

Influence of grain size ratio and silt content on the liquefaction potentials of silty sands

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Abstract. Soil liquefaction has been one of the most important concerns in geotechnical earthquake engineering in recent years, due to its damages to structures and its destructive effects. The cyclic liquefaction of silty sands, in particular, remains of great interest for both research and application. Although many factors are known that affect the liquefaction resistance of sands, the effect of fine grain content is perhaps one of the most studied and still controversial. In this study, 48 deformation-controlled cyclic simple shear tests were performed on BS and CS silt samples mixed with 5%, 15% and 30% by weight of Krk085, Krk042 and Krk025 sands in constant-volume conditions to determine the liquefaction potential of silty sands. The tests were carried out at 30% and 50% relative density and under 100 kPa effective stress. The results revealed that the liquefaction potential of silty sand increases with increasing average particle size ratio ($D_{50\text{sand}}/d_{50\text{silt}}$) of the mixture for a fixed silt content. Furthermore, for identical base sand, the liquefaction potentials of coarse grained sands increase with increasing silt content, while the respective potentials of fine grained sands generally decrease. However, this situation may vary depending on the silt grain structure and is affected by the nature of the fine grains. In addition, the variation of the void ratio interval was shown to provide a good intuition in determining the liquefaction potentials of silty sands, while the intergranular void ratio alone does not constitute a criterion for determining the liquefaction potentials of silty sands.

Keywords: cyclic simple shear; fines content; liquefaction; sand; silt

1. Introduction

Soil liquefaction is a devastating phenomenon that is largely responsible for the ground-related damage in civil engineering structures during earthquakes throughout the world. In general, fine sands and silty sands with low plasticity provide the formation of undrained conditions due to their low permeability and are more sensitive to liquefaction. Since the liquefaction events in the 1964 Niigata ($M = 7.5$) and 1964 Great Alaska ($M = 9.2$) earthquakes, numerous research studies have been conducted on the liquefaction of sands. Previously, only clean sands and sands with a small amount of fines content were assumed to undergo liquefaction, but in the 1999 Izmit ($M = 7.6$) and 1999 Chi-Chi ($M = 7.7$) earthquakes, many evidence for the possible liquefaction of cohesive soils was observed (Mohan *et al.* 2019). For this reason, recent research studies have focused on the liquefaction sensitivity of silty sands with fines content (Lade *et al.* 2009, Dash and Sitraham 2011, Gomez *et al.* 2019). While some researchers stated that the increase in fine grain content increased the liquefaction resistance (Dezfulian 1984, Kuerbis *et al.* 1988,

Amini and Qi 2000), some others reported that the liquefaction resistance decreased with the increase in fine grain content (Lade and Yamamuro 1997, Vaid 1994, Xenaki and Anthanasopoulos 2003, Papadopoulou and Tika 2008, Cubrinovski *et al.* 2010). In addition, in some studies, the liquefaction resistance was stated to decrease with an increase in the fines content up to the threshold content and increase with increasing fines content after the threshold value (Law and Ling 1992, Thevanayagam and Mohan 2000, Altun *et al.* 2005, Ghahremani and Ghalandarzadeh 2006, Chang and Hong 2008, Wang and Wang 2010, Alberto *et al.* 2015). Finally, in some studies, the liquefaction resistance of sand-silt mixtures was established to be more closely related to the skeleton void ratio of the soil rather than the fines content (Kuerbis *et al.* 1988, Bouferra and Shahrour 2004).

The tests of Dezfulian (1984) on field samples underscored the fact that liquefaction resistance increases significantly with increasing silt content after a small initial decrease. Polito and Martin (2001) stated that a clear correlation cannot be made regarding the effect of clay content on the liquefaction resistance of clayey sand. Yamamuro and Lade (1997) carried out monotonic undrained triaxial compression tests on clean Ottawa sand and silty Nevada sand under various confining stresses. The test results depicted that the static liquefaction potential increases with decreasing confining stress for both soils. Castelli (2019) carried out a soil liquefaction study within the framework of the seismic retrofit design of the "Ritiro

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viaduct" foundations located along the A20 highway connecting Messina to Palermo (Italy). In situ results by the seismic dilatometer Marchetti tests (SDMT), although higher, are comparable to data from the combined resonant column (RCT) tests and were able to identify stratigraphic variations.

