist tamping (Kuerbis and Vaid, 1988; Carraro and Prezzi, 2008). Vaid et al. (1999) later compared air pluviation, moist tamping and water pluviation methods and debated that water pluviation is a convenient way to simulate the natural alluvial deposition and hydraulic fills. Moreover, stress-strain responses of water pluviated specimens were stated to be fairly close to their so called undisturbed counterparts (Vaid et al., 1999; Høeg et al., 2000). Nevertheless, considering the fact that each soil deposit has its own creep and aging effects influencing its in situ fabric and stress-strain response, duplicating the natural deposition process and the exact in situ soil behavior afterwards with any laboratory specimen preparation method is very difficult if not impossible.

Missing aspects and unknowns in literature

Current geotechnical engineering practice and research considers fines content and/or plasticity index to characterize the behavior of silty sands. In other words, the limiting grain size of 0.075mm is treated as a dividing number in order to assess the influence of fines. Is the laboratory densification technique important for the resulting response of silty sand specimens? Does a sand with same amount of different fines give similar undrained response? Does fines content influence the undrained behavior same for a sand with different silts? This dissertation seeks the answers to the aforementioned questions. Each of the questions is investigated and reported on in an individual article contained in separate chapters.

In Chapter 2, an overview of specimen preparation methods for silty sands and densification techniques is given. A new specimen densification technique is introduced. Influence of densification technique on undrained response of silty sands is compared with different soils and densification techniques in the literature.

In Chapter 3, variations in liquefaction behavior of a sand caused by changes in silt gradation is investigated at a constant fines content. Sand specimens were tested with three different essentially nonplastic silts at various densities achieved by the new densification technique explained in Chapter 2. Different comparison bases were utilized to explain the observed behavior change.

In Chapter 4, influence of silt size and content on liquefaction behavior of sands is investigated. Similar to Chapter 3, sand specimens were tested with three different essentially nonplastic silts, but this time at different fines contents. Different comparison bases were utilized to explain the observed behavior change. Influence of silt size on initial soil fabric is discussed at small fines content and at greater fines content respectively.

In Chapter 5, conclusions are given and practical implications of the findings are discussed together with the suggestions and future research.

INFLUENCE OF DENSIFICATION METHOD ON SOME ASPECTS OF UNDRAINED SILTY SAND BEHAVIOR

Mehmet Murat Monkul and Jerry A. Yamamuro

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Absract

Different specimen preparation methods such as moist tamping, dry funnel deposition, slurry deposition, dry air pluviation have been reported in the literature to investigate the undrained behavior of silty sands. Similarly, different means have been used to densify the soils prepared with such methods. Ongoing research shows that the change in undrained behavior (e.g. change in initial peak deviator stress and instability angle) due to different deposition densities is significantly affected by the densification technique utilized within a particular deposition method. It is believed that those variations are closely related with changes in the initial soil fabric that is achieved after the deposition. In this study, a relatively new densification technique, avoiding mold tapping, is used with the dry funnel deposition method. This new method of densification is thought to create a soil fabric that is much closer to the initial fabric than other techniques. The experimental results show that the change in undrained behavior with increasing density by densification is much less pronounced when compared to the other densification methods reported in the literature.

Introduction

Laboratory testing of soils is an essential part of geotechnical engineering both for research and design purposes. Triaxial compression tests are perhaps among the most widely used tool for investigating the undrained behavior of cohesionless soils and obtaining corresponding strength parameters.

For design practice, laboratory deposited specimens are usually consolidated under a confining pressure corresponding to the in-situ effective overburden stress. However, for both design and research purposes, densification after deposition might be needed in order to obtain a desired density.

It is well known that depositional method for specimen preparation influences the undrained reponse of sands and silty sands greatly (Vaid et. Al. 1999; Høeg et al., 2000; Yamamuro and Wood, 2004). On the other hand, influence of densification styles embedded in to the commonly used depositional methods on undrained behavior of silty sands is not known.

In this study, a new densification method for dry funnel deposition is developed. Influence of this densification method on some aspects of undrained silty sand behavior such as initial peak principal stress difference (q_{peak}) and effective instability friction angles (ϕ'_i) is investigated via triaxial compression tests and comparisons are made with other silty sands in literature densified with other means.

Overview of Specimen Preparation Methods for Silty Sands and Densification Techniques

Various deposition methods such as moist tamping, dry funnel deposition, slurry deposition, dry air pluviation are employed to prepare silty sand specimens in the literature. How well the specimens prepared with those methods represent the actual in situ soil behavior is often questioned. Considering the fact that each soil deposit has its own creep and aging effects influencing its in situ fabric, this question is beyond the scope of this paper.

Moist Tamping

Moist tamping (MT) is a commonly used method for silty sand preparation. Details of the method are well explained in literature (Ladd, 1978; Frost and Park, 2003). Using moist tamping for silty sands has been subjected to some criticism because reconstituting homogeneous samples can be a problem (Ishihara, 1993; Pitman et al., 1994; Vaid, 1994, Vaid et al., 1999).

Densification (obtaining greater density) of the specimens is achieved by adjusting the moist weight of the soil required for each layer. As the name of the method implies, layers are formed by tamping. Achieving wide range of densities (from very loose or dense) is the major advantage of this method.

Slurry Deposition

Slurry deposition (SD) is another commonly used specimen preparation method for silty sands. It was proposed that the slurry deposition method is able to simulate the fabric of hydraulic fills and produces homogeneous specimens compared to moist tamping (Kuerbis and Vaid, 1988; Carraro and Prezzi, 2008). Polito and Martin II (2001) compared the moist tamping method with slurry deposition method through a limited number of tests. Even though the specimens prepared by slurry deposition method had relative densities two times greater than specimens prepared by moist tamping, the cyclic resistance of the samples prepared by slurry deposition was close to the half of that prepared by moist tamping method. Murthy et al. (2007) reported that moist tamped specimens had considerably larger initial peak principal stress difference (q_{peak}) than slurry deposited specimens.

Densification of the specimens is performed via mechanical vibrator or soft hammer (Kuerbis and Vaid, 1988; Carraro and Prezzi, 2008).

Water Sedimentation

Different water sedimentation (WS) techniques for silty sands have been used in the literature. Some involve depositing dry soil through water (Zlatovic and Ishihara, 1997; Vaid at al., 1999), while others involve depositing pre-saturated soil through water (Yamamuro and Wood, 2004).

Densification of the specimens is performed by tapping the base (Vaid et. al., 1999) or side of the mold (Huang and Huang, 2007) by a soft hammer.

Air Pluviation

Various air pluviation (AP) techniques have been explained in the literature for silty sands (Brandon et al., 1991; Thevanayagam, 1998; Vaid et al., 1999; Georgiannou, 2006; Wood et al., 2008; Monkul and Yamamuro, 2010a). The most common method is to rain the soil through a dispersing screen down a tube with an equivalent inside diameter as the split mold.

Vaid et al. (1999) performed undrained simple shear tests and reported that volumetric contractiveness of the Syncrude silty sand increased with water pluviation, air pluviation and moist tamping, respectively for the same relative density.

Densification of the specimens can be performed either by tapping (Vaid et. al., 1999) or tamping of multiple deposition layers (Thevanayagam, 1998) or decreasing the deposition rate (Brandon et al., 1991; Wood et al., 2008; Monkul and Yamamuro, 2010a).

Dry Funnel Deposition

Dry funnel deposition (DFD) is also a common specimen preparation method for silty sands (Ishihara, 1993; Zlatovic and Ishihara, 1995; Lade and Yamamuro, 1997; Yamamuro and Wood, 2004; Bahadori et al., 2008; Sitharam and Dash 2008; Wood et al., 2008).

Densification of the specimens was essentially achieved by tapping. After the funnel containing silty sand was carefully raised along the axis of symmetry, the split mold was gently tapped in a symmetrical pattern (Lade and Yamamuro, 1997). Later, Wood et al. (2008) named this technique as tapped funnel deposition (TFD) and started to prepare specimens by raising the funnel faster which require less tapping and named as fast funnel deposition (FFD). Sitharam and Dash (2008) used multi layer deposition with different densities and tapped the mold for each layer separately to achieve a uniform density at the end.

Influence of Densification Technique on Initial Soil Fabric

The overall volumetric contractive soil behavior of silty sands is thought to be composed of two components. The first component is based on the elimination of unstable or ‘metastable’ soil grain contacts. ‘Metastable’ contacts occur when the smaller silt grains get lodged between the larger sand grains. These are considered ‘metastable’ because they are highly unstable and even small additional forces will result in the smaller silt grain being dislodged into the void space. The second component of volumetric contractiveness is associated with general contraction of the larger sand skeleton. This is the component that dominates if the soil is a loose clean sand as opposed to a silty sand. The grain contacts associated with general reduction of the larger sand skeleton are much more stable and require relatively larger shear forces to initiate this type of volumetric contractive behavior. Since silty sands have both of these two components, it has been shown that the stress-strain behavior of loose silty sands can be quite different from conventional loose clean sands (Yamamuro and Lade, 1997).

The term “metastable structure” was probably first introduced by Terzaghi (1956) in order to explain the collapse of fine grained cohesionless sediments. Hanzawa et al. (1979) also discussed “metastable” contacts in order to explain the static liquefaction potential at a silty sand deposit which was later subjected to ground improvement. More recently, “metastable” contacts for a particular silty sand was also quantified by Yamamuro and Wood (2004) and Yamamuro et al. (2008).

Virtually all specimen preparation methods reviewed so far involve a densification technique utilizing either vibrating, tamping or tapping. These densification techniques are believed to inevitably and significantly influence the soil fabric and the resulting undrained response. These densification techniques may affect silty sands much more than clean sands.

It is hypothesized that using tapping, tamping or vibrating to densify the soil might cause selective elimination of the “metastable” contacts between sand and silt grains, since these are the most susceptible contacts to vibration. Much greater levels of vibration are necessary to invoke general contraction of the sand skeleton.

The selective elimination of “metastable” contacts by mold tapping or vibrating is believed to greatly change the overall soil fabric as shown in Fig. 2.1. Fig. 2.1(a) shows the soil fabric for a silty sand achieved after a low energy deposition process. As densification is applied via tapping, tamping or vibrating, the amount of “metastable” contacts are substantially reduced as shown in Fig. 2.1(b). This reduction would significantly decrease the volumetric contractiveness and pore pressure generation during undrained shearing stage associated with a relatively small increase in density. Thus, a small change in density from tapping or vibration may result in a disproportionate change in the undrained behavior.

Therefore, regardless of how close a specimen preparation method to natural deposition, its densification technique may significantly influence its undrained behavior. In order to investigate this influence, a new densification technique is developed for dry funnel deposition. This new technique is simple and does not involve any vibrating, tamping or tapping. A funnel with a brass tube attached to its spout is positioned at the bottom of the split mold. Once dry silty sand is poured into the funnel, it is raised gently along the axis of symmetry of the specimen. Longer tubes were attached to the funnel to achieve greater densities but with similar soil fabric. In this technique, densification is achieved with the increased depositional energy due to increased tube lengths, as illustrated in Fig. 2.2. Since there is no following tapping or vibrating to achieve the target density it is thought that the undrained behavior will reflect a more smooth and continuous change with resulting density because the relative number of 'metastable' contacts will be proportional to the density. The limitation of this densification technique was the inability to create a wide range of densities.

Soils Tested and Experimental Program

Nevada Sand-B with a specific gravity (G_s) of 2.68 is used as a base sand and mixed with non-plastic Loch Raven silt (G_s=2.73), resulting a silty sand with 20% fines (particles smaller than 0.074mm in diameter) by dry weight. Corresponding grain size distribution curve is given in Fig. 2.3.

Strain-controlled monotonic undrained triaxial compression tests were performed with cylindrical specimens of 7.1cm diameter by 14.2 cm height (H/D=2). Lubricated ends and oversized end platens were used in order to promote uniform strains. Specimens were flushed with CO_2 in a dry state for 40 minutes prior to saturation. De-aired water was percolated from the bottom through the top of the specimens A back pressure of 100 kPa was applied prior to the B value check to ensure full saturation. Obtained minimum B values were 0.99 for all tests. The strain rate used was 0.05%/min during undrained shearing after the specimens were isotropically consolidated under 30kPa confining pressure. During the entire specimen preparation process care was taken in order to keep the effective stress at a maximum value of 15 kPa to prevent over-consolidation.

Results of Undrained Triaxial Compression Tests

Change of principal stress difference (q) with axial strain is shown in Fig. 2.4. Consolidated void ratios (e) and corresponding relative densities (D_r) are also shown on the same figures for specimens with three different densities (L1, L2, L3). As can be observed in Fig. 2.4 complete static liquefaction occurred for the specimens with the smaller two densities (L1 and L2). Static liquefaction occurs when the principal stress difference (q) is reduced to zero and remained zero with axial strain, while excess pore water pressure reaches a plateau. Static liquefaction coincided with the formation of large wrinkles in the membranes surrounding the specimens. Axial strain for static liquefaction increases slightly with increasing density (Fig. 2.4).

Temporary liquefaction was observed for specimen L3 with the greatest density (e_c= 0.74). Temporary liquefaction is exhibited by the principal stress difference achieving an initial peak (q_{peak}), which then reduces to a local minimum nonzero value (quasi steady state, q_{qss}) and then it increases with axial strain to a maximum value which is the true steady state strength. The decline of the principal stress difference from q_{peak} to q_{qss} corresponds to the region where the excess pore pressure reaches its maximum value. Similarly, due to the suppression of dilation, the excess pore pressure declined with continued shearing, which caused the principal stress difference to increase beyond q_{qss} to its ultimate value.

Greater specimen densities than shown in Fig. 2.4 were needed in order to observe complete stable behavior. As mentioned before, the nature of the depositional method employed in this study did not allow achieving denser specimens than shown in Fig. 2.4.

Comparisons with Different Silty Sands Densified with other Techniques in the Literature

Various silty sands tested at isotropically consolidated undrained monotonic triaxial conditions are selected and necessary values are read or calculated either from the stress-strain diagrams, stress paths or tables, whichever was available in the related literature. Test series in Table 2.1 were selected, so that the confining stress for a particular silty sand was either the same or very close, but with different relative densities.

Influence of Densification Technique on the Initial Peak Principal Stress Difference (q_{peak})

Comparisons are made with other silty sands in the literature whether densification technique influences the initial peak principal stress difference (q_{peak}). The q_{peak} gives a critical clue about the evolution of the collapse surface (Sladen, 1985) or the instability line (Lade, 1993) with increasing density, since the instability line passes through q_{peak}. The same surface is also termed with different names in the literature (e.g. critical effective stress ratio line (Vaid and Chern, 1983), peak strength envelope (Konrad, 1993), flow liquefaction surface (Kramer, 1996), yield strength envelope (Olson and Stark, 2003a)). When the instability line is reached, granular soils cannot sustain more shear stress and start to deform plastically under decreasing shear stress for undrained conditions. Fig. 2.5 shows typical stress paths for a silty sand in Cambridge p'-q space. As the relative density increases by various densification techniques, q_{peak} also increases.

The q_{peak} can also be related with the cyclic response of soils to a certain extent. Several researchers have experimentally verified that the instability line passing through q_{peak} obtained from monotonic undrained tests is also the trigger line for cyclic liquefaction or softening for sands (Vaid and Chern, 1985; Konrad, 1993), silty sands (Yamamuro and Covert, 2001) and sand with silt and clay mixture (Lo et al, 2008) for a given void ratio.

Fig. 2.6 shows the initial peak principal stress difference normalized with confining stress, q_{peak}/σ'_c versus the relative density, D_r for various silty sands with different fines contents in the literature. These silty sands were prepared by moist tamping, except the results from this study, which were prepared by tubed funnel deposition.

As the name of the method implies, the specimens in Fig. 2.6 are densified by tamping, except the data from this study. For the series with more than two data points, there is a clear concave upward trend for all the curves, meaning that there is a more pronounced increase in q_{peak} as relative density increases from densification. As the relative density increases, the undrained behavior is more greatly affected.

Fig. 2.7 shows the change of initial peak principal stress difference normalized with confining stress, $\Delta(q_{peak}/\sigma'_c)$ versus the relative density change, ΔD_r for the silty sands plotted in Fig. 2.6. In this diagram steeper lines/curves indicate a greater sensitivity of the undrained behavior to changes in relative density. The upper boundary is set by MT2 & MT5 and the lower boundary is set by MT3 for the moist tamped specimens. Note that specimens from this study are located below the lower boundary for moist tamped specimens. Two reference rectangles are also drawn in Fig. 2.7 at 10% and 20% change of relative density, so that the rectangles include all of the silty sands within the densification range except MT2 & MT5. Upper sides of the rectangles show that corresponding increase in q_{peak}/σ'_c of various silty sands is less than or equal to

0.13 and 0.2 for ΔD_r of 10% and 20%, respectively. For changes of relative density greater than 20%, change in q_{peak}/σ'_c diverges significantly for different silty sands.

Fig. 2.8 shows the change of initial peak principal stress difference normalized with confining stress, $\Delta(q_{peak}/\sigma'_c)$ versus the relative density change, ΔD_r for various silty sands with different fines contents in the literature, this time prepared with dry funnel deposition. All the specimens in Fig. 2.8 are densified by tapping the mold in a symmetrical pattern, except the data from this study. For most of the series with more than two data points, there is a concave downward trend for the curves, meaning that there is a less pronounced increase in q_{peak} as the change in relative density during densification increases. This concave downward trend is believed to be caused by the collapse of more metastable contacts between sand and silt grains in the dry soil during the initial stages of densification compared to higher level densification by further tapping the mold.

Similar to Fig. 2.7, two reference rectangles are drawn in Fig. 2.8 at 10% and 20% change of relative density, so that the rectangles include all of the silty sands. Upper sides of the rectangles show that corresponding increase in q_{peak}/σ'_c of various silty sands is less than or equal to 0.14 and 0.2 for ΔD_r of 10% and 20%, respectively. These reference values are essentially very close to the ones obtained for moist tamped specimens (Fig. 2.7). However, note that the concave upward trend for the moist tamped specimens in Fig. 2.7 would result a much bigger $\Delta(q_{peak}/\sigma'_c)$ for relative density changes greater than 20% compared to the dry funnel deposited specimens in Fig. 2.8.

Unfortunately, there is very limited data in literature with silty sand specimens densified after slurry deposition. And virtually no data with silty sand specimens densified after dry air pluviation or water sedimentation (i.e. specimens tested under same confining stress but at different relative densities achieved by densification). Fig. 2.8 shows the change of initialpeak principal stress difference normalized with confining stress, $\Delta(q_{peak}/\sigma'_c)$ versus the relative density change, ΔD_r for some slurry deposited specimens. Unlike moist tamped or dry funnel deposited specimens, specimens in Fig. 2.9 does not have a clear trend of continuously increasing q_{peak}/σ'_c with increasing relative density.

Comparisons of same test series are also made in terms of the effective instability friction angle (ϕ'_i). This parameter is essentially the effective stress friction angle mobilized at q_{peak}, where shear stress reaches its initial peak and can be calculated from the slopes of the instability lines shown in Fig. 2.5. Observations and trends were the same as discussed for the normalized initial peak principal stress difference, $\Delta(q_{peak}/\sigma'_c)$. For instance, with densification corresponding to 20% relative density increase, instability friction angle (ϕ'_i) increased as high as 8.6° for both MT6 and DFD5 but increased of only 1.2° for the specimens of this study.

Summary and Conclusions

Densification techniques employed in most of the conventional deposition methods for silty sands involve either tamping, tapping or vibrating. In order to investigate the influence of those techniques, a new densification technique without tamping, tapping or vibrating is employed.

Evolution of instability parameters such as initial peak principal stress difference (q_{peak}) and effective instability friction angle (ϕ'_i) with densification amount (ΔD_r) and technique is investigated. Parameters of interest are compiled from undrained monotonic triaxial test results of various silty sands in literature with fines content ranging between 5% and 50%.

It was observed that the undrained response of a silty sand is considerably affected by the selective elimination of the "metastable" contacts because of the employed densification technique. If the densification technique involves tamping (i.e. moist tamping), test series show a concave upward trend for the relationship between normalized initial peak principal stress difference ($\Delta(q_{peak}/\sigma'_c)$) and densification amount (ΔD_r). However, if the densification technique involves tapping (i.e. dry funnel deposition), test series show a concave downward trend for the relationship between normalized initial peak principal stress difference ($\Delta(q_{peak}/\sigma'_c)$) and densification amount (ΔD_r). No specific trend was observed for slurry deposited specimens.

Tubed funnel deposition is employed as a new technique of densification requiring no tamping, tapping or vibrating. It was observed that the test series densified with this technique showed much smaller increase in normalized initial peak principal stress difference ($\Delta(q_{peak}/\sigma'_c)$) compared to the test series densified with other techniques such as tamping or tapping. This is believed to occur because more “metastable” contacts are preserved with the new technique.

How closely the conventional densification techniques involving tamping, tapping, vibrating versus the new technique presented in this study results a soil fabric to predict the real in-situ undrained behavior is not known. However, this study points out that the densification technique is a significant influencing factor for laboratory testing of silty sands.

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Table 2.1. Silty sands used in comparison.

Test Series	Reference	Sand	Silt	FC (%)
MT1	Murthy et al. (2007)	Ottawa	SilCoSil #106	5
MT2	Thevanayagam et al.(2002)	Foundry	SilCoSil #40	7
MT3	Zlatovic and Ishihara (1997)	Nevada	Nevada	8
MT4	Murthy et al. (2007)	Ottawa	SilCoSil #106	10
MT5	Ishihara (2008)	Jamuna River sand	silt with mica	10
MT6	Yang et al. (2006)	Hokksund	Chengbei	20
MT7	Yang et al. (2006)	Hokksund	Chengbei	30
MT8	Yang et al. (2006)	Hokksund	Chengbei	50
DFD1	Yamamuro and Lade (1997)	Nevada	Nevada	6
DFD2	Yamamuro and Wood (2004)	Nevada	ATC silt<#270	10
DFD3	Lade and Yamamuro (1997)	Nevada	Nevada	20
DFD4	Yamamuro and Covert(2001)	Nevada	ATC silt<#270	40
DFD5	Lade and Yamamuro (1997)	Nevada	Nevada	50
SD1	Murthy et al. (2007)	Ottawa	SilCoSil #106	5
SD2	Murthy et al. (2007)	Ottawa	SilCoSil #106	10
SD3	Murthy et al. (2007)	Ottawa	SilCoSil #106	15
	this study	Nevada-B	Loch Raven	20

Fig. 2.1. Evolution of soil fabric in the silty sand laboratory specimens , a) after deposition, b) after densification.