One of the important issues in liquefaction tests is the selection of a packing index as a control parameter to compare the liquefaction behavior of clean sand to the behavior fine-grained sand. The packing indices usually adopted in the literature are the void ratio, the intergranular void ratio and/or the relative density. Polito and Martin (2001) found that the liquefaction resistance of silty sands depends on the relative density of the mix more than the other parameters. Based on a majority of the existing studies, Carraro et al. (2003) stated that an increase in the non-plastic fines content increases the liquefaction resistance of silty sand if the relative density is used as the basis for comparison, and if the void ratio is used, the liquefaction resistance decreases.

Liu et al. (2013) investigated the effect of gradation on the undrained behavior of granular materials. They performed a series of undrained triaxial tests with two different materials, namely the glass balls and Houston sand. They found that the undrained shear strength decreased with an increase in the coefficient of uniformity from 1.1 to 20, which consequently increased the risk of liquefaction. A series of undrained monotonic triaxial tests were performed by Taiba et al. (2016) on sand samples with low plasticity fine percentage ranging from 0 to 40%. The results showed that the undrained shear strength decreases when there is an increase in the coefficient of uniformity, a decrease in D_{10} , D_{30} , D_{50} and D_{60} , and an increase in the fines content.

In addition to these findings, Monkul and Yamamuro (2011) showed that the effect of fines content can be significantly affected by the nature of the fines and the resulting monotonic undrained sand behavior can be considerably different for the same stress conditions depending on the percentage of silt (e.g., complete liquefaction or completely stable). They stated that the liquefaction potential of the silty sand steadily increases with increasing fines content for the selected interval (0-20%) if the ratio of the average grain size of the sand ($D_{50, \text{sand}}$) to the average grain size of the silt particles ($d_{50, \text{silt}}$) is sufficiently small. Yet, the liquefaction potential of silty sand decreases when the $D_{50, \text{sand}} / d_{50, \text{silt}}$ ratio is increased. They also suggested that in addition to fines content and plasticity, the relative size of silt grains should be considered in geotechnical engineering practice to characterize the liquefaction potential of silty sands.

A study was conducted by Baziar and Sharafi (2011) on the effect of fines content on the cyclic resistance ratio (CRR) and the dissipation of energy and development of excess pore pressure until liquefaction by using an energy-based approach. They stated that the cumulative liquefaction energy is independent of the cyclic stress ratio (CSR) under constant relative density and confining pressure, but the ambient pressure and fines content have a deep impact on the cumulative liquefaction energy.

In another study conducted by Monkul et al. (2016), on the other hand, undrained monotonic triaxial tests were carried out on samples obtained by mixing the sand in three different gradations with non-plastic silt in three different gradations. The results depicted that the static liquefaction potentials of the three sand samples increased with a decrease in the coefficient of uniformity of the silt grain matrix (CU_{silt}) in sands. Moreover, they stated that the static liquefaction potential increased with a decrease in the mean grain diameter ratio ($D_{50, \text{sand}} / d_{50, \text{silt}}$), caused by the variation in the silt grade of the base sand. They also stated that there is a coupled relationship between the fines content and silt properties (grading, average size, shape effects) on the static liquefaction behavior of sands.

Eseller-Bayat et al. (2017) performed stress-controlled cyclic simple shear tests on sand samples containing 10% silt or clay to uncover the combined effects of plasticity index, fines content (FC), relative density (D_r) and CSR. The results indicated that clean sand samples showed a low liquefaction potential compared to sands with 10% FC, while the effect of plasticity of the fines on the liquefaction potential became evident as FC increased and CSR decreased in relatively dense samples.