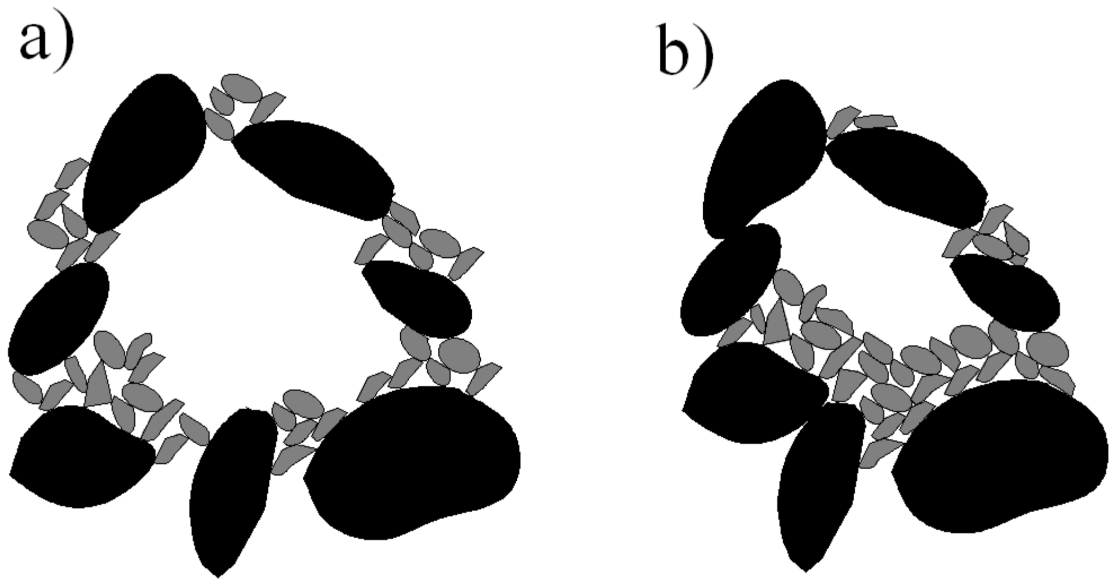


Fig. 2.2. New densification technique for dry funnel deposition with tubes of different length attached to the spout of the funnel.

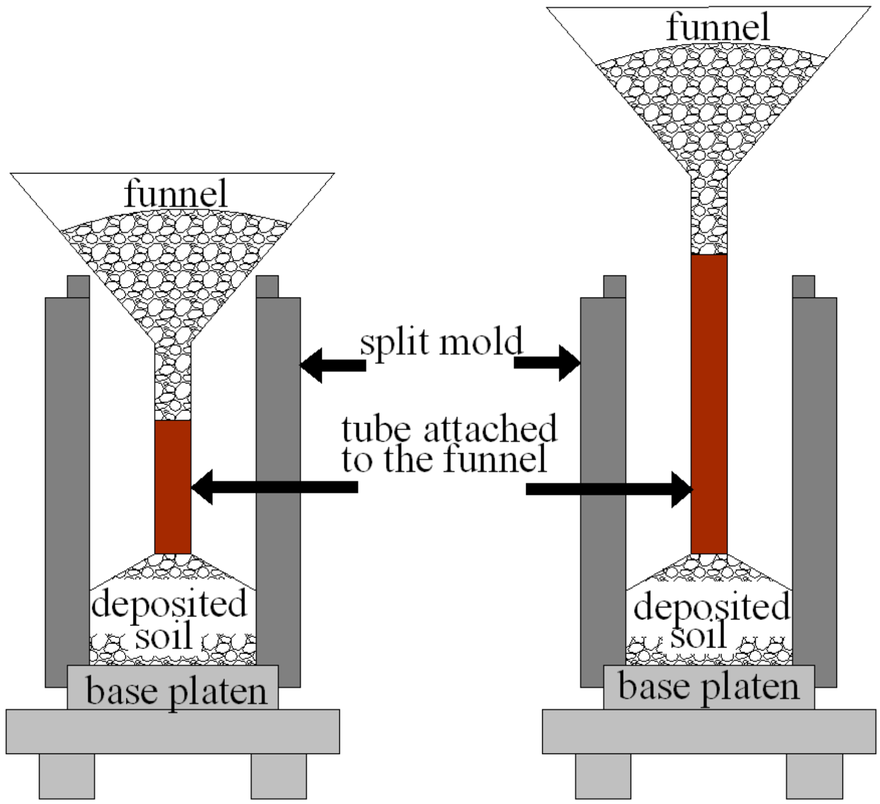


Fig. 2.3. Grain size distribution curve of the silty sand used in experimental program.

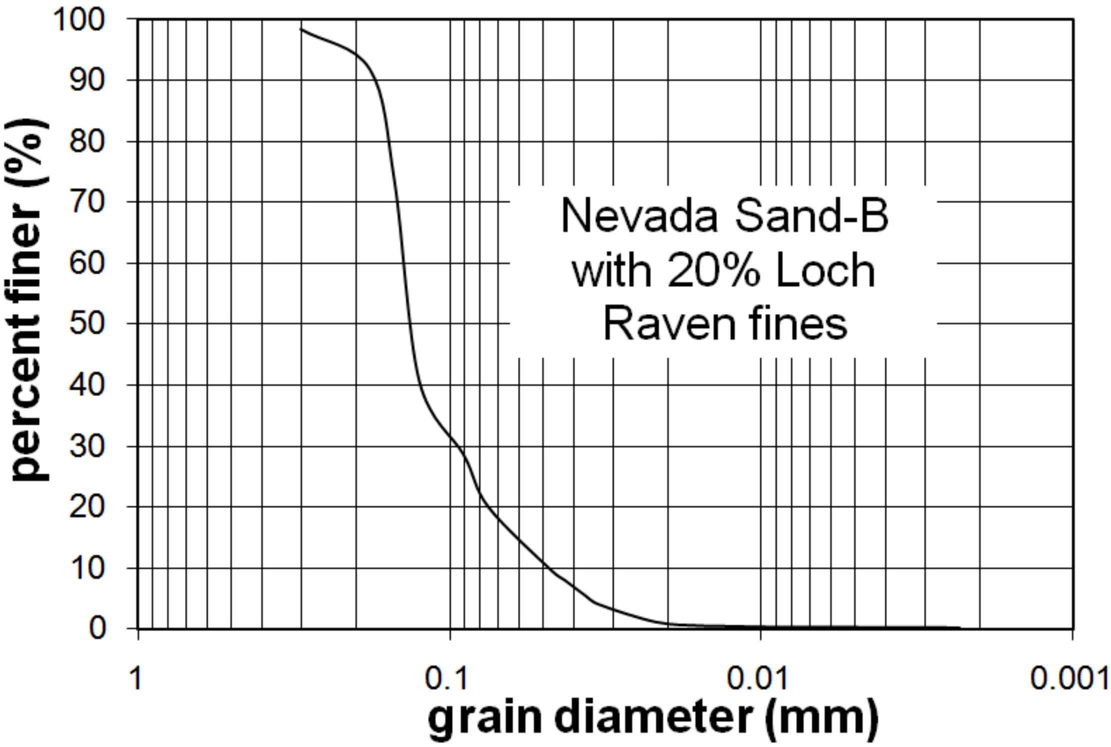


Fig. 2.4. Stress-strain response of Nevada Sand-B with 20% Loch Raven fines under 30 kPa confining stress at three different densities.

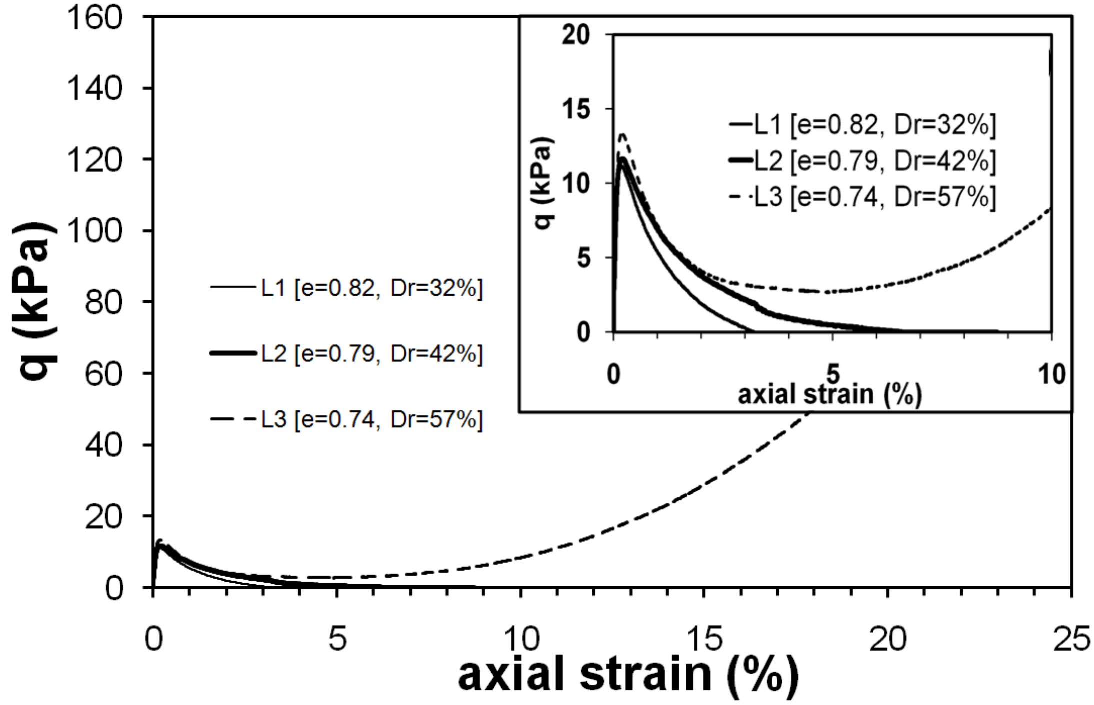


Fig. 2.5. Evolution of q_{peak} and the instability line for a loose silty sand due to densification.

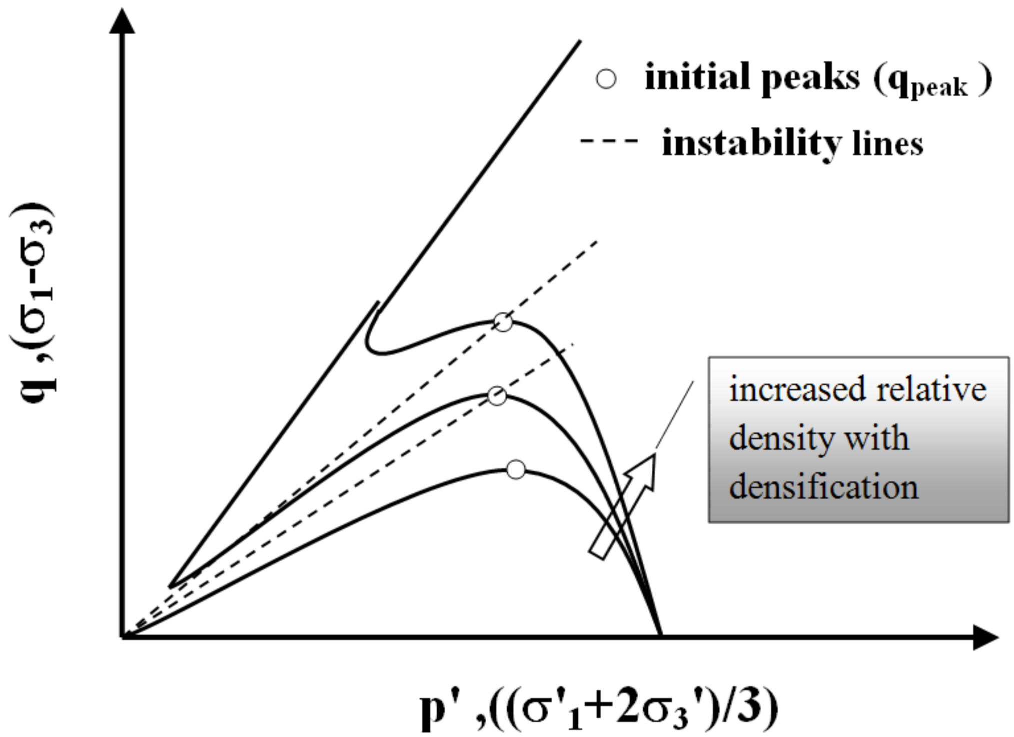


Fig. 2.6. Normalized initial peak principal stress difference versus relative density for different silty sands prepared with moist tamping.

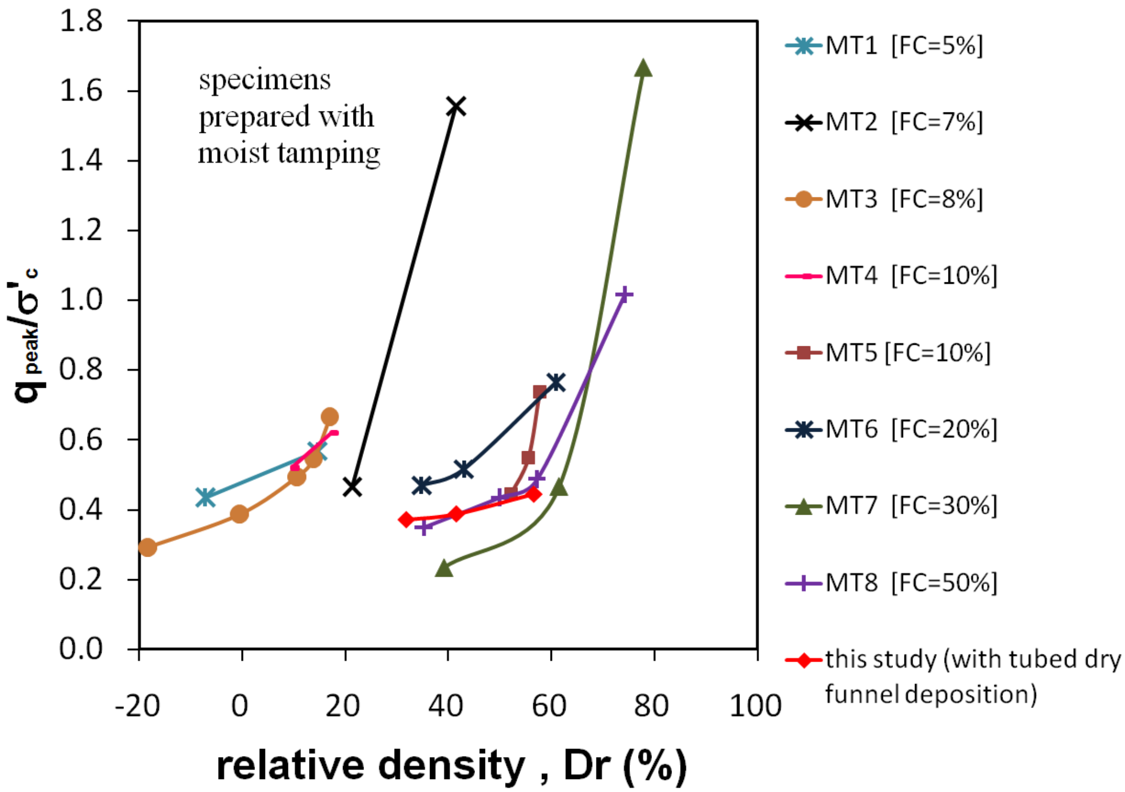


Fig. 2.7. Change in normalized initial peak principal stress difference versus change in relative density for moist tamped specimens.

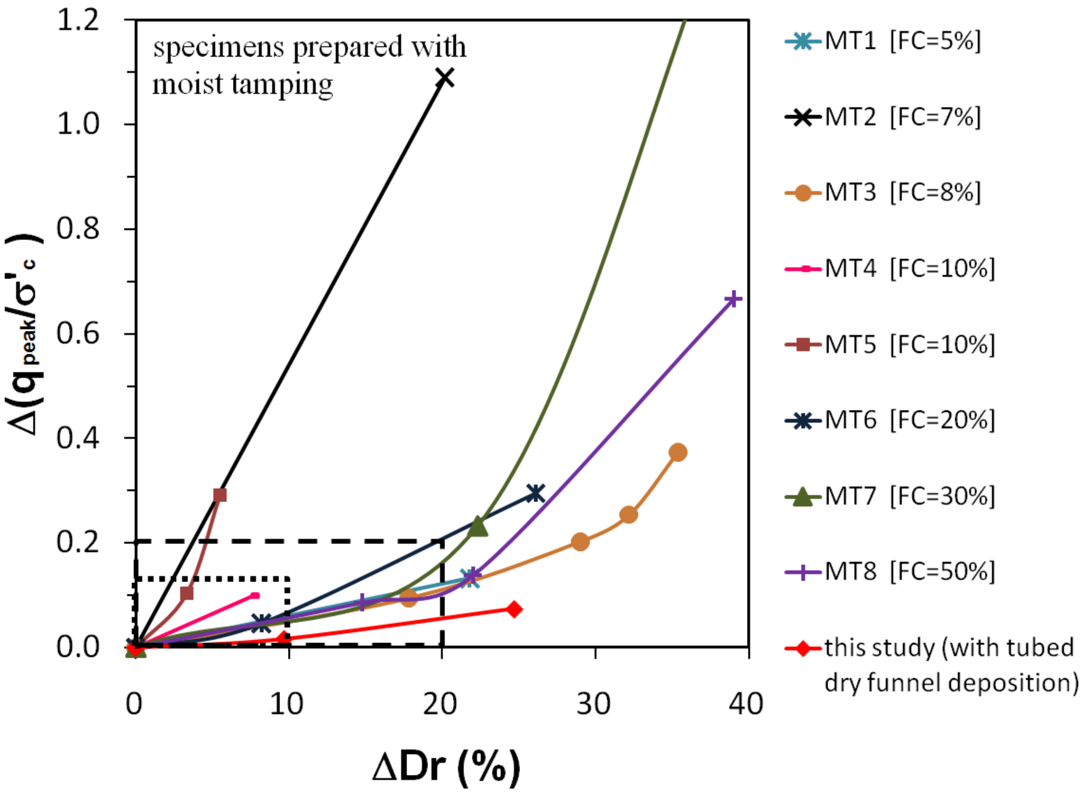


Fig. 2.8. Change in normalized initial peak principal stress difference versus change in relative density for dry funnel specimens.

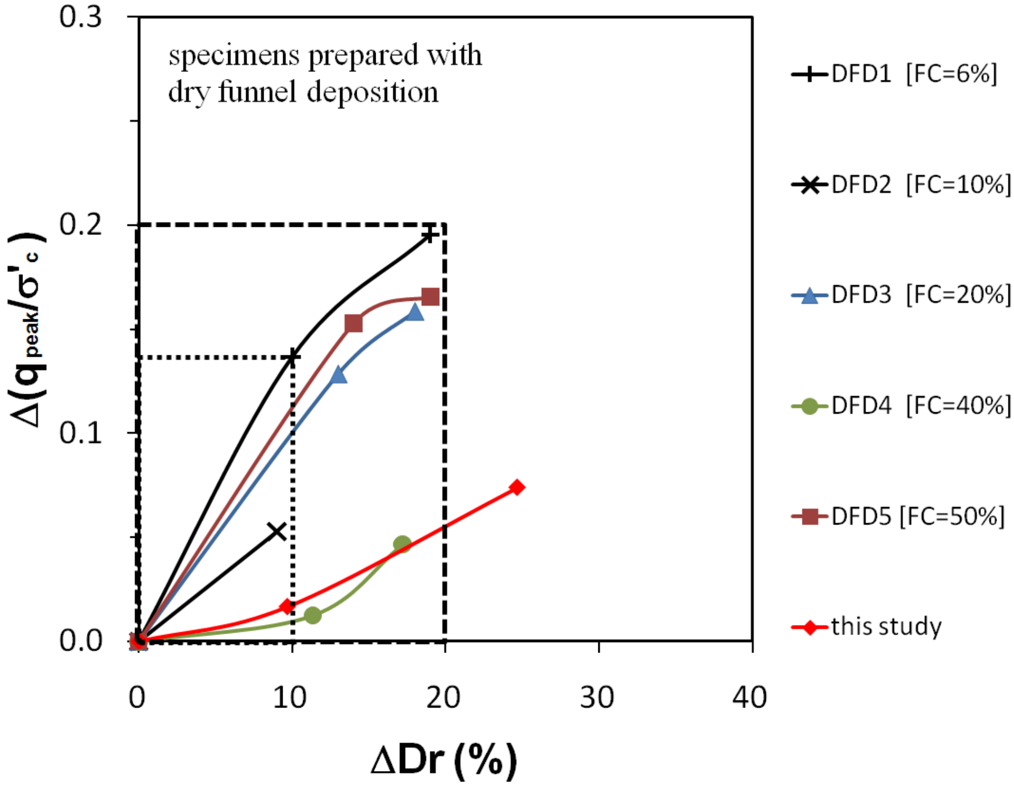
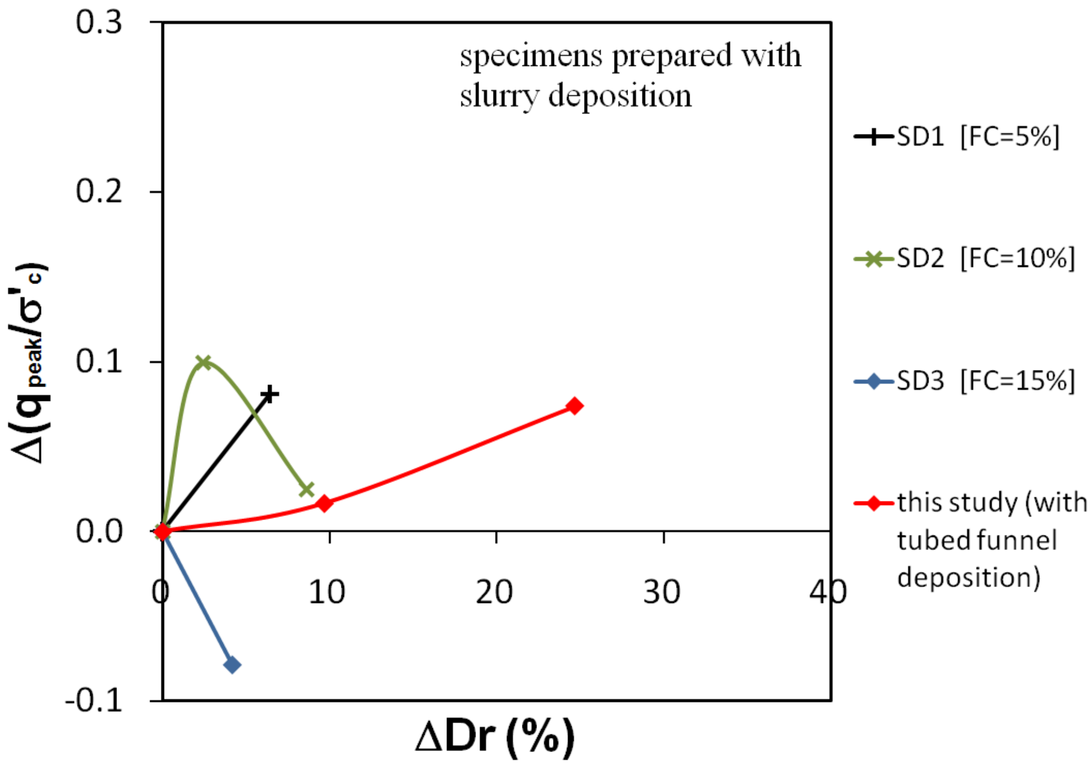


Fig. 2.9. Change in normalized initial peak principal stress difference versus change in relative density for slurry deposited specimens.