As can be seen from the aforementioned studies, conflicting results were reported regarding the effect of fines content on the liquefaction sensitivity of sands. These studies show that the main parameters to be considered for liquefaction resistance of fine sands are the plasticity index, fines content, packing index parameter and cyclic stress ratio (CSR). However, most of the previous studies focused on the nature and properties of the sand grain matrix. This was perhaps a reasonable approximation assuming that it constitutes the dominant grain matrix sand for both clean and silty sands. However, there are few studies on how and to what extent the gradation and shape properties of the silt grain matrix affect the liquefaction behavior of these soils in silty sand, and the relationship is not yet fully known. In addition, since a great majority of the previous studies investigated the effects of the aforementioned factors separately, it is not clear whether the effects of these factors are independent or coupled.

Such various observations are probably also due to uncertainties regarding the determination of the maximum and minimum void ratio. Cubrinovski and Ishihara (2000) proposed the void ratio range ($e_{\text{max}} - e_{\text{min}}$) as an indicative measure for the liquefaction potential of sandy soils, as it includes the combined effect of gradation, grain shape and fine grain content. Accordingly, a high void ratio range ($e_{\text{max}} - e_{\text{min}}$) is an indication of high liquefaction potential. Yang et al. (2015) presented a study of several state variables, including void ratio (e), skeleton void ratio (e_{sk}), and equivalent intergranular void ratio (e_{eq}). In their study, they suggested that compared to skeletal void ratio and equivalent intergranular void ratio, global void ratio remains a simple and useful state variable suitable for critical state soil mechanics framework and geotechnical applications.

In addition, Wei and Yang (2019) conducted a comprehensive experimental study within the framework of critical state soil mechanics in order to address the complex

effects of fine grains. In the study, two batches of sand-silt mixtures formed by mixing the same type of non-plastic silt with two different base sands were tested under a range of packing densities, confining pressures and silt content. They also noted a unified correlation between the state parameter (ψ) and cyclic resistance, which collectively takes into account the effect of packing density and confining pressure. The proposed correlation is independent of packing density, confining pressure, fines content and base sand and provides an estimate of the cyclic resistance of silty sands under different conditions. Moreover, Wei and Yang (2021) stated that the liquefaction resistance of fine sand-fine mixtures, which is defined as the cyclic resistance ratio (CRR) leading to failure in a certain number of loading cycles, is related to the state parameter defined in the critical state theory, independent of particle size inequality and fine grain content.

The aim of this study is to evaluate the simultaneous effects of the grain size and silt content of the silt on three base sands of the same geological origin, considering the above-mentioned reasons. For this purpose, deformation-controlled dynamic simple shear tests were carried out on 48 silty sand samples obtained by mixing the sand samples in three different gradations with two different non-plastic silts having different contents (i.e., $FC \leq 30\%$). Interesting findings, revealing that the above-mentioned parameters have a unified effect on the seismic liquefaction potentials of fine sands, were obtained and the results are discussed.

2. Experimental setup and samples

The tests within the scope of the present study were carried out using the cyclic simple shear test device produced by Wille Geotechnics (Fig. 2). Cyclic simple shear is probably the most popular laboratory test for investigating the dynamic behavior of soils after cyclic triaxial testing. Cyclic simple shear testing has some advantages over cyclic triaxial testing. The cyclic loading mechanism in the simple shear test better resembles earthquake loading conditions than the cyclic triaxial test. In simple shear, the consolidation is anisotropic and can be assumed to represent the steady state in the field. Also, due to the smaller size of simple shear specimens compared to typical triaxial test specimens, specimen preparation is relatively easy compared to triaxial test specimens. However, its important disadvantage is that it does not take the confining pressure into account. Baxter *et al.* (2010) compared the response of samples confined by the wire-reinforced membrane considering the ambient pressure against Teflon-coated rings with the same direct simple shear. Teflon-coated rings impart greater lateral stiffness during the consolidation step, but the stress-strain response during shear was similar for the two confinement systems.