VARIATIONS IN LIQUEFACTION BEHAVIOR OF SAND CAUSED BY CHANGES IN SILT GRADATION

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Abstract

Prior research efforts have been performed regarding the effect of non plastic silts on the liquefaction behavior of sands. This research mainly focused on influence of fines content, confining stress and depositional techniques. In this study, strain-controlled monotonic undrained triaxial compression tests were performed on a single base sand mixed with three different essentially nonplastic silts. In order to focus on the silt gradation effect, other mentioned factors like fines content (20%), confining stress (30kPa) and deposition method (dry funnel deposition) were kept the same for all tests. The results of this study have shown that silt size is indeed an important factor influencing the liquefaction potential of silty sands. Different comparison basis for undrained behavior such as loosest possible density after deposition, intergranular void ratio, void ratio and relative density were evaluated. It was observed that as the mean grain diameter ratio (D_{50}/d_{50}) of the sand grains to silt grains decreases, liquefaction potential for a silty sand increases. This tendency is attributed to more metastable contacts with increasing silt size.

CE Database Key words: Grain Size, Sand, Silts, Soil Liquefaction, Soil Properties, Soil Strength, Soil Test, Triaxial Tests, Pore Pressure

Introduction

Liquefaction of clean sands has been investigated intensely for over four decades. Relatively lately, research on silty sands has also been performed, considering the fact that silty sand is the most common type of natural soil in situ prone to liquefaction. Related literature mainly focused on three aspects 1) influence of fines content on liquefaction potential (Kuerbis et al., 1988; Pitman et al., 1994; Zlatovic and Ishihara, 1995; Lade and Yamauro, 1997), 2) influence of confining stress (Yamamuro and Lade, 1997; Thevanayagam, 1998), 3) influence of specimen preparation method (Brandon et al., 1991; Høeg et al., 2000; Yamamuro et al., 2008; Wood et al., 2008). A summary of some of the previous literature with factors of particular interest for this study are extracted in Table 3.1. Different conclusions in the last column of Table 3.1 may be interpreted because of differences in comparison bases, deposition methods and/or confining stresses used in the studies.

Currently, when liquefaction assessment of silty sands is being performed, the effects of the fines are characterized by only content (FC) and/or plasticity index (PI). If this were true, all sands with same amount of nonplastic fines should give similar undrained response under comparable conditions. Experimental data presented in this paper show that the size of silt particles relative to sand grains is also a major factor in the characterization of silty sands for their liquefaction potential.

Soils Tested

Nevada Sand-B is used as base sand for all silty sands in the experimental program. Three different essentially nonplastic silts with different gradations were chosen: Loch Raven, SilCoSil #125 and Potsdam. Nevada Sand, Loch Raven silt, and Potsdam silt are all naturally occurring soils, while SilCoSil #125 is a product of the U.S. Silica Company. Nevada Sand-B is mixed with each silt type so that the resulting silty sands contain 20% fines (particles smaller than 0.074mm in diameter) by dry weight. Gradations of base sand, silts and silty sands with 20% FC are shown in Fig. 3.1.

Optical microscope images of the three different silts are given in Fig. 3.2. In general both Loch Raven and SilCoSil appear to be more angular than Potsdam. Specific gravities (G_s), maximum (e_{max}), minimum void ratios (e_{min}), mean grain diameters of sand (D_{50}) and silts (d_{50}) are given in Table 3.2. Note that Potsdam silt has a PI of 3.8%. Ishihara (1993) concluded that low plasticity range (PI<10) does not change the cyclic liquefaction resistance of sandy soils much but it increases for the higher plasticity ranges. Bray et al. (2004) reported many sites at Adapazari, Turkey, mainly silty soils with a PI range 0 to 12, liquefied during the 1999 Kocaeli earthquake. Guo and Prakash (1999) observed that cyclic liquefaction resistance of silt-clay mixtures even decreases with plasticity index for $PI<\approx 4$.

Maximum and minimum void ratios of Nevada Sand-B with different silts and various fines contents were determined with the method described by Lade et al. (1998). Corresponding values are plotted in Fig. 3.3.

Experimental Program

Strain controlled monotonic undrained triaxial compression tests were performed on Nevada Sand-B mixed with three different silts (FC=20%). Cylindrical specimens of 7.1cm in diameter (D) by 14.2 cm in height (H) were used (H/D=2) together with lubricated ends and oversized end platens in order to promote uniform strains.

Specimens were formed by dry funnel deposition technique. In this technique, a funnel with a tube attached to its spout is positioned at the bottom of the split mold. Once dry silty sand is poured into the funnel, it is raised gently along the axis of symmetry of the specimen. Different ranges of densities were of interest for this study. Tapping of the mold to densify the soil was avoided in order to prevent the potential selective elimination of the "metastable" contacts between sand and silt grains. The term "metastable structure" was probably first introduced by Terzaghi (1956) in order to explain the collapse of fine grained cohesionless sediments. Hanzawa et al. (1979) also used "metastable" contacts in order to explain the static liquefaction potential at a silty sand deposit which was later subjected to ground improvement. Recently, "metastable" contacts for a particular silty sand was also quantified by Yamamuro and Wood (2004) and Yamamuro et al. (2008). The selective elimination of "metastable" contacts by mold tapping is believed to change the overall soil fabric considerably (Monkul and Yamamuro, 2010b). Hence, instead of tapping the mold, longer tubes were attached to the funnel to achieve greater densities but with similar soil fabric. A limitation of this method is the inability to create a wide range of densities. Therefore, some of the triaxial test results do not include results performed at greater densities, because this method of deposition could not produce greater values than shown. Note that the minimum density for each silty sand was the smallest value that could be achieved for that soil.

Specimens were then flushed with CO_2 in a dry state for 40 minutes prior to saturation. De-aired water was percolated from the bottom through the top of all specimens for a period of 18.5 hours to facilitate greater degrees of saturation, especially for the very fine Potsdam silt. The same time period for percolation was used for all specimens regardless of silt type to prevent any differences in the undrained behavior that could be attributed to time effects. Considerable volume change during saturation is reported for loose sands (Sladen and Handford, 1987), therefore, volume change during saturation was monitored by a calibrated burette that was connected to the cell fluid. During this stage, the change in height of the specimens was measured by a LVDT. A back pressure of 100 kPa was applied prior to the B value check to ensure full saturation. Obtained B values were a minimum of 0.99 for all tests.

Previous research reported that increasing strain rate decreases the volumetric contractiveness of the silty sands. Therefore, slow deformation control was used to be conservative when testing undrained silty sand behavior (Yamamuro and Lade, 1998). The strain rate was adjusted to 0.05%/min during shearing after the specimens were isotropically consolidated under 30kPa confining pressure. During the entire specimen preparation process care was taken in order to keep the effective stress at a maximum value of 15 kPa and prevent over-consolidation.

Test data were corrected for various factors such as piston friction, piston uplift, weight/buoyancy effects (i.e. piston, top cap etc.) and membrane stiffness. Since the mean grain diameter of the base sand is small (Table 3.2), the membrane penetration effect was not considered significant (Frydman et al., 1973; Lade and Hernandez, 1977).

Results of Undrained Triaxial Compression Tests

The principal stress difference (q) and the excess pore pressure (Δu) plotted against axial strain is shown in Fig. 3.4(a) and Fig. 3.4(b), respectively, for Nevada Sand-B with 20% Loch Raven fines. Consolidated void ratios (e_c) and corresponding relative densities (D_r) are also shown on the same figures for specimens with three different densities (L1, L2, L3). As can be observed in Fig. 3.4(a) complete static liquefaction occurred for the specimens with the two smaller densities (L1 and L2). Static liquefaction occurs when the principal stress difference (q) is reduced to zero and remained zero with increasing axial strain, while excess pore water pressure reached a plateau (Fig. 3.4(b)). Static liquefaction coincided with the formation of large wrinkles in the membranes surrounding the specimens. Axial strain for static liquefaction increases slightly with increasing density (Fig. 3.4(a)).

Temporary liquefaction was observed for specimen L3 with the greatest density (e_c= 0.74). Temporary liquefaction is exhibited by the principal stress difference achieving an initial peak (q_{peak}), which then reduces to a local minimum nonzero value (quasi steady state, q_{qss}) and then it increases with axial strain to a maximum value which is the true steady state strength. The decline of the principal stress difference from q_{peak} to q_{qss} corresponds to the region where the excess pore pressure reached its maximum value in Fig. 3.4(b). Similarly, due to the suppression of dilation, the excess pore pressure declined with continued shearing, which caused the principal stress difference to increase beyond q_{qss} to its ultimate value.

Greater specimen densities than shown in Fig. 3.4 were needed in order to observe complete stable behavior with Loch Raven fines. As mentioned before, the nature of the depositional method employed in this study did not allow achieving denser specimens than shown in Fig. 3.4.

The principal stress difference (q) and the excess pore pressure (Δu) plotted against axial strain is shown in Fig. 3.5(a) and Fig. 3.5(b), respectively, for Nevada Sand-B with 20% SilCoSil fines. Note that both absolute and relative densities of the tested specimens (S1, S2, S3) are greater compared to the specimens with Loch Raven fines (L1, L2, L3). This is consistent with the pattern shown in Fig. 3.3, where sand with SilCoSil fines has a denser packing tendency than sand with Loch Raven fines at FC=20%. The smaller size of the SilCoSil grains (Table 3.2) enables them to be positioned into the voids inbetween the sand grains (intergranular voids) much easier than the Loch Raven fines, causing denser specimens. Fig. 3.5(a) shows temporary liquefaction behavior for specimen S1 (e_c=0.69). Both the principal stress difference and the excess pore water pressure followed the same general trend of temporary liquefaction as explained for specimen L3.

For specimen S2, the principal stress difference initially increased with axial strain and stayed constant for a limited period (i.e. $q_{peak}= q_{qss}$) before further increasing with axial strain (Fig. 3.5(a)). Therefore, it can be assumed that specimen S2 is located on the boundary between the regions of temporary liquefaction and completely stable behavior for Nevada Sand-B with SilCoSil. As expected, specimen S3 showed completely stable behavior (continuous increase in principal stress difference with axial strain), because it was denser than S2.

The principal stress difference (q) and the excess pore pressure (Δu) plotted against axial strain is shown in Fig. 3.6(a) and Fig. 3.6(b), respectively, for Nevada Sand-B with 20% Potsdam fines. Both specimens (P1 and P2) showed completely stable behavior. The depositional method could not produce smaller densities with Potsdam fines than exhibited by P1.

Discussion

Specimen P1 had a greater absolute density than the specimens L1 and S1. Densities of these specimens (L1, S1, P1) are named as the loosest possible density after deposition in Table 3.1, according to which soil would tend to fall into a "quasi-natural" void ratio, provided that the depositional method is exactly the same. The "quasi-natural" void ratio represents the loosest possible density of the soil deposited in exactly the same manner for different soils, ensuring the same amount of energy for deposition. It is not surprising that the loosest possible densities (L1, S1, P1) were ordered according to the mean grain size of the silts given in Table 3.2 (i.e. the greater the silt grain size, the greater the e_c).

When Figs. 3.4, 3.5 and 3.6 are examined individually, regardless of the specimen density, the excess pore pressure response for a particular silty sand was almost identical until a certain value of axial strain. It then starts to deviate depending on the density of the specimen. The value of this axial strain, where pore pressures starts to deviate, changes with silt type: largest for the sand with Loch Raven fines, smallest for the sand with Potsdam fines. This trend also seems to be related with the mean grain size of the silts given in Table 3.2 (i.e. the greater the size of the silt grains, the greater the axial strain where pore pressures starts to deviate).

Different Comparison Bases

It is clear from the results of the undrained triaxial compression tests that the different silts affect the liquefaction potential of the base sand differently, which is Nevada Sand-B in this study. Table 3.1 shows that there are various comparison bases used in literature regarding the fines content effect on liquefaction resistance/dilatancy of silty sands. Some of those are loosest possible density after deposition, intergranular void ratio, void ratio and relative density.

Loosest Possible Density after Deposition

Fig. 3.7 shows the mean grain diameter ratios ($D_{50\text{-sand}}/d_{50\text{-silt}}$) for the specimens with the loosest possible density after deposition. As $D_{50\text{-sand}}/d_{50\text{-silt}}$ increases from 2.6 to 5.9, the undrained behavior evolved from complete liquefaction to temporary liquefaction. With the further increase of the ratio to 10.1, the silty sand became fully stable. Therefore, if the loosest possible density after deposition is chosen for the comparison basis, liquefaction potential of the silty sand increases with decreasing mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$).

Intergranular Void Ratio

Different parameter names such as granular void ratio (Lupini et al., 1981; Georgiannou, 2006), skeleton void ratio (Kuerbis et al., 1988; Pitman et al., 1994; Lade and Yamamuro,1997), void ratio of the granular phase (Mitchell, 1993), or intergranular void ratio (Thevanayagam, 1998; Monkul and Ozden, 2007), all of which are actually the same concept, have been used in the literature related with the shear strength and compressibility of sandy soils. In this study the term intergranular void ratio (e_s) will be used to refer to this parameter hereafter. Equation (2.1a) shows the intergranular void ratio as the void ratio of the sand matrix without the fines.

$$e_s = (V_v + V_f)/V_s \qquad (2.1a)$$

where V_v, V_f, V_s are the volume of voids, fines and sand, respectively. Hence, the (V_v+V_f) term in the numerator corresponds to the volume of intergranular void space. Eq. (2.1a) can be rearranged in terms of G, G_f, e and FC as follows in Eq. (2.1b).

$$e_s = \frac{e + \frac{G}{G_f} . \frac{FC}{100}}{1 - \frac{G}{G_f} . \frac{FC}{100}} \qquad (2.1b)$$

where e is the overall void ratio, G is the specific gravity of the overall soil (weighted average of sand and silt constituents are used in this study), G_f is the specific gravity of fines in the soil and FC refers to the percentage of fines by total weight of dry soil.

Fig. 3.8 shows the intergranular void ratios of the consolidated specimens calculated by Eq. (2.1b). Accordingly, there is a distinct tendency that as the $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio decreases, silty sands appear to have greater intergranular void ratios, meaning that the larger sand grains are displaced in to a looser state. Note that e_s values of all specimens tested are larger than the maximum void ratio of the base sand ($e_s \geq e_{max\text{-base sand}}$) drawn with a dashed line in Fig. 3.8. This indicates that sand grains are forced apart by the silt grains.

Fig. 3.8 also shows that for a particular silty sand with the same fines content (20%) and initial confining stress (30kPa), the liquefaction potential increases with increasing intergranular void ratio. This trend is also valid within the tested range in terms of liquefaction behavior regardless of the silt gradation: specimens P1, P2, S2, S3 were fully stable, as e_s of the specimens increased (S1 and L3), temporary liquefaction behavior is observed, and with further increases in e_s, specimens started to fully liquefy (L1 and L2). Thus, the intergranular void ratio could provide a reasonable basis of comparison between the three silty sands for the test data shown.

If a constant intergranular void ratio is chosen as the comparison basis, values were not at comparable ranges among all silt types in this study (Fig. 3.8). However, considering that the value of e_s of specimen P1 was located between S2 and S3 but closer to S2, their undrained responses can be compared (Figs. 2.5(a) versus 2.6(a)). Accordingly, the increase of principal stress difference for P1 was greater than both S2 until 9.5% axial strain and S3 until 6.5% axial strain. The amount of increase in q was much greater for P1 initially, since the maximum excess pore pressure (Δu_{max}) generated for P1 was significantly smaller than those generated for both S2 and S3. At larger strains, q_{S2} caught and eventually passed q_{P1}, because the decrement in Δu was smaller and more gradual for P1 than S2. Hence, for the same intergranular void ratio Potsdam fines makes Nevada Sand-B stronger than SilCoSil fines for a limited axial strain.

Void Ratio

Void ratios of the consolidated specimens are plotted in Fig. 3.9. Similar to intergranular void ratio, there is a distinct tendency that as the $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio decreases, silty sands appear to have greater void ratios. Void ratios of the tested specimens are smaller than the $e=e_{max\text{-base sand}}$ boundary in Fig. 3.9. This indicates that some of the silt grains are located inside the intergranular voids.

Fig. 3.9 shows that for a particular silty sand with the same fines content (20%) and initial confining stress (30kPa), liquefaction potential increases with increasing void ratio. If constant void ratio is chosen as the comparison basis, again specimens S2 and P1 are comparable (Fig. 3.9). It was previously explained that S2 was located at the boundary between the regions of temporary liquefaction and completely stable behavior for the sand with SilCoSil fines. This means any greater void ratio with SilCoSil fines, like the one of S1 should exhibit temporary liquefaction. As can be seen in Fig. 3.9 specimen P1 had a greater void ratio but showed fully stable behavior. Hence, for the same void ratio SilCoSil fines makes Nevada Sand-B more liquefiable than Potsdam fines. Thus, void ratio as the only basis of comparison is not consistent for all three silty sands for the test data shown.

When Fig. 3.8 and Fig. 3.9 are analyzed together, it is observed that as the $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio decreases, both the void ratio and intergranular void ratio of the specimens increased, with same amount of energy applied to the specimen before shearing (same depositional method and consolidation stress). This increase in both e_s and e created a soil fabric much more volumetrically contractive and therefore much more liquefiable.

Relative Density

Fig. 3.10 shows the relative densities of the consolidated specimens that were tested. Unlike the two parameters previously discussed (e_s and e), relative density values from the tested specimens were not ordered according to the $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio. Accordingly, for the same amount of energy applied to the specimens before shearing, (same depositional method and consolidation stress) silty sand with Loch Raven fines tend to have the smallest relative density, whereas silty sand with SilCoSil fines tend to have the greatest relative density.

If constant relative density is chosen as the comparison basis, an evaluation can be made between all three silt types (Fig. 3.10). In order to compare the influence of

Loch Raven fines versus Postdam fines specimens L2 and P1 can be compared (D_r=41%). Specimen L2 had fully liquefied, whereas P1 was fully stable. Influence of SilCoSil fines versus Postdam fines specimens can be compared through specimens S1 and P1. Specimen S1 exhibited temporary liquefaction, even though its relative density (58%) was considerably larger than D_r of P1 (41%), which was stable. Influence of Loch Raven fines versus SilCoSil fines can be compared through specimens L3 (D_r=57%) and S1 (D_r=58%) in which both exhibited temporary liquefaction. Both q_{peak} and q_{qss} values were greater for S1 (Fig. 3.5(a)) than L3 (Fig. 3.4(a)). Therefore, the instability friction angle (ϕ_i) for specimen S1(23°) was also greater than ϕ_i of L3 (17°). Hence, for a selected relative density Nevada Sand-B is more liquefiable with Loch Raven fines than SilCoSil fines, and SilCoSil fines makes Nevada Sand-B more liquefiable than Potsdam fines. In other words, for the same relative density, fines content and confining stress, as $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio decreases the sand becomes more liquefiable. Thus, relative density as the only basis of comparison is not consistent for all three silty sands for the test data shown.

Influence of Mean Grain Diameter Ratio on Initial Soil Fabric

Influence of mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) on the many factors discussed so far is believed to be closely related with the initial fabric achieved prior to shearing. Previous research had shown that silty sands might have a significant percentage of “metastable” grain contacts (silt grains located inbetween sand grains), before shearing (Yamamuro and Wood, 2004; Yamamuro et al., 2008). Silty sands can be expected to become more volumetrically contractive as the percentage of these “metastable” contacts increases. Fig. 3.11 shows the hypothesized relationship between the mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) and the initial fabric achieved before shearing in this study. As the $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio decreases from Fig. 3.11(a) to Fig. 3.11(b), the percentage of “metastable” contacts increases, while stable contacts (sand to sand) and silt only contacts (silt to silt) decreases. This is due to the fact that the smaller silt grains have a greater mobility and capacity to easily fit into the intergranular voids between the sand grains during deposition and/or consolidation. This trend is also confirmed by Figs. 2.8 and 2.9, where both the void ratio and intergranular void ratio of the specimens had increased with decreasing $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio. It should be noted that particle shape or gradation might also be a secondary factor. Fig. 3.2 shows that Potsdam fines are not only smaller, but also more round in shape compared to the other fines, which could possibly enhance the chance of reducing “metastable” contacts. In this case, the size effect and the shape effect could have concurrently worked to reduce the liquefaction potential of the sand with Potsdam fines. The particle shape effect must be relatively small compared to the particle size effect. If it were not, the liquefaction susceptibility would be the same for both the Loch Raven and SilCoSil silts, which were both angular. However, since liquefaction potential clearly increased with decreasing $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio, it can be concluded that the particle size effect is much more significant than the particle shape effect.

As the amount of “metastable” contacts increased at low confining stresses, the silty sand became more compressible during shearing, which resulted in an increase in the potential for liquefaction. This general concept was experimentally verified by Yamamuro and Wood (2004) and Yamamuro et al. (2008).

Summary and Conclusions

In this study, an experimental program was performed to investigate the influence of silt gradation on the liquefaction potential of silty sands. Three different essentially non-plastic silts (i.e. Loch Raven, SilCoSil and Potsdam) with varying grain size distributions were employed. In order to assess the resulting undrained response other major influencing factors such as base sand (Nevada Sand-B), fines content (20%), confining stress (30 kPa) and deposition method (dry funnel deposition) was kept constant throughout the experimental program. Mold tapping to achieve greater density specimens was avoided. This is believed to promote preservation of the “metastable” grain contacts and maintain the same overall soil fabric. However, this depositional method has a limited the range of minimum and maximum test densities.

It was found that mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) is a very important factor influencing the undrained behavior of a silty sand. Accordingly:

1) As the mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) increased, the undrained behavior evolved from complete liquefaction (with Loch Raven fines) to temporary liquefaction (with SilCoSil fines) to fully stable (with Potsdam fines) for the same base sand.

2) Commonly used comparison bases in the literature, such as void ratio, intergranular void ratio and relative density, for assessing the influence of fines content on liquefaction resistance/dilatancy of silty sands do not work for the same base sand with different silts, even though fines content, stress conditions and deposition method were the same. For example, for the same relative density, fines content and stress conditions, as the $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio decreases the sand becomes more liquefiable.

3) Current geotechnical engineering practice considers only the fines content and/or the PI (Atterberg Limits) in assessments and correlations regarding the influence of fines on liquefaction of silty sands. This study showed that for the same fines content and stress conditions in the field, the undrained response of a sand can be vastly different (e.g. complete liquefaction versus completely stable) depending on the silt gradation.

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Table 3.1. Summary of some of the previous literature with factors of particular interest.

Ref.	Type of sand	D_{50} sand (mm)	Type of fines	d_{50} fines (mm)	D_{50}/d_{50}	deposition method	type of testing	σ'_{3c} (kPa)	comparison basis	FC range (%)	effect of FC on liquefaction resistance or dilatancy
1	Ottawa sand	0.4	silt	-	-	moist tamping	cyclic triaxial	-	same intergranular void ratio	0-20	increase
2	Brenda mine tailings sand (20/200) (angular)	0.25	Kamloops silt	0.012	20.8	slurry deposition	undrained triaxial	350	similar intergranular void ratio	0-22.3	increase
3	Ottawa sand (subrounded)	0.39	crushed silica fines (angular)	-	-	moist tamping	undrained triaxial	350	loosest possible density after deposition	0-40	increase
4	Ottawa sand (subrounded)	0.39	Sil-Co-Sil #106	0.02*	19.5	slurry deposition	drained triaxial	400	similar relative density	0-20	increase
5	Old Alluvium sand	0.73*	crushed quartz	0.04*	18.3	moist tamping	undrained triaxial	215	same intergranular void ratio	0-9	increase
6	Ottawa sand (rounded)	0.6	Sil-Co-Sil #125	0.017	35.3	moist tamping	cyclic triaxial	98	same void ratio	0-30	decrease
7	Toyoura sand	0.17	Toyoura silt	0.01	17	moist tamping & dry funnel deposition water sedimentation	undrained triaxial	50 & 500	loosest possible density after deposition	0-30	decrease
8	Nevada sand (50/200) (angular)	0.16	Nevada fines	0.05	3.2	dry funnel deposition	undrained triaxial	25	loosest possible density after deposition	0-30	decrease
	Ottawa sand (50/200) (angular)	0.2			4					0-50	
9	sand	0.25	kaolin silt	0.009*	27.8	dry air pluviation	undrained triaxial	100	intergranular void ratio	0-27	decrease (depending on es)
10	Monterey sand (0/30) (subangular to subrounded)	0.43	Yatesville silt	0.03	14.3	moist tamping	cyclic triaxial	100	relative density	0-40	decrease (depending on D_r)
	Yatesville sand (subangular to subrounded)	0.18			6						
11	Ham River Sand (subangular)	0.27*	HPF4 Silt	0.04*	6.8	dry air pluviation	undrained triaxial	49	loosest possible density after	0-2.5	increase

							(anisotropically con.)		deposition		
			silt size mica	0.01*	27					0-2.5	decrease
12	Ottawa sand (rounded)	0.39	Sil-Co-Sil #106	0.02*	19.5	mod. slurry deposition & moist tamping	undrained triaxial	btwn. 148 and 653	-	0-15	decrease
13	Firoozkuh sand	0.27	Firoozkuh silt	0.03	9	dry deposition	hollow cyl. torsional shear	100 & 200	loosest possible density after deposition	0-30	decrease
14	Quartz sand (well rounded)	0.3	Assyros silt	0.02	15	moist tamping	cyclic triaxial	50 & 300	similar void ratio	0-35	decrease
15	Ahmedabad sand	0.3	quarry dust	-	-	dry funnel deposition	cyclic triaxial	100	same void ratio	0-20	decrease
16	Ottawa Sand (rounded)	0.31	Sil-Co-Sil #106	0.02*	15.5	slurry deposition	drained triaxial	400	similar relative density	0-15	decrease (for low relative densities)
17	Nevada Sand-B (angular)	0.14	Loch Raven	0.055	2.6	tubed dry funnel deposition	undrained triaxial	30	loosest possible density after deposition, void ratio, intergranular void ratio, relative density	20	-
			SilCoSil #125	0.024	5.9						
			Potsdam	0.014	10.1						

References: 1) Shen et al. (1977), 2)Kuerbis et al. (1988) and Vaid (1994), 3) Pitman et al. (1994), 4)Salgado et al. (2000), 5) Ni et al. (2004), 6)Erten and Maher (1995), 7) Zlatovic and Ishihara (1995), 8)Lade and Yamamuro (1997), 9) Thevanayagam (1998), 10)Polito and Martin II (2003), 11)Georgiannou (2006), 12)Murthy et al. (2007),13) Bahadori et al. (2008), 14) Papadopoulou and Tika (2008), 15) Sitharam and Dash (2008), 16) Carraro et al. (2009), 17) this study

*representative values of D_{50} and/or d_{50} were read from the gradation curves.

Table 3.2. Some properties of the soils used in the experimental program.

	Nevada Sand-B	Loch Raven Silt	SilCoSil #125	Potsdam Silt
Specific Gravity Gs	2.68	2.73	2.68	2.82
e_{min}	0.624	0.834	1.101	0.878
e_{max}	0.926	1.245	1.550	1.327
mean grain diameter (mm)	0.142	0.055	0.024	0.014
$D_{50\text{-sand}}/d_{50\text{-silt}}$	-	2.6	5.9	10.1

Fig. 3.1. Grain size distribution of the soils used in the experimental program.

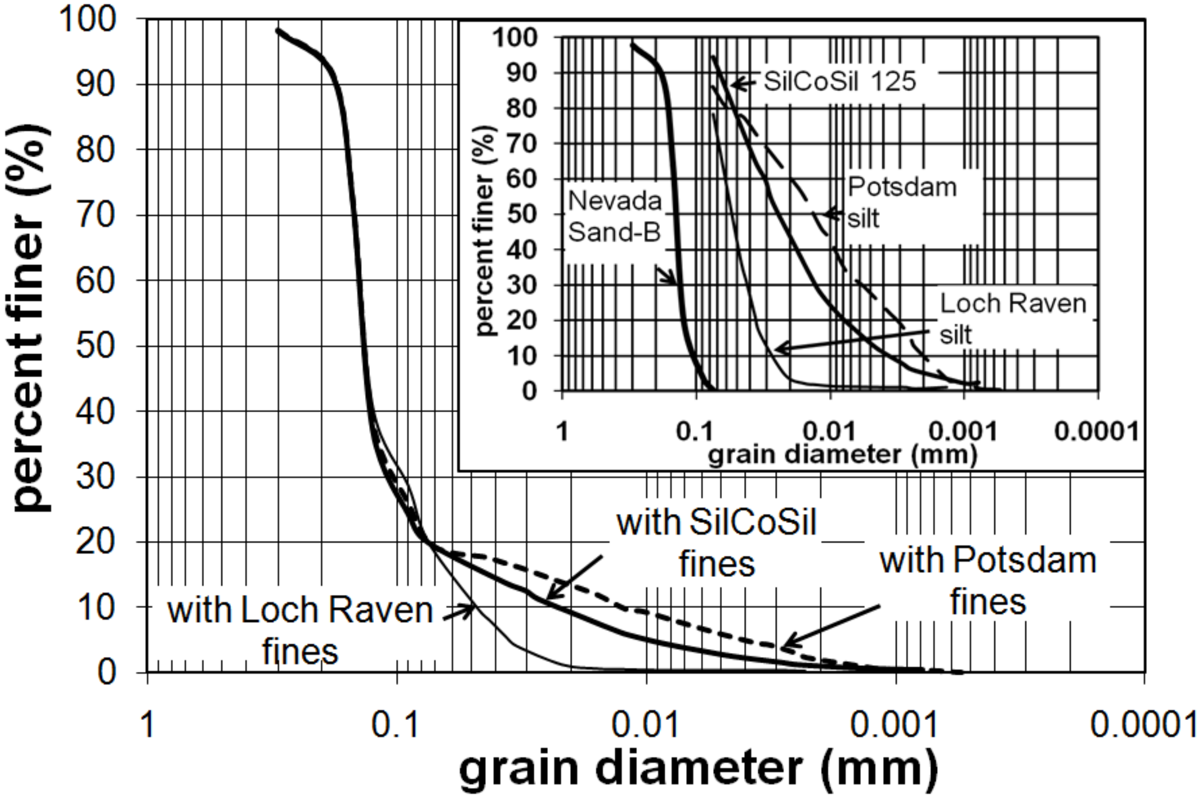
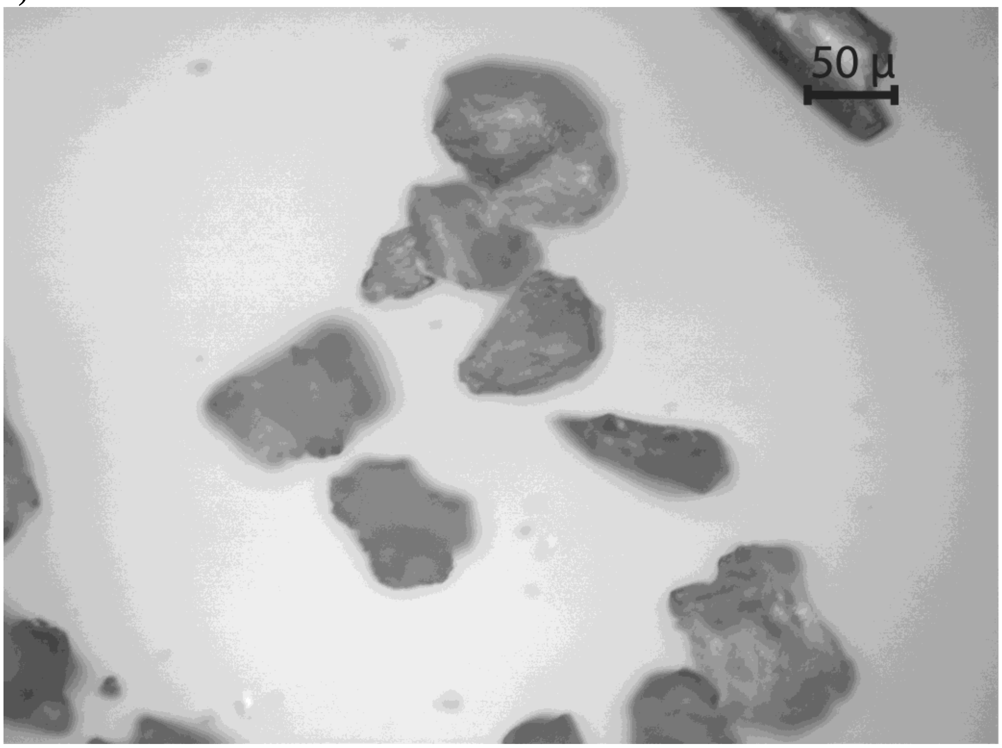
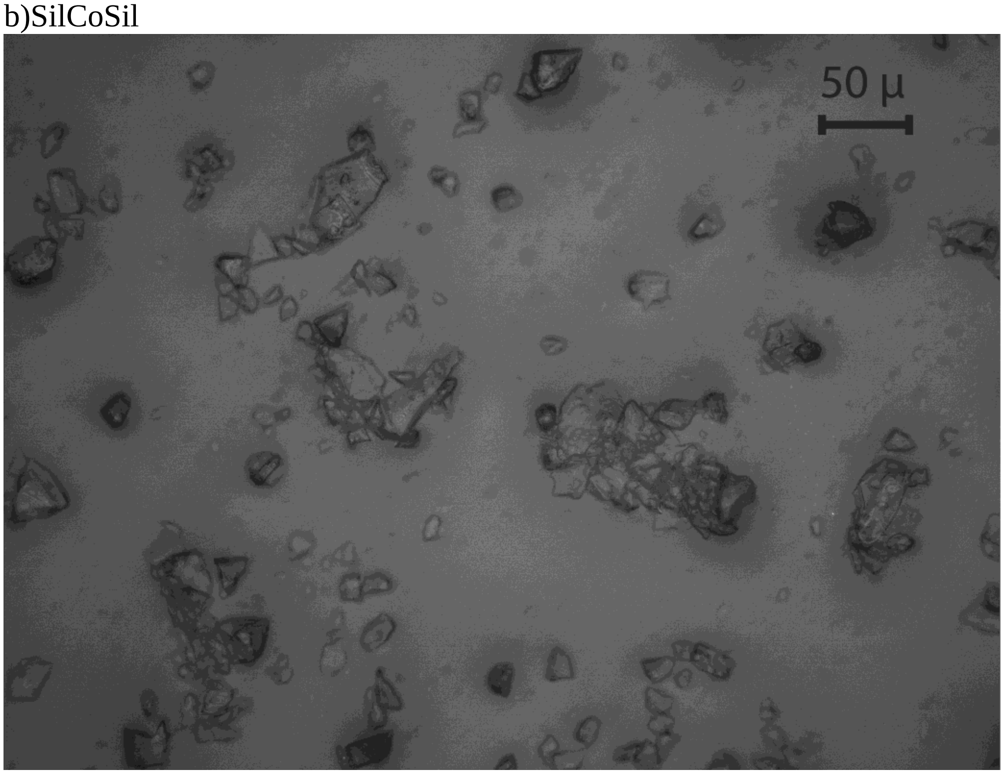


Fig. 3.2. Appearance of different silts under optical microscope,
a)Loch Raven silt



b)SilCoSil



c) Potsdam silt

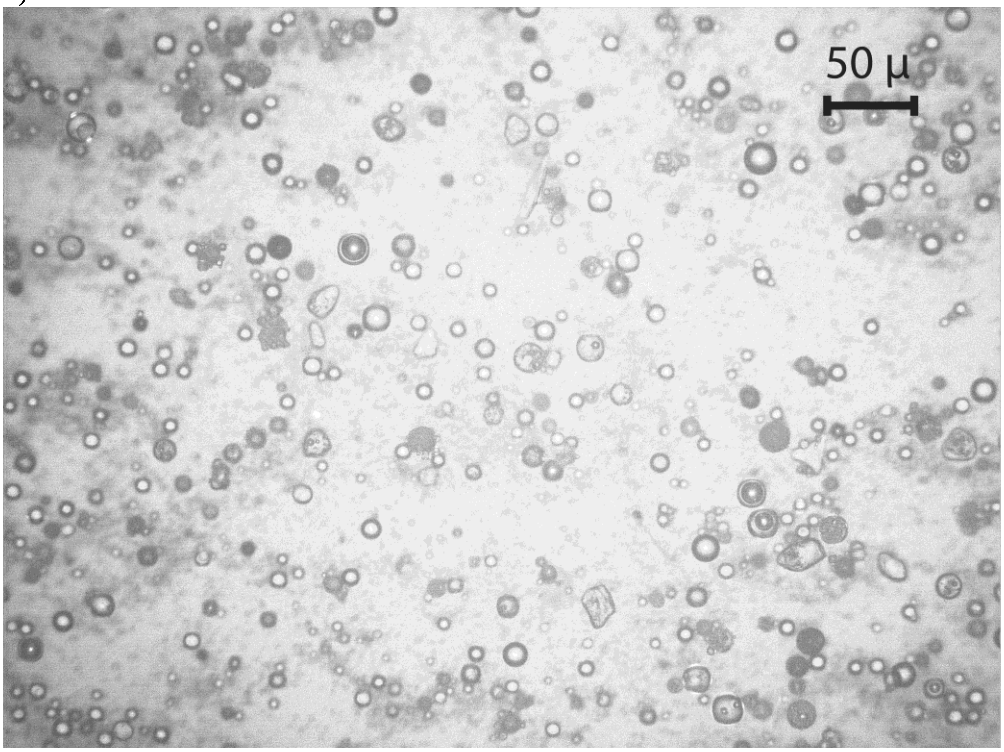


Fig. 3.3. Limiting void ratios of silty sands for different fines contents.

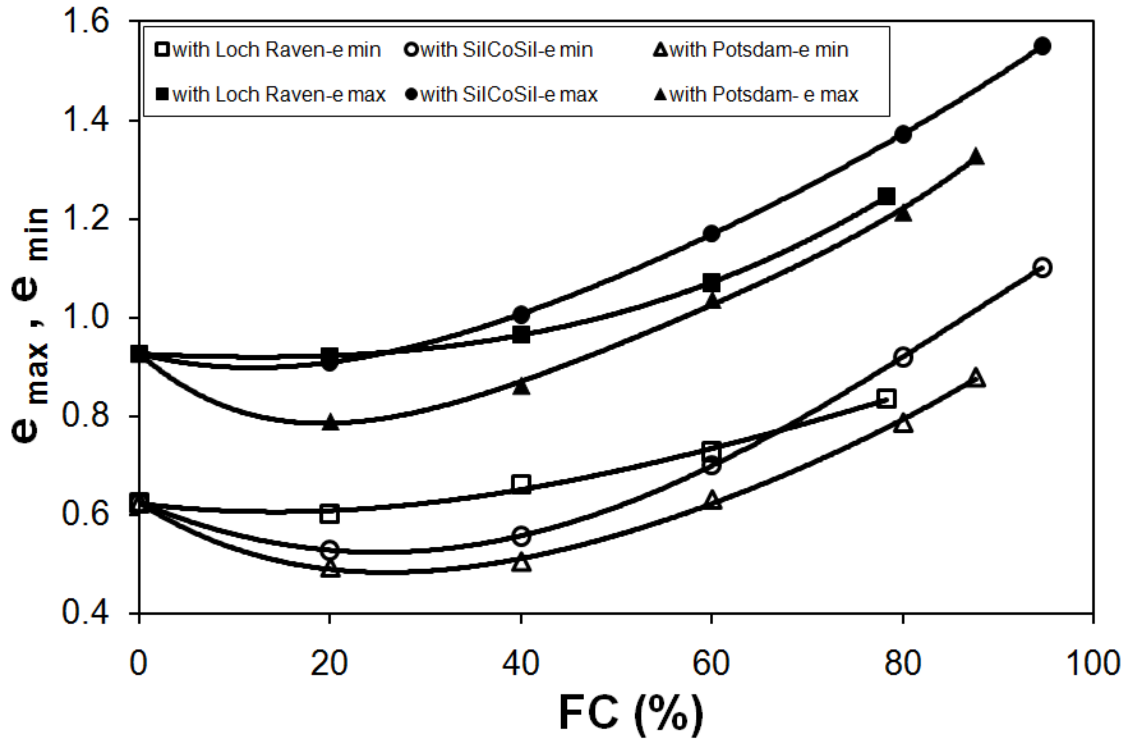
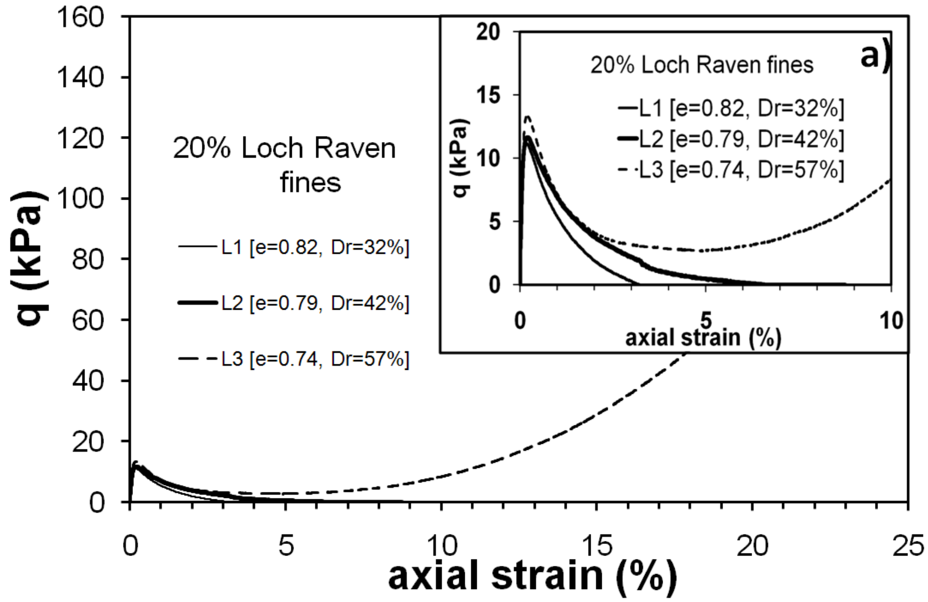


Fig. 3.4. a) Principal stress difference versus axial strain response; b) change of excess pore pressure with axial strain for Nevada Sand-B with 20% Loch Raven fines at 30 kPa confining stress.



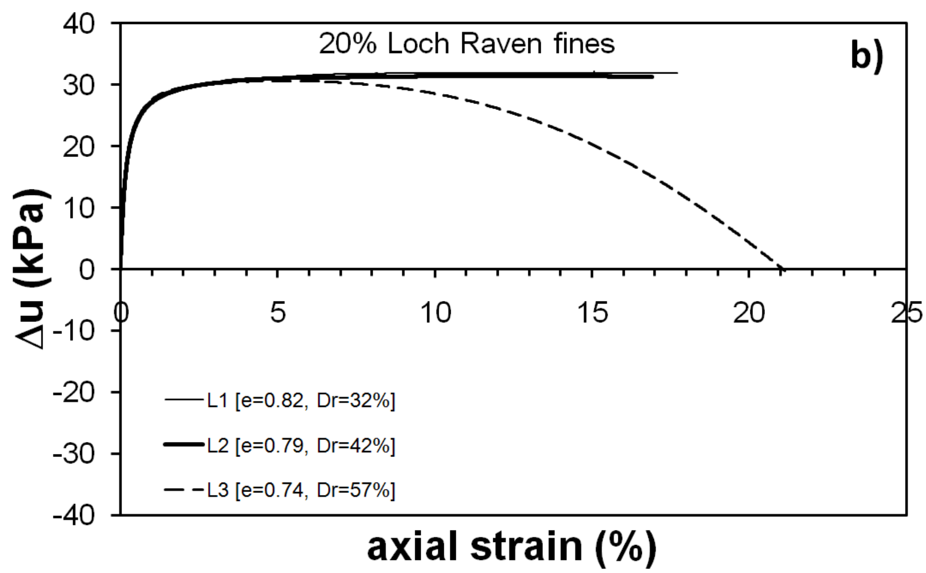
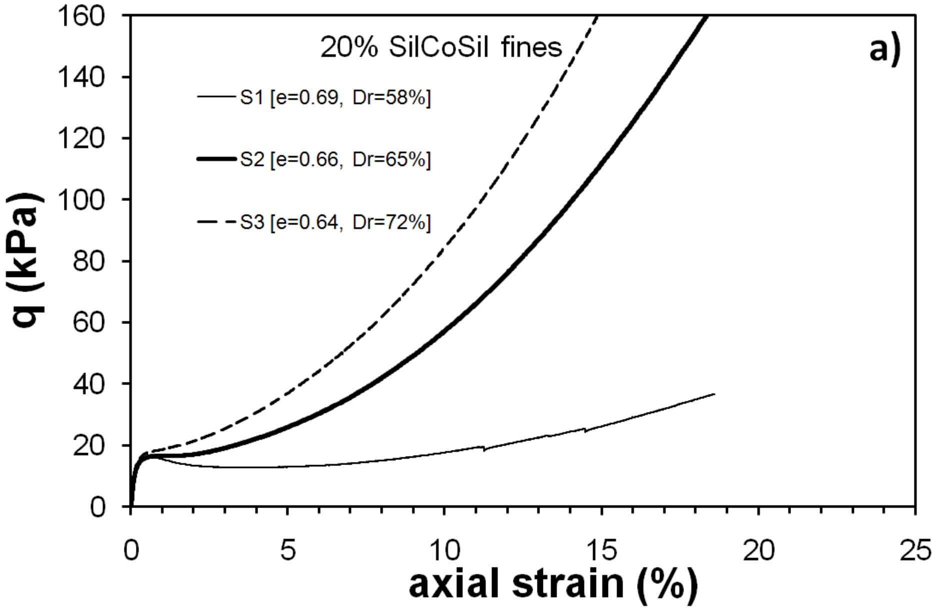


Fig. 3.5. a) Principal stress difference versus axial strain response; b) change of excess pore pressure with axial strain for Nevada Sand-B with 20% SilCOSil fines at 30 kPa confining stress.



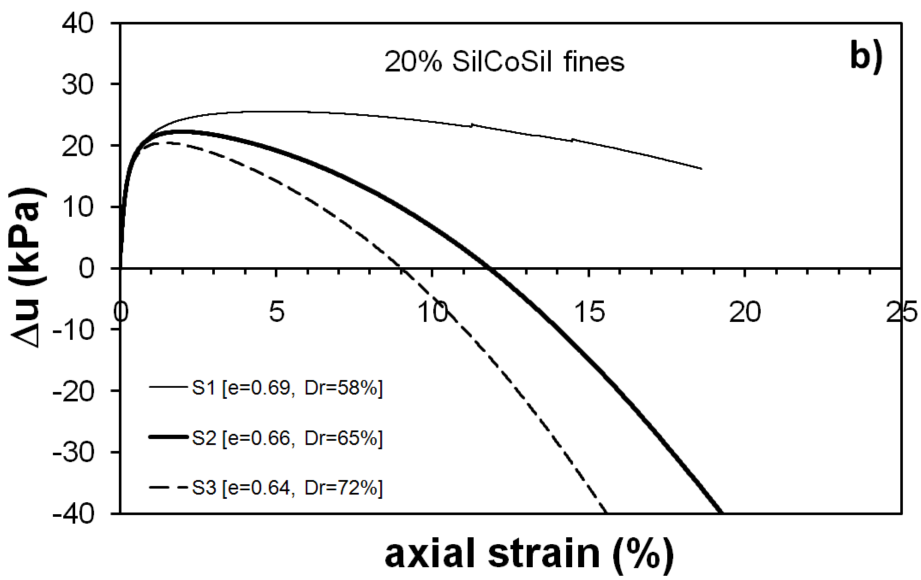


Fig. 3.6. a) Principal stress difference versus axial strain response; b) change of excess pore pressure with axial strain for Nevada Sand-B with 20% Potsdam fines at 30 kPa confining stress.

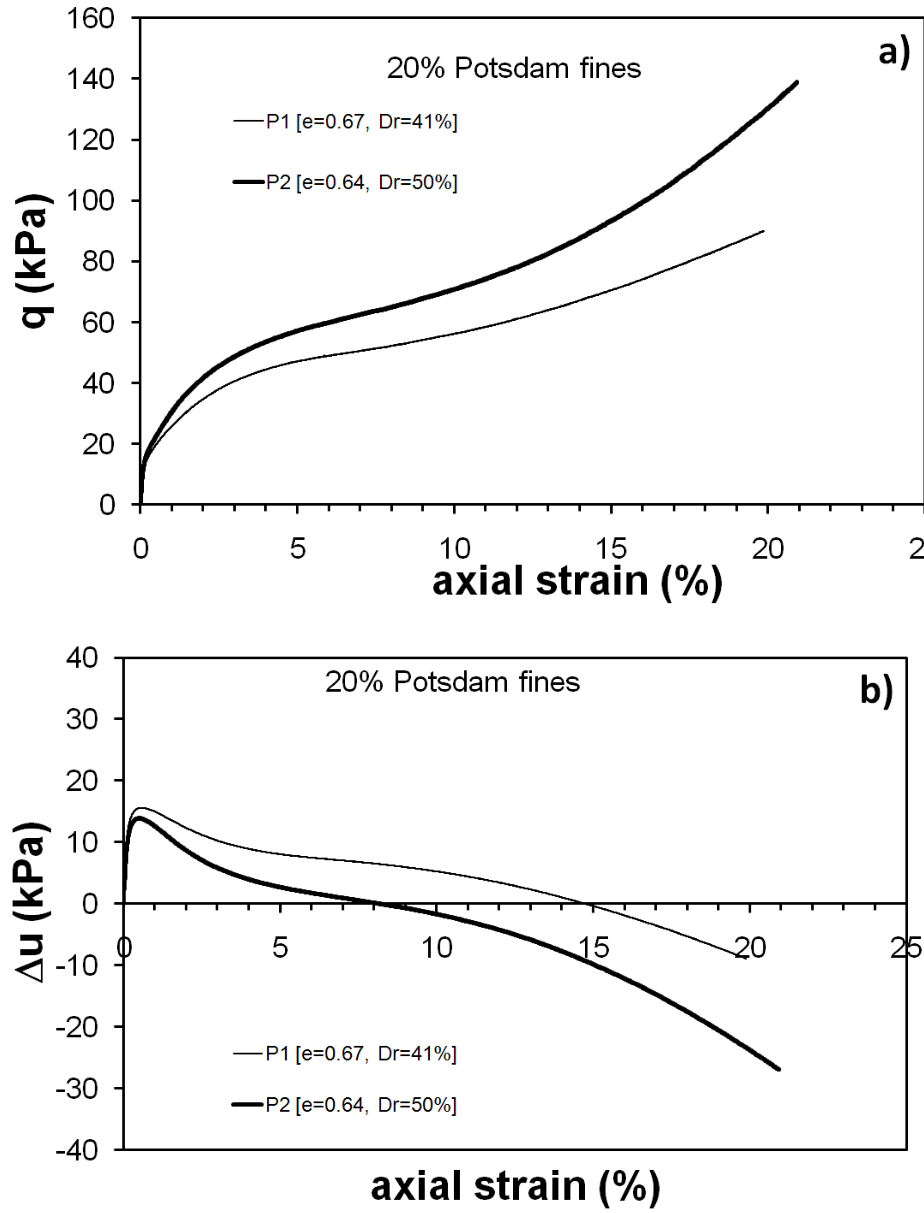


Fig. 3.7. Change of mean grain diameter ratio and liquefaction potential for the loosest possible density specimens.

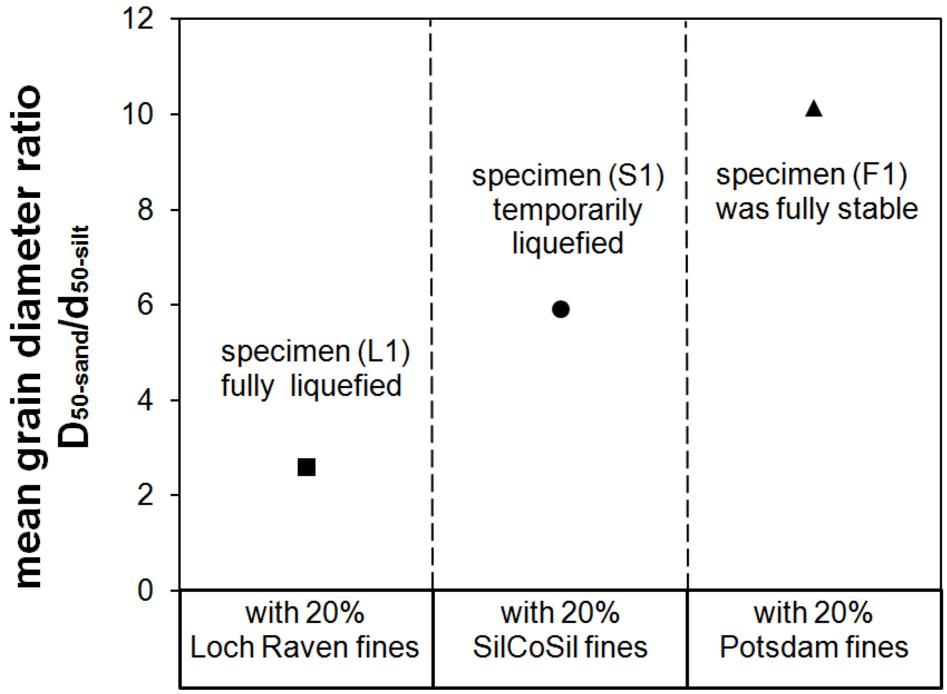


Fig. 3.8. Change of intergranular void ratio and liquefaction potential for tested specimens.

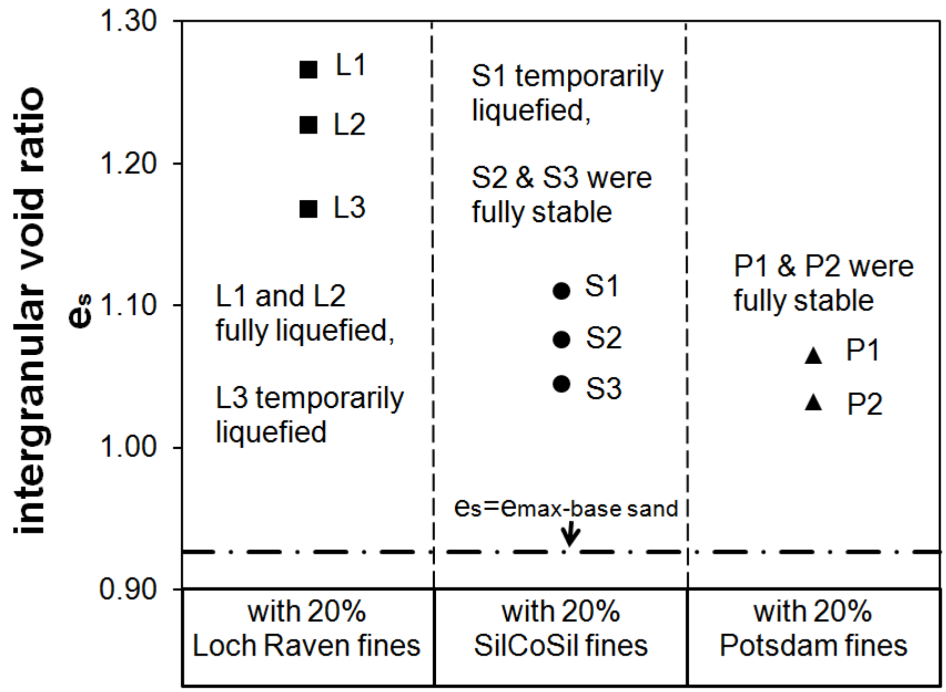


Fig. 3.9. Change of void ratio and liquefaction potential for tested specimens.

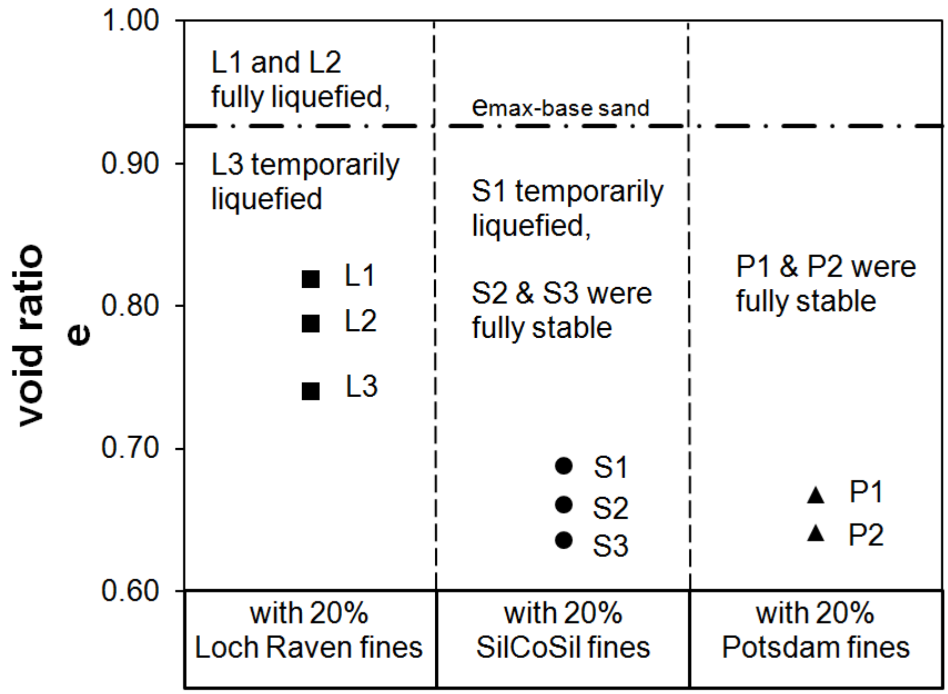


Fig. 3.10. Change of relative density and liquefaction potential for tested specimens.

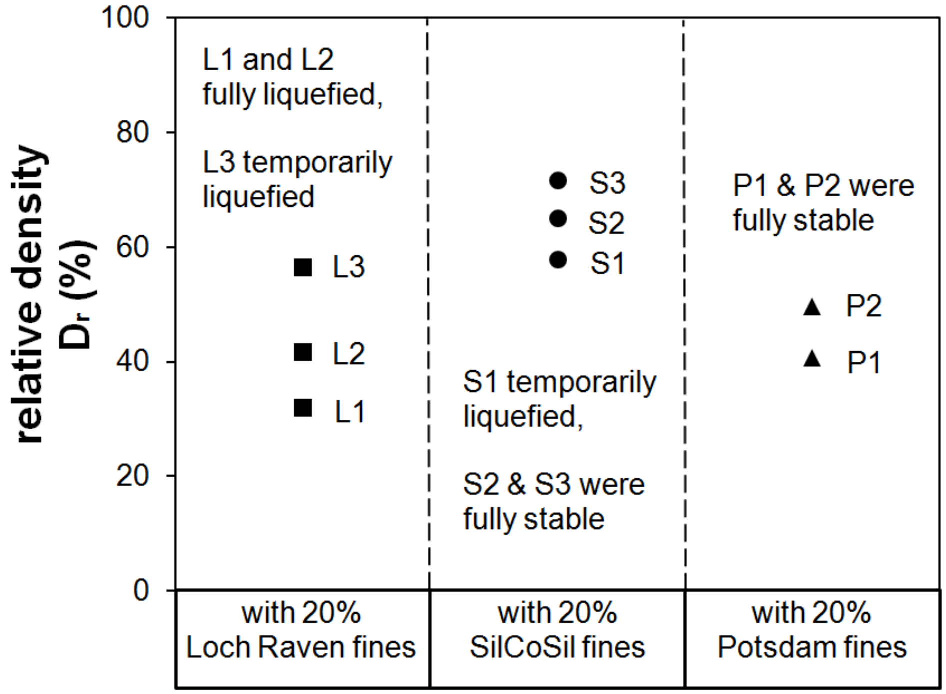
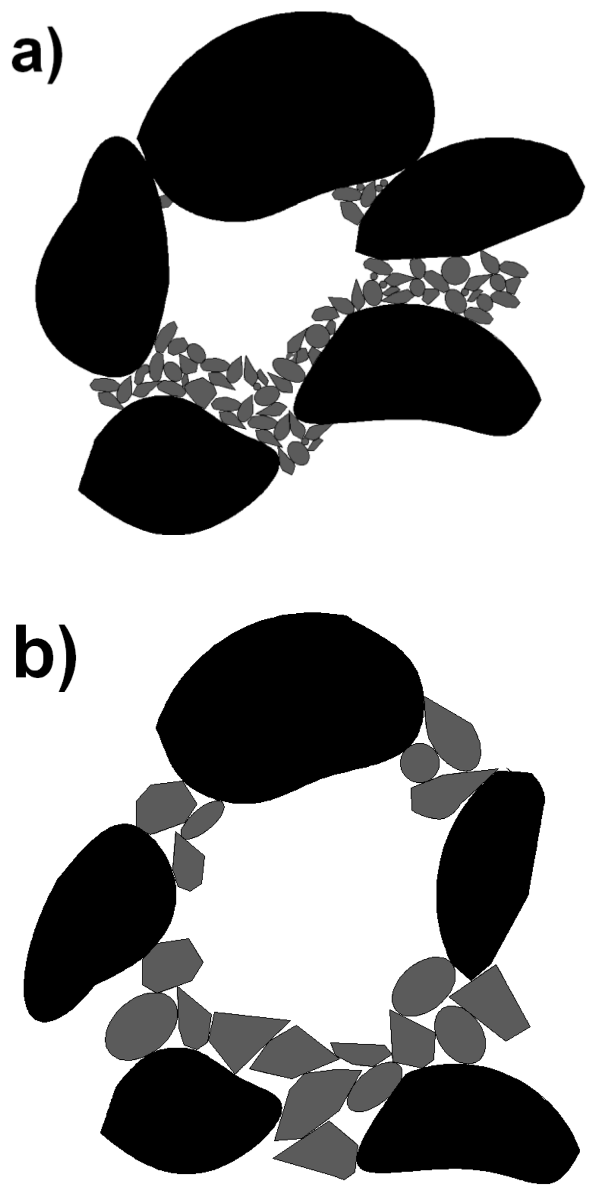


Fig. 3.11. Initial fabric achieved before shearing becomes more compressible as $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio decreases a) soil fabric with high $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio; b) soil fabric with low $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio.



INFLUENCE OF SILT SIZE AND CONTENT ON LIQUEFACTION BEHAVIOR OF SANDS

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Abstract

Previous research regarding fines content influence on liquefaction potential of sands did not established a consensus. Currently, the conclusions about the influence of non-plastic silts on the liquefaction potential of sands are still somewhat contradictory. This study investigates the fines content influence on liquefaction potential of a single base sand mixed with three different essentially nonplastic silts through strain-controlled monotonic undrained triaxial compression tests. Confining stress (30kPa) and deposition method (dry funnel deposition) were kept the same, while fines content was varied, in order to solely focus on how different silts and their contents influence the undrained response of the sand under comparable conditions. It was found that silt size is an important factor influencing the liquefaction potential of silty sands: if the mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) of the sand grains to silt grains is sufficiently small, the liquefaction potential of the sand increases steadily with increasing fines content for the studied range (0-20%). As mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) increases, the liquefaction potential of the sand first decreases then increases with fines content. For such cases, liquefaction potential of the silty sand might actually be less than the liquefaction potential of the clean sand. Differences in undrained behavior are explained based on the influence of mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) on the initial soil fabric.

Key words: Grain Size, Sand, Silts, Soil Liquefaction, Soil Properties, Soil Strength, Soil Test, Triaxial Tests, Pore Pressure

Introduction

Soil liquefaction is one of the most interesting phenomena in geotechnical engineering that has been under research for decades. This is probably because its consequences may be catastrophic whether it is caused by seismic or static loading. With this concern, the liquefaction mechanism has been investigated since the 1960s with initial focus on clean sand behavior. Relatively lately, research on silty sands has also been performed, because silty sands are perhaps the most common type of natural in situ soil that is prone to liquefaction.

Focus of the previous literature on liquefaction of silty sands could be grouped on three major aspects: 1) influence of fines content (Kuerbis et al., 1988; Pitman et al., 1994; Zlatovic and Ishihara, 1995; Lade and Yamauro, 1997; Yamamuro and Covert, 2001), 2) influence of confining stress (Yamamuro and Lade, 1997; Thevanayagam, 1998), and 3) influence of specimen preparation method (Brandon et al., 1991; Høeg et al., 2000; Yamamuro et al., 2008; Wood et al., 2008). Among these three aspects, influence of non-plastic fines on liquefaction potential of sands appears to result in somewhat contradictory conclusions. According to the results of some studies, presence of non-plastic fines increases the liquefaction resistance/dilatancy of sands (Shen et al., 1977; Kuerbis et al., 1988; Pitman et al., 1994; Salgado et al., 2000; Ni et al., 2004; Georgiannou, 2006), while results of some other studies imply that the presence of non-plastic fines decreases the liquefaction resistance/dilatancy of sands

(Erten and Maher, 1995; Zlatovic and Ishihara, 1995; Lade and Yamamuro, 1997; Thevanayagam and Mohan, 2000; Murthy et al., 2007; Bahadori et al., 2008; Papadopoulou and Tika, 2008; Sitharam and Dash, 2008; Carraro et. al., 2009). A summary of related literature with factors of particular interest for this study is given in Table 4.1. Recently, influence of different silts on liquefaction potential of a sand at constant fines content (20%) was also investigated by Monkul and Yamamuro (2010).

The goal of the present study is not necessarily to establish a harmonization among different studies, since they are all legitimate for the particular basis of comparison and conditions. However, factors influencing the different conclusions in the last column of Table 4.1 are important in order to understand and interpret the influence of non-plastic fines on liquefaction potential of sands. Some of these factors are different comparison bases, different deposition methods and/or different confining stresses. Experimental data presented in this paper shows that the size of silt particles relative to sand grains is another major factor in assessing the fines content effect on liquefaction behavior of sand.

Soils Tested

Base sand used in the experimental program is Nevada Sand-B. Silty sands were obtained by mixing the same base sand with three different essentially nonplastic silts with different gradations. These silts were named as Loch Raven, SilCoSil #125 and Potsdam. Nevada Sand, Loch Raven silt, and Potsdam silt are all naturally occurring soils, while SilCoSil #125 is a product of the U.S. Silica Company. Each silt type was mixed with Nevada Sand-B so that the resulting silty sands contain 5% and 20% fines (particles smaller than 0.074mm in diameter) by dry weight. Base sand and silts' gradation curves are plotted in Fig. 4.1. Fig. 4.2 shows the optical microscope images of the silts. Accordingly, both Loch Raven and SilCoSil are more angular than Potsdam, which was rounded.

Some properties such as maximum (e_{max}), minimum void ratios (e_{min}), specific gravities (G_s), mean grain diameters of sand (D_{50}) and silts (d_{50}) are given in Table 4.2. It should be noted that Potsdam silt has a very low PI of 3.8%. Ishihara (1993) mentioned that silts in the low plasticity range (PI<10) does not change the cyclic liquefaction resistance of sandy soils much, but it increases for the greater plasticity ranges. Many sites in Adapazari, Turkey were observed to have liquefaction, which have mainly silty soils with a PI range from 0 to 12, during the 1999 Kocaeli earthquake (Bray et al., 2004). Gratchev et al. (2006) reported that clayey sands with low plasticity index are also quite susceptible to liquefaction. Guo and Prakash (1999) observed that cyclic liquefaction resistance of silt-clay mixtures even decreases with plasticity index for PI<≈4.

Maximum and minimum void ratios of Nevada Sand-B with different silts and various fines contents are shown in Fig. 4.3. Corresponding values in Fig. 4.3 were determined with the method described by Lade et al. (1998).

Experimental Methods

Cylindrical specimens of 7.1cm in diameter (D) by 14.2 cm in height (H) (H/D=2) were formed by the dry funnel deposition technique. This method involves a funnel with a tube attached to its spout. Once the tip of the tube is positioned at the bottom of the split mold, silty sand is poured into the funnel in dry condition. The funnel is then raised gently along the axis of symmetry of the specimen.

Strain controlled monotonic undrained triaxial compression tests were performed on Nevada Sand-B mixed with three different silts at three different fines contents (i.e. FC=0%, 5%, 20%). Lubricated ends and oversized end platens were used in order to promote uniform strains.

Specimens were then flushed with CO_2 in a dry state for 40 minutes prior to saturation. De-aired water was percolated from the bottom through the top of all specimens for a period of 18.5 hours to facilitate greater degrees of saturation, especially for the very fine Potsdam silt. The same time period for percolation was used for all specimens regardless of silt type and fines content to prevent any differences in the undrained behavior that could be attributed to time effects. Considerable volume change during saturation was reported for loose sands (Sladen and Handford, 1987). Therefore, volume change during saturation was monitored by a calibrated burette that was connected to the cell fluid. During this stage, the change in height of the specimens was measured by a LVDT. A back pressure of 100 kPa was applied prior to the B value check to ensure full saturation. Obtained B values were a minimum of 0.99 for all tests.

Previous research reported that increasing strain rate decreases the volumetric contractiveness of the silty sands. Therefore, slow deformation control was used to be conservative when studying undrained silty sand behavior (Yamamuro and Lade, 1998). The strain rate was adjusted to 0.05%/min during shearing after the specimens were isotropically consolidated under 30kPa confining pressure. During the entire specimen preparation process care was taken in order to keep the effective stress at a maximum of 15 kPa and prevent over-consolidation.

Test data were corrected for various factors such as piston friction, piston uplift, weight/buoyancy effects (i.e. piston, top cap etc.) and membrane stiffness. Since the mean grain diameter of the base sand is small (Table 4.2), membrane penetration effect was not considered significant (Frydman et al., 1973; Lade and Hernandez, 1977).

Undrained Triaxial Compression Test Results

Fig. 4.4(a) and Fig. 4.4(b) show the change of principal stress difference (q) and the excess pore pressure (Δu) with increasing axial strain for Nevada Sand-B with Loch

Raven fines. Relative densities after consolidation (D_r) and corresponding void ratios (e_c) are also shown on the same figures for specimens with three different fines contents (0%, 5%, 20%) which were formed with loosest possible densities after deposition. Static liquefaction occurred for the specimens with Loch Raven fines regardless of fines content (Fig. 4.4(a)). Static liquefaction occurs when the principal stress difference (q) is reduced to zero and remains at zero with axial strain, while the excess pore water pressure reaches a plateau (Fig. 4.4(b)). Formation of large wrinkles in the membranes surrounding the specimens coincided with the static liquefaction.

Fig. 4.5(a) and Fig. 4.5(b) show the change of principal stress difference (q) and the excess pore pressure (Δu) with increasing axial strain for Nevada Sand-B with different amounts of SilCoSil fines. Achieved densities were corresponding to the loosest possible densities after deposition. As fines content is increased to 5%, there is a drastic behavior change from complete liquefaction to fully stable, showing that liquefaction resistance increased significantly due to the addition of small amount of SilCoSil fines. As the fines content is further increased to 20%, undrained behavior is changed from fully stable to temporary liquefaction, showing that liquefaction resistance decreased compared to the sand with 5% fines. Temporary liquefaction is exhibited by the principal stress difference achieving an initial peak (q_{peak}), which then reduces to a local minimum nonzero value (quasi steady state, q_{qss}) and then it increases with axial strain to a maximum value which is the true steady state strength. The decline of the principal stress difference from q_{peak} to q_{qss} corresponds to the region where the excess pore pressure reached its maximum value in Fig. 4.5(b). Due to the suppression of dilation, the excess pore pressure declined with continued shearing, and this caused the principal stress difference to increase beyond q_{qss} to its ultimate value.

Fig. 4.6(a) and Fig. 4.6(b) show the change of principal stress difference (q) and the excess pore pressure (Δu) with increasing axial strain for Nevada Sand-B with different amounts of Potsdam fines. Similar to the previous specimens, achieved densities were corresponding to the loosest possible densities after deposition. As fines content is increased to 5%, there is a drastic behavior change from complete liquefaction to fully stable, showing that liquefaction resistance increased significantly due to the addition of a small amount of Potsdam fines. This trend is similar to the observed behavior change for sand with addition of 5% SilCoSil fines, but addition of 5% Potsdam fines appears to boost the liquefaction resistance even more significantly (Fig. 4.6(a)). As the fines content is further increased to 20%, undrained behavior remained fully stable, but the liquefaction resistance decreased compared to the sand with 5% fines due to the increased positive excess pore water pressure generation (Fig. 4.6(b)).

According to the monotonic undrained triaxial test results, mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) is one of the key factors influencing the fines content effect on the liquefaction potential of sands. Considering that other major factors such as confining stress (30kPa), deposition method (dry funnel deposition) and base sand gradation were kept the same, it is observed that for a sufficiently small mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) such as with Loch Raven fines (Table 4.2), increasing the fines content decreases the liquefaction resistance of the sand consistently (decreasing q_{peak} in Fig. 4.4(a)). As the mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) increases, such as with SilCoSil fines, increasing fines content first increases the liquefaction resistance, than starts to decrease it. As the mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) further increases, such as with Potsdam fines, adding small amount of fines (i.e. 5%) may significantly increase the liquefaction resistance, but further addition of fines decreases it. Experiments also showed that for soils with sufficiently large mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$), the liquefaction potential of the clean sand might be greater than the liquefaction potential of the silty sand. However, for relatively smaller mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$), the liquefaction potential of the silty sand is greater than the liquefaction potential of the clean sand.

Discussions

The densities of the tested specimens with different fines contents shown in Figs. 4.4 to 4.6 are the loosest possible densities after deposition, according to which the soil would tend to fall into a “quasi-natural” void ratio, provided that the depositional method is exactly the same. The “quasi-natural” void ratio represents the loosest possible density deposited in exactly the same manner for different soils. This ensures the same amount of energy of deposition. The loosest possible density after deposition is a commonly used comparison basis (Table 4.1) for assessing the influence of fines content on liquefaction potential of sands (Kuerbis et al., 1998; Vaid, 1994; Zlatovic and Ishihara, 1995; Lade and Yamamuro, 1997; Georgiannou, 2006; Bahadori et al., 2008). However, the influence of mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) on other parameters such as void ratio (e), intergranular void ratio (e_s), and relative density (D_r) of the specimens formed by the loosest possible density after deposition might also help to explain the observed changes in liquefaction potential due to fines content.

Void Ratio

Consolidated void ratios of the tested specimens with different fines contents are plotted in Fig. 4.7. There is a tendency that as the $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio decreases, silty sands appear to have greater void ratios.

When Loch Raven fines were added, the void ratio remained almost constant with increasing fines content up to 20%. A similar trend is observed in the maximum and minimum void ratio curves of Nevada Sand-B with Loch Raven fines shown in Fig. 4.3. Apparently, due to the low $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio, even though the fines content increases, rather than mostly filling the intergranular voids between the sand grains, the fines are also significantly loosening the sand skeleton simultaneously. Therefore, void ratios remained almost unchanged in both Fig. 4.3 and Fig. 4.7 with increasing Loch Raven fines up to 20%.

Fig. 4.7 shows that as the $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio becomes larger (for SilCoSil and Potsdam fines), the void ratio decreases consistently with increasing fines content. As expected, the amount of drop in void ratio increases as $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio increases, especially at low fines contents, where fines mostly filled the intergranular voids.

Fig. 4.7 also shows that void ratio alone cannot be a consistent comparison basis for the influence of fines content on liquefaction potential of a sand (i.e. the greater the void ratio, the greater the liquefaction potential of the soil). This is due to the fact that soil fabric is altered, even though the same base sand and silt is used with different proportions. For example, when 5% SilCoSil fines are added to the base sand, liquefaction potential decreased with decreasing void ratio. With further addition of SilCoSil fines, liquefaction potential started to increase again even though void ratio continued to decrease between FC=5% and 20%.

Intergranular Void Ratio

Different parameter names such as sand structure void ratio (Shen et al., 1977), granular void ratio (Lupini et al., 1981; Georgiannou, 2006), skeleton void ratio (Kuerbis et al., 1988; Pitman et al., 1994; Lade and Yamamuro,1997), void ratio of the granular phase (Mitchell, 1993), or intergranular void ratio (Thevanayagam, 1998; Ni et al., 2004; Monkul and Ozden, 2007), all of which encompass the same concept, have been used in the literature related with the shear strength and compressibility of sandy soils. In this study the term intergranular void ratio (e_s) will be used to refer to this parameter hereafter. Equation (4.1a) shows the intergranular void ratio as the void ratio of the sand matrix without the fines.

$$e_s = (V_v+V_f)/V_s \tag{4.1a}$$

where V_v, V_f, V_s are the volume of voids, fines and sand, respectively. Hence, the (V_v+V_f) term in the numerator corresponds to the volume of intergranular void space. Eq. (4.1a) can be rearranged in terms of G, G_f, e and FC as follows in Eq. (4.1b).

$$e_s = \frac{e + \frac{G}{G_f} . \frac{FC}{100}}{1 - \frac{G}{G_f} . \frac{FC}{100}} \tag{4.1b}$$

where e is the overall void ratio, G is the specific gravity of the overall soil (weighted average of sand and silt constituents are used in this study), G_f is the specific gravity of fines in the soil and FC refers to the percentage of fines by total weight of dry soil.

Fig. 4.8 shows the intergranular void ratios of the consolidated specimens calculated by Eq. (4.1b). The maximum void ratio of the base sand (e_s=$e_{max\text{-}base\ sand}$) is also shown with a dashed line. In general, intergranular void ratios of the specimens increased with increasing fines content except for the specimen with 5% Potsdam fines. There is a tendency that as the $D_{50\text{-}sand}/d_{50\text{-}silt}$ ratio decreases, silty sands appear to have greater intergranular void ratios for the same amount of fines content. This is because larger silt grains (e.g. Loch Raven) would not fit inside the intergranular voids as easily as relatively smaller silt grains (e.g. Potsdam). Instead, they would mostly push the sand grains apart, which would increase the intergranular void ratio.

When Nevada Sand-B is tested with SilCoSil fines, the undrained behavior drastically changed from complete liquefaction to stable with 5% fines. Fig. 4.8 shows that the intergranular void ratio of the soil is increased by adding 5% SilCoSil fines compared to the clean sand. However e_s is still below the maximum void ratio of the base sand ($e_s<e_{max\text{-}base\ sand}$). This implies that most of the sand grains are still in contact, even though the sand skeleton has been loosened by the SilCoSil fines. As fines content is further increased to 20%, undrained behavior changes from stable to temporary liquefaction, where this time e_s is greater than the maximum void ratio of the base sand ($e_s>e_{max\text{-}base\ sand}$).

When Nevada Sand-B is tested with Potsdam fines, the undrained behavior drastically changed from complete liquefaction to stable with 5% fines, similar to SilCoSil fines. Fig. 4.8 shows that the intergranular void ratio of the soil remains constant by adding 5% Potsdam fines compared to the clean sand. This implies that the sand grain contacts are preserved and virtually all Potsdam fines are confined inside the intergranular voids between the sand grains. This also manifested itself in the drastic behavior change shown in Fig. 4.6(a). As the fines content is further increased to 20%, the soil becomes significantly more contractive compared to the 5%, but it is still stable even though e_s is greater than the maximum void ratio of the base sand ($e_s > e_{max\text{-}base\ sand}$).

Fig. 4.8 also shows that similar to void ratio, intergranular void ratio alone cannot be a consistent comparison basis for the influence of fines content on liquefaction potential of a sand (i.e. the greater the intergranular void ratio, the greater the liquefaction potential of the soil). This is due to the fabric alteration discussed before. If the $D_{50\text{-}sand}/d_{50\text{-}silt}$ ratio is sufficiently large (e.g. with Potsdam fines), at low fines content (i.e. 5%), the silt decreases the liquefaction potential significantly. Even at greater fines contents (i.e. 20%) silty sand might still have a lower liquefaction potential than the clean sand, even though the intergranular void ratio of the silty sand is significantly greater than both the intergranular void ratio of the clean sand, as well as the maximum void ratio of the base sand (Fig. 4.8). As the $D_{50\text{-}sand}/d_{50\text{-}silt}$ ratio becomes smaller, the influence discussed above gradually diminishes and the liquefaction potential increases with increasing fines content as compared to the clean sand (e.g. with Loch Raven fines).

Relative Density

The relative densities of the tested specimens after consolidation were shown in Fig. 4.9. This figure clearly implies that relative density alone cannot be a consistent comparison basis for the influence of fines content on liquefaction potential of a sand (i.e. the smaller the relative density, the greater the liquefaction potential of the soil).

For example, with addition of 5% SilCoSil fines, the relative density decreased, while the undrained behavior changed from complete liquefaction to completely stable. Increasing the fines content from 5% to 20%, once again changed the undrained behavior from completely stable to temporary liquefaction, even though relative density increased considerably for sand with SilCoSil fines.

Fig. 4.9 also shows that relative density alone cannot be a reliable comparison basis for the liquefaction potential of a sand having the same fines content but with silts of different mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$). For example, at 5% fines content, specimens with both Loch Raven and SilCoSil fines had the same relative density, however their undrained behavior was completely different as seen on Fig. 4.9, i.e. the specimen with Loch Raven fines liquefied, while the specimen with SilCoSil fines was stable. Similarly, at 20% fines content, the specimen with SilCoSil fines had a higher relative density than the specimen with Potsdam fines, yet is more liquefiable. Hence, for the same relative density, fines content and confining stress, as the $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio decreases the sand becomes more liquefiable.

Void ratio range

Cubrinovski and Ishihara (2000) proposed void ratio range (e_{max}-e_{min}) as an indicative measure for liquefaction potential of sandy soils, because it includes the combined influence of gradation, grain shape and fines content. Accordingly, high void ratio range (e_{max}-e_{min}) is an indication of high liquefaction potential. Fig. 4.10 shows the relationship between the void ratio range (e_{max}-e_{min}) and fines content for Nevada Sand-B with different silt types.

When Loch Raven fines are added, the void ratio range gradually increases slightly, until 20% fines content is reached. This is consistent with the observed change of liquefaction potential of specimens with Loch Raven fines prepared at the loosest possible density after deposition. As can be seen in Fig. 4.4(a), liquefaction potential increases gradually with increasing fines content for Loch Raven fines.

When SilCoSil fines are added the void ratio range first decreases for 5% FC and then increases again with further addition of fines to 20% FC. This is consistent with the observed change of liquefaction potential of specimens with SilCoSil fines prepared at the loosest possible density after deposition. Fig. 4.5 shows that liquefaction potential first decreases for 5% FC (from complete liquefaction to fully stable) and then increases again with further addition of fines to 20% FC (from fully stable to temporary liquefaction).

When Potsdam fines were added, similar to the SilCoSil fines, the void ratio range first decreases for 5% FC and then increases again with further addition of fines to 20% FC. This is consistent with the observed change of liquefaction potential of specimens with Potsdam fines prepared at the loosest possible density after deposition. Fig. 4.6 shows that liquefaction potential drastically decreases for 5% FC (from complete liquefaction to fully stable). Note that the corresponding drop in void ratio range is sharpest for sand with Potsdam fines (Fig. 4.10), which correlates well for the most drastic behavior change for the addition of 5% fines among the three different silts. Liquefaction resistance decreases again with further addition of 20% Potsdam fines (Fig. 4.6).

Experiments in this study show that void ratio range (e_{max}-e_{min}) provides a good intuition regarding the change of liquefaction potential with fines content for laboratory specimens prepared at the loosest possible density after deposition. However, numerical values of the void ratio range (e_{max}-e_{min}) do not necessarily enable a direct comparison for liquefaction potential between the loosest possible density specimens of clean sand and silty sand at relatively higher fines contents (i.e. 20%). For instance, the value of the void ratio range is greater for sand with 20% SilCoSil fines than the clean sand (Fig. 4.10), even though clean sand is more liquefiable than the sand with 20% SilCoSil fines (Fig. 4.5). Note that, this comparison is based on the loosest possible density after deposition. Perhaps, sand with 20% SilCoSil fines would be more liquefiable than the clean sand, if they were tested at the same void ratio. However, achieving such a condition is technically not possible with the employed deposition method and may also be unrealistic, considering the same energy (same depositional method and consolidation stress) intentionally used in this study. Similarly, at 20% fines content, the void ratio range is greater for sand with SilCoSil fines than for sand with Loch Raven fines (Fig. 4.10), but Loch Raven fines makes sand more liquefiable than the SilCoSil fines for the specimens at the loosest possible density after deposition.

Influence of Mean Grain Diameter Ratio on Initial Soil Fabric

The influence of mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) on many parameters discussed so far, and most importantly, on the liquefaction potential of sands with different fines content, is believed to be closely related with the initial fabric achieved before shearing. Previous research had shown that silty sands might have a significant percentage of "metastable" grain contacts (silt grains located between sand grains) before shearing (Yamamuro and Wood, 2004; Yamamuro et al., 2008). The term "metastable structure" was probably first introduced by Terzaghi (1956) in order to explain the collapse of fine grained cohesionless sediments. Hanzawa et al. (1979) also used "metastable" contacts in order to explain the static liquefaction potential of a silty sand deposit which was later subjected to ground improvement. Silty sands can be expected to become more volumetrically contractive as the percentage of the "metastable" contacts increases. Experimental results discussed in this paper suggest that, formation of these "metastable" grain contacts is strongly influenced by the gradation characteristics of the silt, and mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) is selected as a reflective and simple means to investigate this influence.

Mean grain diameter ratio and fabric at small fines content

When a small amount of fines is added to the sand (i.e. 5%), and when the mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) is sufficiently high, such as with Potsdam fines, the silt grains would mostly end up in the intergranular voids in between the sand grains instead of forming metastable contacts. This is because smaller silt grains have a greater mobility and capacity to easily fit into the intergranular voids between the sand grains during deposition and/or consolidation. In fact this can be verified by the aid of Figs. 4.7 and 4.8, which show decreasing void ratio and constant intergranular void ratio respectively with the addition of 5% Potsdam fines. This, of course, significantly decreases the liquefaction potential of the silty sand compared to the clean sand.

As $D_{50\text{-sand}}/d_{50\text{-silt}}$ decreases such as with SilCoSil fines, addition of a small amount of fines (i.e. 5%) does still not seem to generate enough metastable contacts to weaken the soil compared to the clean sand. Note that this time, the intergranular void ratio increases (Fig. 4.8) while the void ratio decreases (Fig. 4.7). As $D_{50\text{-sand}}/d_{50\text{-silt}}$ becomes sufficiently small, such as with Loch Raven fines, addition of a small amount of fines (i.e. 5%) produces a different mechanism than the addition of the other silts with smaller grain sizes. Instead of mainly filling the intergranular voids, the silt grains have a tendency to form metastable grain contacts, which in turn weaken the soil compared to the clean sand. Unlike the silts with larger $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratios, this time the void ratio does not decrease (Fig. 4.7), while the intergranular void ratio increases (Fig. 4.8). This different mechanism also manifests itself in Fig. 4.3, where the e_{max}

and e_{min} curves were flat with Loch Raven fines, while the corresponding curves with SilCoSil and Potsdam fines declined. Fig. 4.3 also shows that the amount of decline decreases with decreasing mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$).

Mean grain diameter ratio and fabric at greater fines content

When a greater amount of fines is added to the sand (i.e. 20%), silts with relatively larger mean grain diameter ratios ($D_{50\text{-sand}}/d_{50\text{-silt}}$), such as Potsdam and SilCoSil, will continue to primarily fill the intergranular voids between the sand grains and secondarily further loosen the sand skeleton. That is why they have significantly lower void ratios (Fig. 4.7) and at the same time produce significantly higher intergranular void ratios (Fig. 4.8) compared to the clean sand. Since there are significant amounts of fines located in the intergranular voids, liquefaction potential of those silty sands might be lower than that of the clean sand, even though the intergranular void ratio of the silty sand is much higher than the clean sand. However, compared to the silty sand with smaller fines content (e.g. 5%), liquefaction resistance of the silty sand decreased because of the loosened sand skeleton (Fig. 4.8).

As $D_{50\text{-sand}}/d_{50\text{-silt}}$ becomes sufficiently small such as with Loch Raven fines, addition of greater amount of fines (e.g. 20%) would work different than for the other silts. This different mechanism is explained before for the small amounts of fines with small $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratios. Instead of mainly filling the intergranular voids, silt grains have a tendency to form even more metastable grain contacts, which increases the liquefaction potential compared to both the clean sand and silty sand with smaller amounts of fines (e.g. 5%). This tendency is clearly seen in Fig. 4.7, where the void ratio remained almost the same for the entire 0-20% fines content range, while the intergranular void ratio steadily increased (Fig. 4.8).

Shape effect of silt grains on initial fabric

How much the shape effects of the silt grains influence the initial soil fabric discussed so far is a legitimate question to ask. For instance, Fig. 4.2 shows that Potsdam fines are not only smaller, but also more round in shape compared to the other fines, which could possibly enhance the chance of reducing the number of “metastable” contacts. In this case the size effect and the shape effect could have concurrently worked to reduce the liquefaction potential of the sand with Potsdam fines. Detailed investigation of the silt grain shape effects on the liquefaction potential of sand is beyond the scope of this study. However, the particle shape effect must be relatively small compared to the particle size effect. If it were not, the liquefaction susceptibility of the sand would be similar both with the Loch Raven and SilCoSil silts which were both angular. However, since liquefaction potential clearly increased with decreasing $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio, it can be concluded that the particle size effect of silts on liquefaction potential of a sand is much more significant than the particle shape effect.

Summary and Conclusions

In this study the influence of silt size and non-plastic fines content on the liquefaction potential of a sand was investigated. Undrained triaxial compression tests were performed on a base sand mixed with three different essentially non-plastic silts with various gradations at three different fines contents. Other major influencing factors such as base sand (Nevada Sand-B), confining stress (30 kPa) and deposition method (dry funnel deposition) were kept exactly the same throughout the experimental program for assessing the resulting undrained response.

It was found that mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) is a very important factor influencing the liquefaction potential of a sand with various fines contents. Accordingly,

1) If the mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) is large, addition of non-plastic fines initially decrease and then start to relatively increase the liquefaction potential of the sand. For this case, clean sand might have a greater liquefaction potential than the silty sand at comparable conditions.

2) If the mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) is sufficiently small, addition of non-plastic fines steadily increases the liquefaction potential of a sand. For this case, silty sand would be more liquefiable than the clean sand at comparable conditions.

3) Commonly used comparison bases in the literature, such as void ratio, intergranular void ratio and relative density, are not sufficient for assessing the influence of fines on liquefaction resistance/dilatancy of silty sands. For example, for the same relative density, fines content and stress conditions, as the $D_{50\text{-}sand}/d_{50\text{-}silt}$ ratio decreases the sand becomes more liquefiable. For a specific fines type, the sand might become more liquefiable with increasing fines content, even though relative density increases or vice versa.

4) Current geotechnical engineering practice mostly considers fines content and/or the PI (Atterberg Limits) in assessments and correlations regarding the influence of fines on liquefaction of sands. This study showed that the influence of fines content may be significantly affected by the nature of the fines, and the resulting undrained response of a sand can be vastly different (e.g. complete liquefaction versus completely stable) for the same stress conditions depending on the silt gradation.

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Table 4.1. Summary of some of the previous literature with factors of particular interest (modified after Monkul and Yamamuro,2010).

Ref.	***Type of sand***	***D_{50} sand (mm)***	***Type of fines***	***d_{50} fines (mm)***	***D_{50}/d_{50}***	***deposition method***	***type of testing***	***σ'_{3c} (kPa)***	***comparison basis***	**FC range (%)**	***effect of FC on liquefaction resistance or dilatancy***
1	Ottawa sand	0.4	silt	-	-	moist tamping	cyclic triaxial	-	same intergranular void ratio	0-20	increase
2	Brenda mine tailings sand (20/200) (angular)	0.25	Kamloops silt	0.012	20.8	slurry deposition	undrained triaxial	350	similar intergranular void ratio	0-22.3	increase
3	Ottawa sand (subrounded)	0.39	crushed silica fines (angular)	-	-	moist tamping	undrained triaxial	350	similar initial void ratio	0-40	increase
4	Ottawa sand (subrounded)	0.39	Sil-Co-Sil #106	0.02*	19.5	slurry deposition	drained triaxial	400	similar relative density	0-20	increase
5	Old Alluvium sand	0.73*	crushed quartz	0.04*	18.3	moist tamping	undrained triaxial	215	same intergranular void ratio	0-9	increase
6	Monterey sand (0/30) (subangular to subrounded)	0.48	Sil-Co-Sil #52	0.0135	35.6	moist tamping	cyclic simple shear	100	same void ratio, intergranular void ratio, relative density	0-20	increase
7	Ottawa sand (rounded)	0.6	Sil-Co-Sil #125	0.017	35.3	moist tamping	cyclic triaxial	98	same void ratio	0-30	decrease
8	Toyoura sand	0.17	Toyoura silt	0.01	17	moist tamping & dry funnel deposition, water sedimentation	undrained triaxial	50 & 500	loosest possible density after deposition	0-30	decrease
9	Nevada sand (50/200) (angular)	0.16	Nevada fines	0.05	3.2	dry funnel deposition	undrained triaxial	25	loosest possible density after deposition	0-30	decrease
	Ottawa sand (50/200) (angular)	0.2			4					0-50	
10	sand	0.25	kaolin silt	0.009*	27.8	dry air pluviation	undrained triaxial	100	same void ratio	0-27	decrease
11	Monterey sand (0/30) (subangular to subrounded)	0.43	Yatesville silt	0.03	14.3	moist tamping	cyclic triaxial	100	relative density	0-40	decrease (depending on D_r)

	Yatesville sand (subangular to subrounded)	0.18			6						
12	Ham River Sand (subangular)	0.27*	HPF4 Silt	0.04*	6.8	dry air pluviation	undrained triaxial (anisotropically con.)	49	loosest possible density after deposition	0-2.5	increase
			silt size mica	0.01*	27					0-2.5	decrease
13	Ottawa sand (rounded)	0.39	Sil-Co-Sil #106	0.02*	19.5	mod. slurry deposition & moist tamping	undrained triaxial	btwn. 148 and 653	-	0-15	decrease
14	Firoozkuh sand	0.27	Firoozkuh silt	0.03	9	dry deposition	hollow cyl. torsional shear	100 & 200	loosest possible density after deposition	0-30	decrease
15	Quartz sand (well rounded)	0.3	Assyros silt	0.02	15	moist tamping	cyclic triaxial	50 & 300	similar void ratio	0-35	decrease
16	Ahmedabad sand	0.3	quarry dust	-	-	dry funnel deposition	cyclic triaxial	100	same void ratio	0-20	decrease
17	Ottawa Sand (rounded)	0.31	Sil-Co-Sil #106	0.02*	15.5	slurry deposition	drained triaxial	400	similar relative density	0-15	decrease (for low relative densities)
18	Nevada Sand-B (angular)	0.14	Loch Raven	0.055	2.6	dry funnel deposition	undrained triaxial	30	loosest possible density after deposition,	0-20	decrease
			SilCoSil #125	0.024	5.9						first increase than relatively decrease
			Potsdam	0.014	10.1						first increase than relatively decrease

References: 1) Shen et al. (1977), 2)Kuerbis et al. (1988) and Vaid (1994), 3) Pitman et al. (1994), 4)Salgado et al. (2000), 5) Ni et al. (2004), 6) Hazirbaba and Rathje (2009) 7)Erten and Maher (1995), 8) Zlatovic and Ishihara (1995), 9)Lade and Yamamuro (1997), 10) Thevanayagam and Mohan (2000), 11)Polito and Martin II (2003), 12)Georgiannou (2006), 13)Murthy et al. (2007),14) Bahadori et al. (2008), 15) Papadopoulou and Tika (2008), 16) Sitharam and Dash (2008), 17) Carraro et al. (2009), 18) this study

*representative values of D_{50} and/or d_{50} were read from the gradation curves.

Table 4.2. Some properties of the soils used in the experimental program.

	Nevada Sand-B	Loch Raven Silt	SilCoSil #125	Potsdam Silt
Specific Gravity Gs	2.68	2.73	2.68	2.82
e_{min}	0.624	0.834	1.101	0.878
e_{max}	0.926	1.245	1.550	1.327
mean grain diameter (mm)	0.142	0.055	0.024	0.014
$D_{50\text{-sand}}/d_{50\text{-silt}}$	-	2.6	5.9	10.1

Fig. 4.1. Grain size distribution of the soils used in the experimental program.

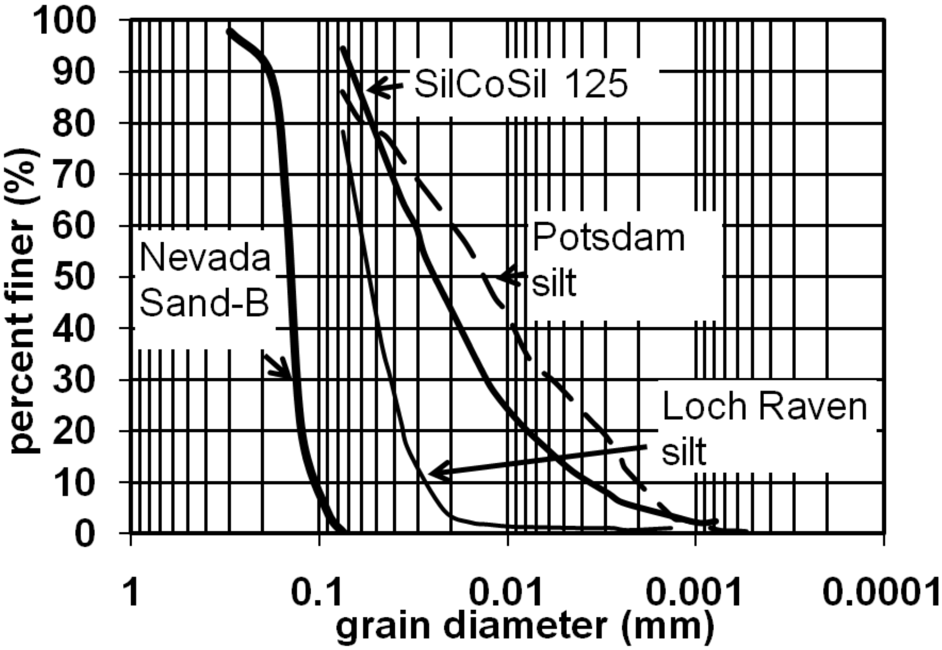
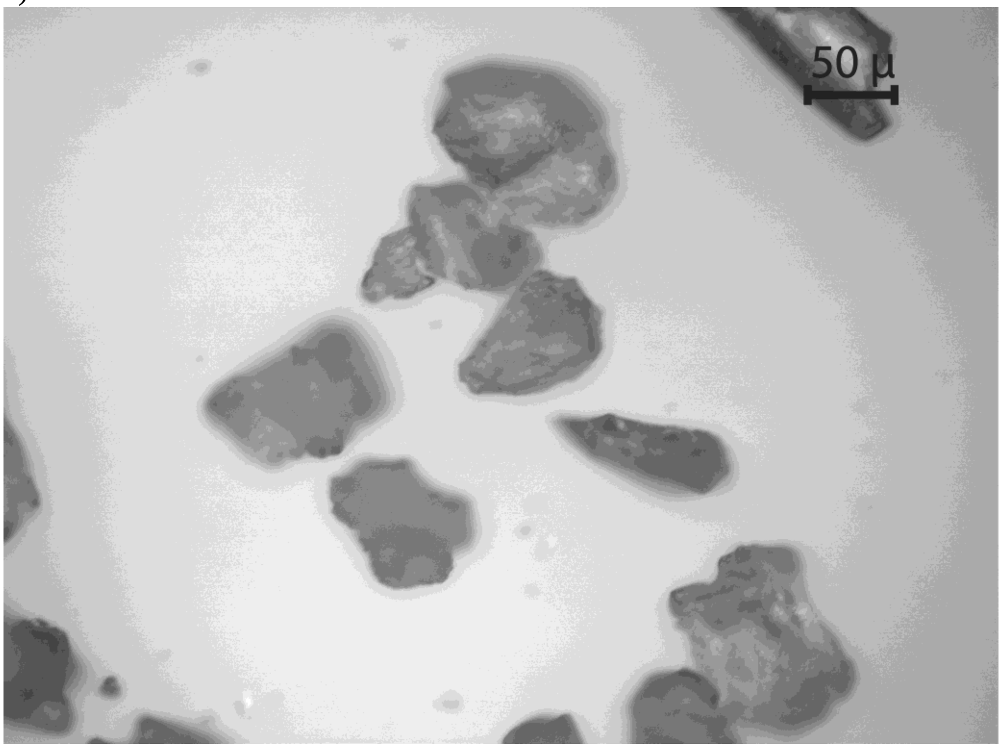
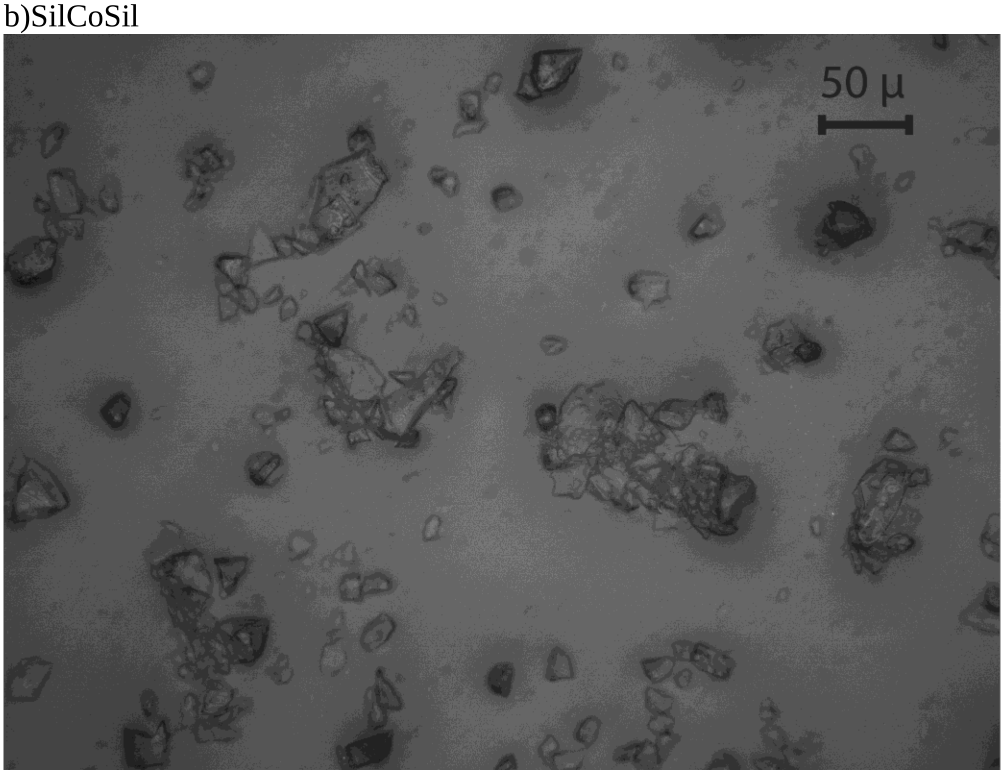


Fig. 4.2. Appearance of different silts under optical microscope,
a)Loch Raven silt



b)SilCoSil



c) Potsdam silt

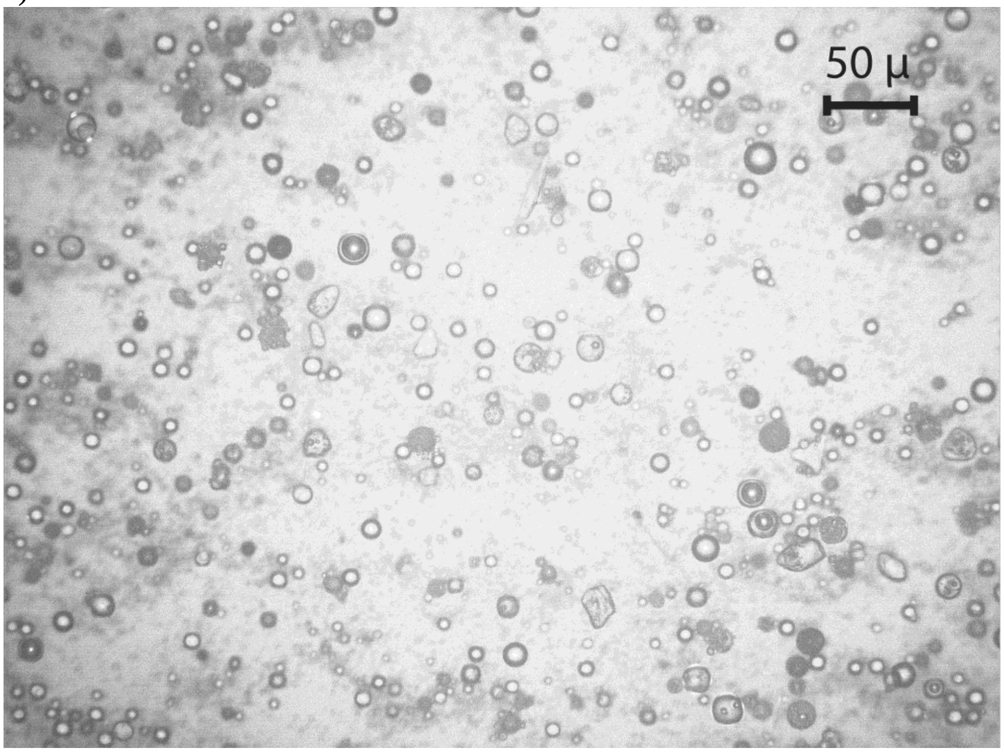


Fig. 4.3. Limiting void ratios of silty sands for different fines contents.

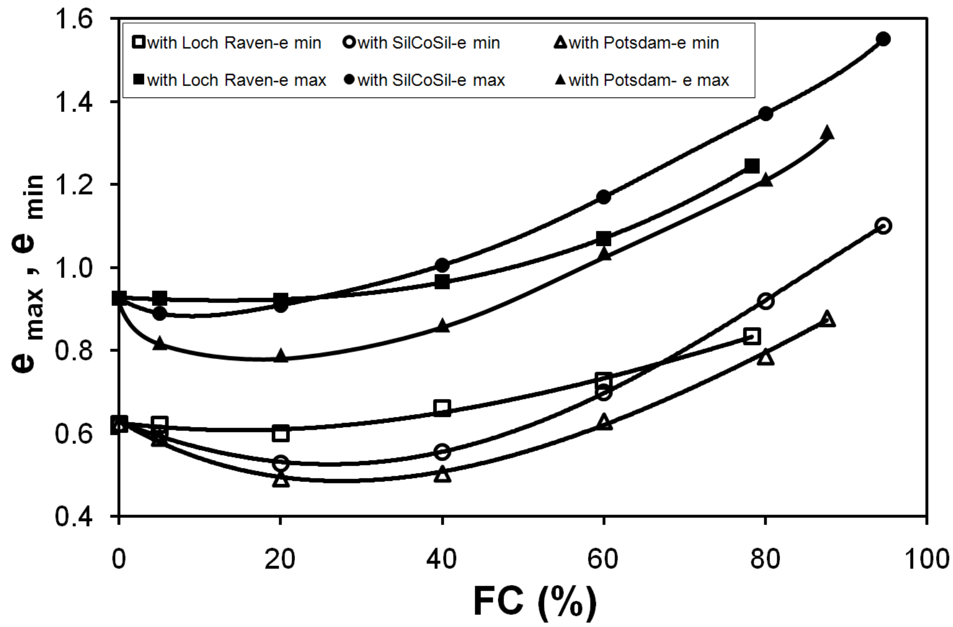
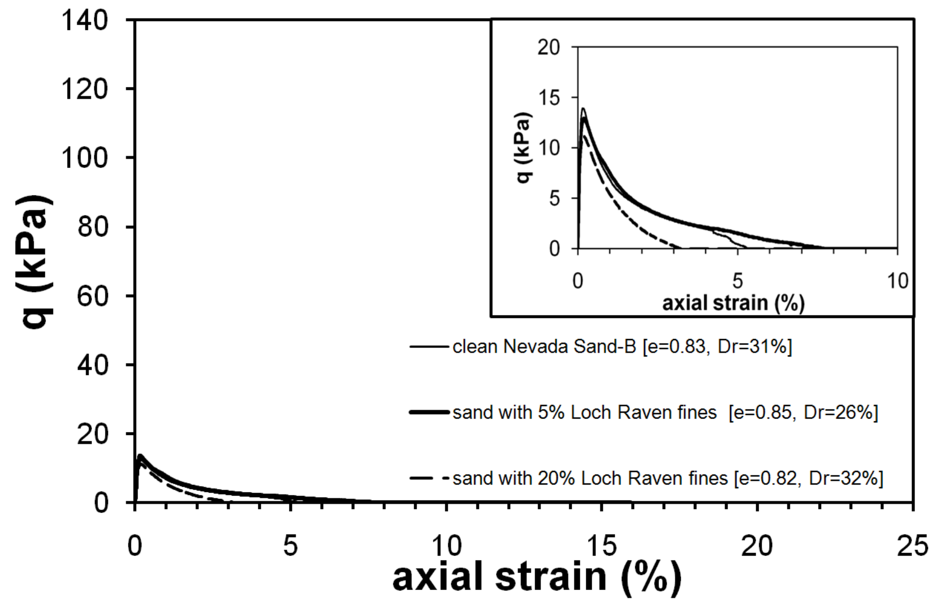


Fig. 4.4 a) Principal stress difference versus axial strain response; b) change of excess pore pressure with axial strain for Nevada Sand-B with different percentages of Loch Raven fines at 30 kPa confining stress.



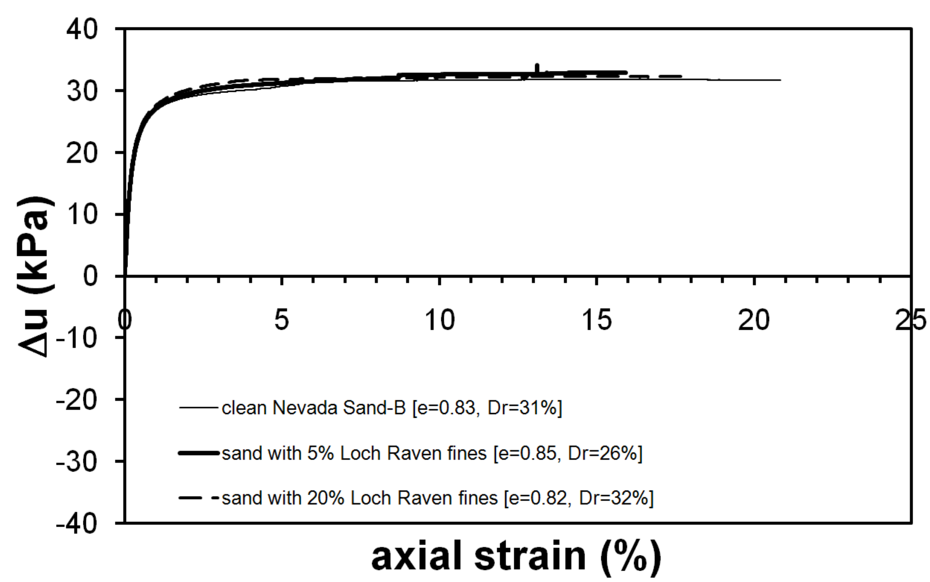
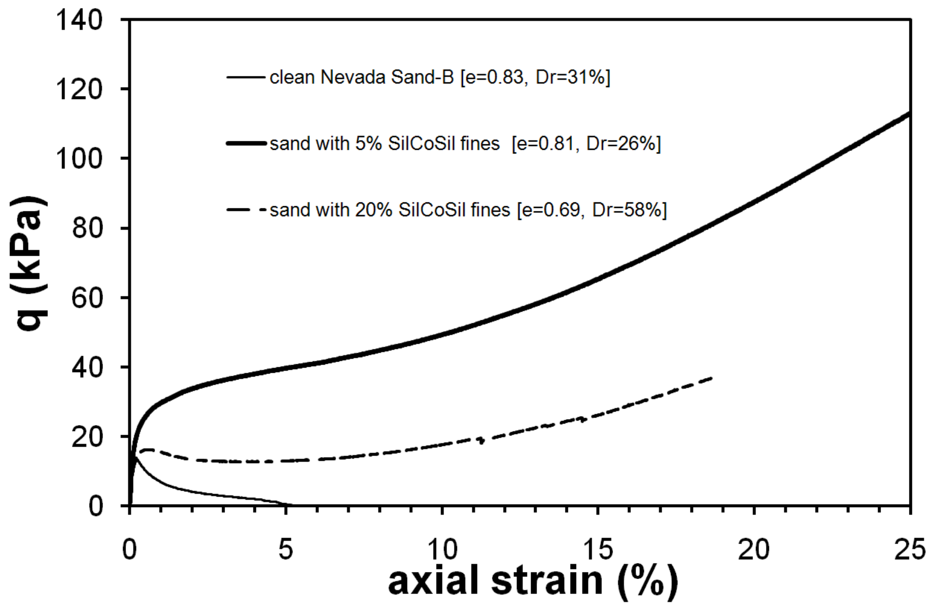


Fig. 4.5 a) Principal stress difference versus axial strain response; b) change of excess pore pressure with axial strain for Nevada Sand-B with different percentages of SilCoSil fines at 30 kPa confining stress.



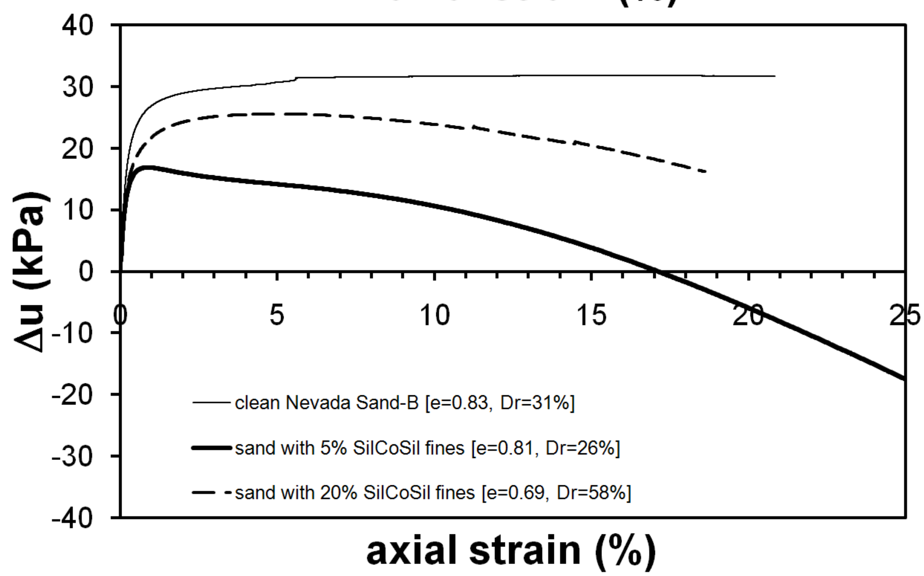


Fig. 4.6 a) Principal stress difference versus axial strain response; b) change of excess pore pressure with axial strain for Nevada Sand-B with different percentages of Potsdam fines at 30 kPa confining stress.

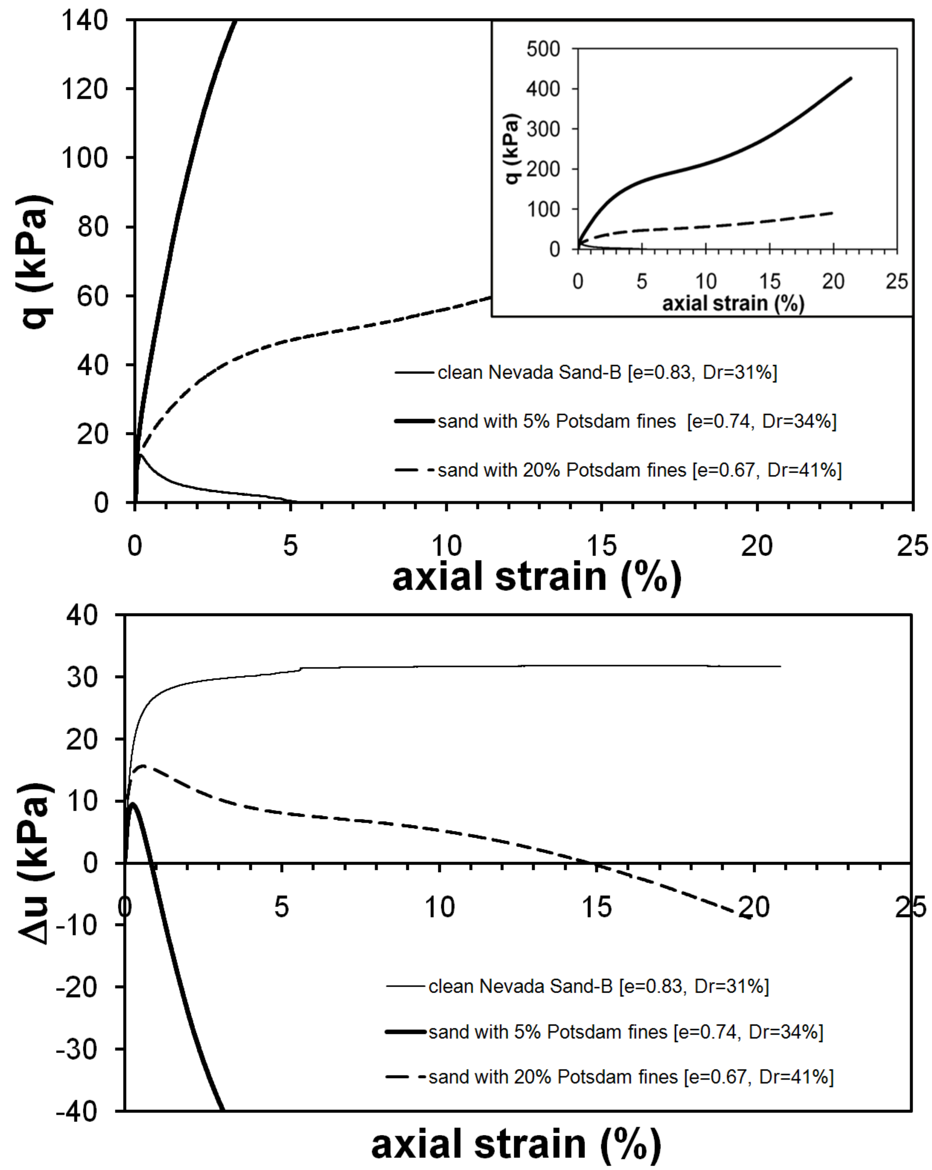


Fig. 4.7. Change of void ratio and liquefaction potential with different fines contents and silts for tested specimens.

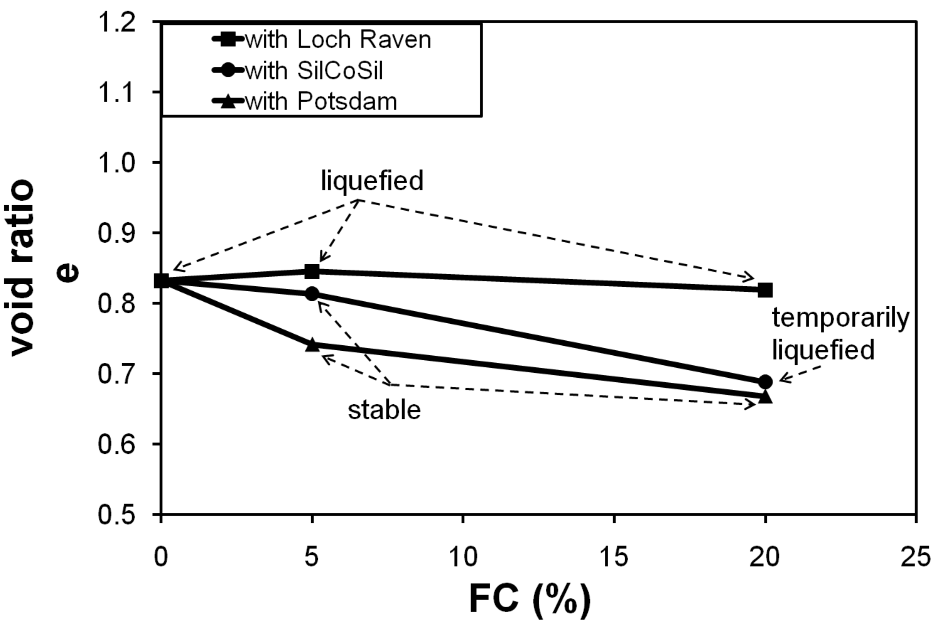


Fig. 4.8. Change of intergranular void ratio and liquefaction potential with different fines contents and silts for tested specimens.

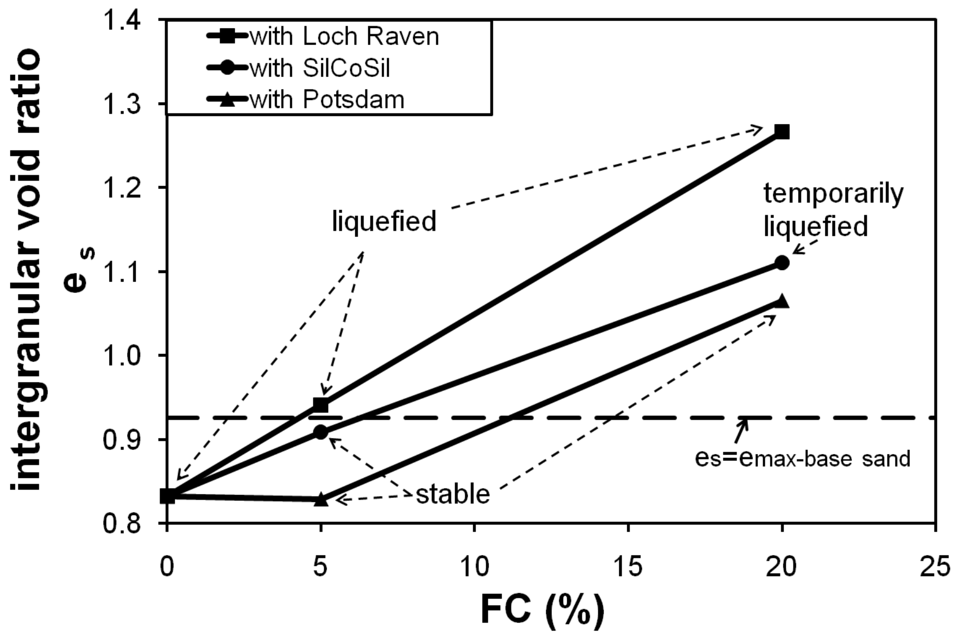


Fig. 4.9. Change of relative density and liquefaction potential with different fines contents and silts for tested specimens.

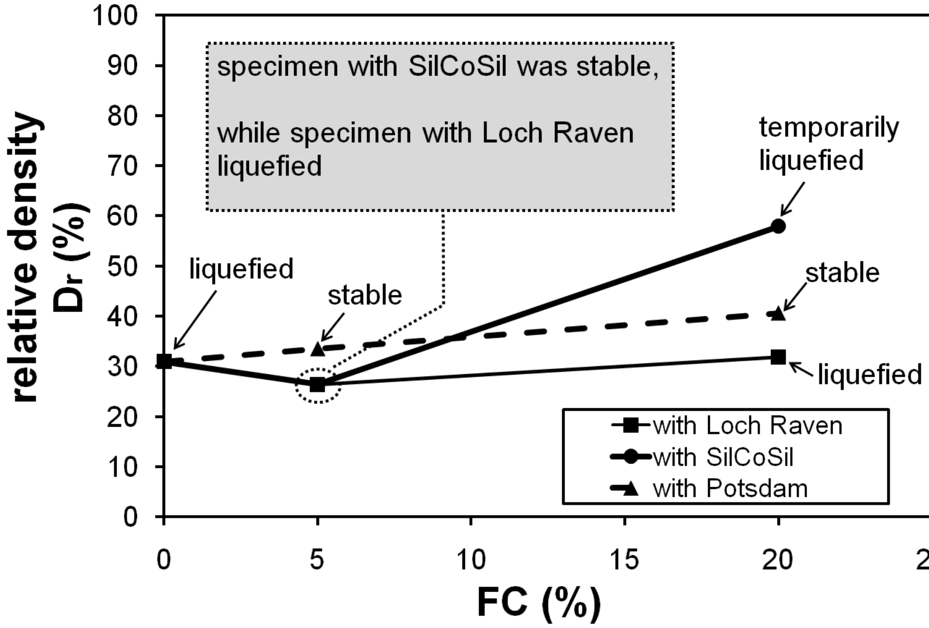
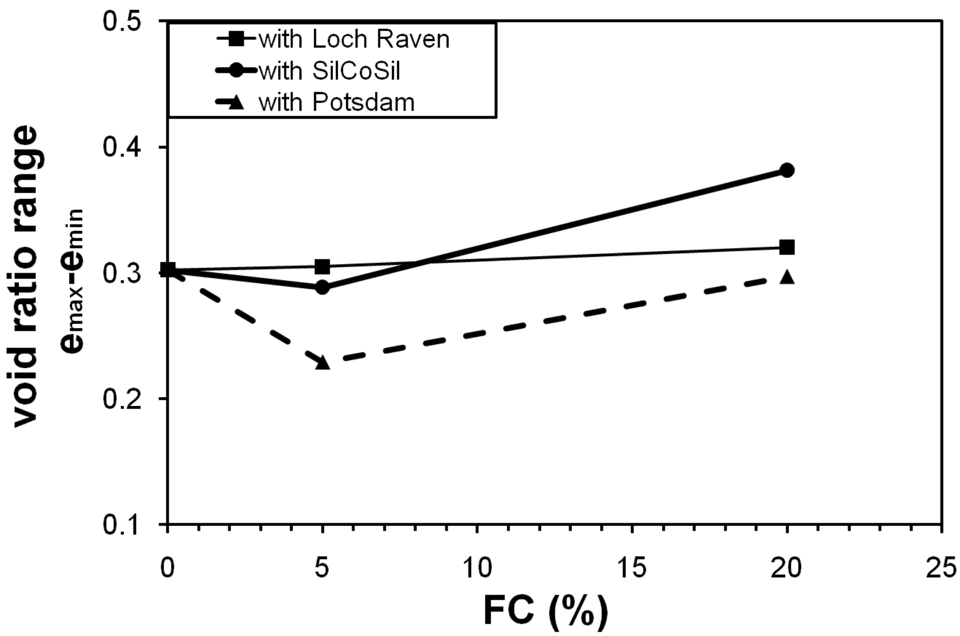


Fig. 4.10. Change of void ratio range with different fines contents and silts.



CONCLUSIONS

In this research an experimental program was performed to investigate the influence of different silts on the liquefaction potential of silty sand. Three different essentially non-plastic silts (i.e. Loch Raven, SilCoSil and Potsdam) with different grain size distributions were employed. The conducted research can be categorized in three main phases.

Densification techniques employed in most of the conventional deposition methods for silty sands involve either tamping, tapping or vibrating. Evolution of instability parameters such as the initial peak principal stress difference (q_{peak}) and effective instability angle (ϕ'_i) with densification amount (ΔD_r) and technique is investigated in the first phase. Parameters of interest are compiled from the literature for undrained monotonic triaxial test results of various silty sands with fines content ranging between 5% and 50%.

It was observed that the undrained response of a silty sand is considerably affected by the selective elimination of the “metastable” contacts because of the employed densification technique. If the densification technique involves tamping (i.e. moist tamping), test series show a concave upward trend for the relationship between normalized initial peak principal stress difference ($\Delta(q_{peak}/\sigma'_c)$) and densification amount (ΔD_r). However, if the densification technique involves tapping (i.e. dry funnel deposition), test series show a concave downward trend for the relationship between normalized initial peak principal stress difference ($\Delta(q_{peak}/\sigma'_c)$) and densification amount (ΔD_r). No specific trend was observed for slurry deposited specimens.

Tubed funnel deposition was developed as a new technique of densification requiring no tamping, tapping or vibrating. It was observed that the test specimens densified with this technique showed much smaller increase in normalized initial peak principal stress difference ($\Delta(q_{peak}/\sigma'_c)$) compared to the test series densified with other techniques such as tamping or tapping. This is believed to occur because more "metastable" contacts are preserved with the new technique.

In the second phase, silt size effect is investigated while other influencing factors like fines content (20%), confining stress (30kPa) and deposition method (dry funnel deposition) were kept the same. Mean grain diameter ratio ($D_{50\text{-}sand}/d_{50\text{-}silt}$) is selected as a reflective and simple means to investigate the silt influence on undrained behavior.

As the mean grain diameter ratio ($D_{50\text{-}sand}/d_{50\text{-}silt}$) increased, the undrained behavior evolved from complete liquefaction (with Loch Raven fines) to temporary liquefaction (with SilCoSil fines) to fully stable (with Potsdam fines) for the same base sand. Commonly used comparison bases in the literature, such as void ratio, intergranular void ratio and relative density, for assessing the influence of fines content on liquefaction resistance/dilatancy of silty sands do not work alone for the same base sand with different silts, even though fines content, stress conditions and deposition method were the same. For example, for the same relative density, fines content and stress conditions, the sand becomes more liquefiable as the $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio decreases.

Current geotechnical engineering practice considers only the fines content and/or the PI (Atterberg Limits) in assessments and correlations regarding the influence of fines on liquefaction of silty sands. This phase showed that for the same fines content and stress conditions in the field, the undrained response of a sand can be vastly different (e.g. complete liquefaction versus completely stable behavior) depending on the silt gradation.

In the third phase the influence of silt size and non-plastic fines content on the liquefaction potential of sands is investigated. Silty sands were tested at three different fines content. Silt size is found to be a very important factor for the fines content influence on liquefaction potential of silty sands.

If the mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) is large, addition of non-plastic fines initially decrease and then start to increase the liquefaction potential of the sand. For this case, clean sand might have a greater liquefaction potential than the silty sand at comparable conditions.

If the mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) is sufficiently small, addition of non-plastic fines steadily increases the liquefaction potential of a sand. For this case, silty sand would be more liquefiable than the clean sand at comparable conditions.

Similar to second phase commonly used comparison bases in the literature, such as void ratio, intergranular void ratio and relative density, are found to be not sufficient for assessing the influence of fines and their content on liquefaction resistance/dilatancy of silty sands. For example, for the same relative density, fines content and stress conditions, as the $D_{50\text{-sand}}/d_{50\text{-silt}}$ ratio decreases the sand becomes more liquefiable. For a specific fines type, silty sand might become more liquefiable with increasing fines content, even though the relative density increases significantly.

Practical Implications of the Findings and Future Research

Even though findings of this research is based on monotonic undrained triaxial tests, it is believed that seismic response of silty sands would be influenced similarly by the silt size and mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$). Several researchers have experimentally verified that the instability line obtained from monotonic undrained tests is also the trigger line for cyclic liquefaction or softening for sands (Vaid and

Chern, 1985; Konrad, 1993), silty sands (Yamamuro and Covert, 2001) and sand with silt and clay mixtures (Lo et al., 2008) for a given void ratio. Therefore, silt size can be postulated to be one of the key factors for the liquefaction of a silty sand deposit in the field due to earthquake loading. For purposes of practical geotechnical engineering silty sand is desirable, provided that the relative size of the silt grains to the sand grains is small ($D_{50\text{-sand}}/d_{50\text{-silt}}$ is large), as it inhibits liquefaction. However, silty sand is undesirable if the relative size of the silt grains is larger, resulting in small values of $D_{50\text{-sand}}/d_{50\text{-silt}}$. Knowing this ratio is especially critical when fine sands are encountered in engineering projects.

In order to establish a critical value for the mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) more tests with different sand and silt types are required. For the sand used in this study the critical value is between 3 and 5 (Table 4.2). In other words, if the mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) is below the critical value, silt is undesirable in the sand. Otherwise, silt is desirable component of the soil. It is highly recommended that both sieve analysis and hydrometer tests are conducted on natural deposits accompanying the field tests in order to establish a database and verification of the findings of this study.

In the evaluation of liquefaction resistance from standard penetration tests (SPT), it has been found that increasing fines content causes an apparent increase in the liquefaction resistance or cyclic resistance ratio (CRR) of sands. However, whether this is due to an increase in CRR or a decrease in penetration resistance is unkown (Youd et al., 2001). Regardless, a fines content correction is suggested to the SPT blow count ($(N_1)_{60}$) in order to obtain an equivalent clean sand value ($(N_1)_{60CS}$) as given in Equations 5.1 (Youd et al., 2001).

$$(N_1)_{60CS} = \alpha + \beta\,(N_1)_{60} \tag{5.1a}$$

$$\alpha = 0,\ \beta = 1.0 \text{ for } FC \leq 5\% \tag{5.1b}$$

$$\alpha = \exp[1.76 - (190/FC^2)]\ ,\ \ \beta = [0.99 + (FC^{1.5}/1{,}000)] \quad \text{for } 5\% < FC < 35\% \tag{5.1c}$$

$$\alpha = 0,\ \beta = 1.2 \text{ for } FC \geq 35\% \tag{5.1d}$$

Based on the findings in this dissertation, the current fines content correction has some shortcomings, as follows:

The first shortcoming is that it always considers that fines content would increase the liquefaction resistance, suggesting that it is desirable to have silt in a sand deposit. This study showed that even though it might be true for many cases, exactly the opposite effect might occur depending on the silt size.

The second shortcoming is that the current fines content correction considers the fines content (FC) as an independent variable in the equations (5.1). Therefore, at the same fines content the very same correction value is applied for all silts. This study showed that liquefaction resistance of a sand is influenced differently for different silts even though the fines content is same.

The third shortcoming is that the current fines content correction implies a steady increase in liquefaction resistance with fines content. Accordingly, the correction applied to a sand with 5% silt is smaller than the correction for 20% silt. However, results of this study show that a sand with 5% silt can have higher liquefaction resistance than the same sand with 20% silt at the same void ratio (Fig. 4.7) or at the same relative density (Fig. 4.9) regardless of the silt size.

The fourth shortcoming is that the current fines content correction involves no correction for $FC \leq 5\%$ (Eqn. 5.1b). Accordingly, a sand with 5% silt is treated as a clean sand. This study showed that sand with 5% silt may be significantly more resistant to liquefaction than the clean sand at the same relative density (e.g. Nevada Sand with SilCoSil silt in Fig. 4.9) or at the same intergranular void ratio (e.g. Nevada Sand with Potsdam silt in Fig. 4.8).

In order to overcome these shortcomings, the fines content correction equations should be modified by including another independent variable such as mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$). This requires a solid database formed on the basis of field tests supported by laboratory tests.

Various failures due to static liquefaction have been reported in the literature, where silty sands were used as engineering materials for various purposes such as, for example hydraulically placed subsea berms for foundation of hydrocarbon exploration platforms (Sladen et al., 1985b), supporting dikes of old dams (Olson et al., 2000), tailings dams (Fourie et al., 2001),and road fill slopes (Ng et al., 2004). Based on the findings of this study it is suggested that silty sands with lower fines content and larger mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) would be preferred among the available sources in order to provide greater liquefaction resistance.

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