The device used in this study, enables researchers to conduct tests under drained constant-volume conditions. In drained constant-volume shear tests, samples are subjected to shear in a way that their volumes are kept fixed under drained conditions throughout the entire test phase. Since the volumetric deformation is equal to the axial deformation

in cyclic simple shear tests, the constant volume is maintained by adjusting the magnitude of the vertical stress on the sample during the test so that the height of the sample does not change. Many investigators showed that the increase and decrease in the effective stress ($\Delta\sigma_v$) in the constant-volume shear test can simulate the increase and decrease in excess pore pressure (Δu) in an equivalent undrained shear test (Suits *et al.* 2009, Finn *et al.* 1994, Raadim *et al.* 1987). In the drained constant-volume shear test, pore water pressure is not measured as drainage is allowed, and the excess pore pressure generated in an equivalent undrained test can be determined from the change in vertical effective stress. In other words, as stated by Bjerrum and Landva (1966) and proved by Dyvik *et al.* (1987), the vertical stress change required for constant volume control is equal to the excess pore pressure in an undrained test ($\Delta\sigma_v = -\Delta u$).

If we can determine the pore water pressure from the vertical effective stress change in the drained constant-volume shear test, we can ask the question whether we need pore water during the experiment. If not, we can consider whether we can test a soil dry, whose liquefaction behavior is examined. Finn and Vaid (1977) stated in their study with Ottawa sand that this situation is possible. Later, in a systematic study, Monkul *et al.* (2015) conducted dynamic simple shear tests with constant volume control on saturated and dry samples from clean silty and clayey sands. The results showed that the liquefaction resistance can be determined from completely dry samples in clean and silty sands, but this outcome was stated to be invalid for clayey sands. Silts are difficult to be saturated with water due to their low permeability, and problems may also be encountered in uniform distribution of pore pressure (Zhou *et al.* 1995). Therefore, the fixed-volume method is particularly advantageous for silty soils because the saturation step of the sample is eliminated and tests are carried out in dry conditions. In the light of the information given and the described test mechanism, all liquefaction tests in this study were carried out with sand and silty sand samples in dry conditions.

2.1 Energy-based approach

In the liquefaction studies, the energy-based approach to evaluate the liquefaction potential of the soil was first proposed by Nemat-Nasser and Shokooh (1979) as an alternative to the stress-based approach. The energy-based approach has important advantages compared to other approaches. These are; 1) Energy is a scalar quantity that takes into account the entire spectrum of ground motion (Baziar *et al.* 2011, Baziar and Jafarian 2007). 2) The cumulative liquefaction energy can be said to include both soil properties and the stress and strain properties (Liang 1995, Law *et al.* 1990).

The cumulative liquefaction energy of a soil sample is equivalent to the area remaining inside the shear stress-shear strain hysteresis loop (Zhang *et al.* 2015, Green 2001). The energy in each cycle and the sum of these energies until the beginning of liquefaction is defined as the cumulative

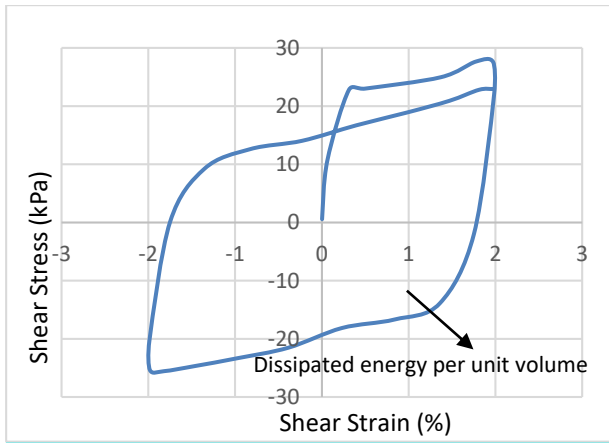


Fig. 1 Typical hysteresis loop under cyclic simple shear (Sonmezer 2019)

liquefaction energy per unit volume of the soil (Alavi and Gandomi 2012). Studies have shown that the cumulative liquefaction energy is an excellent and usable index to evaluate the liquefaction potential of the soil (Kokusho 2013, Sonmezer 2019, Sonmezer *et al.* 2020). The strain energy in each loading cycle is equivalent to the area remaining inside the hysteresis curve in Fig. 1. In the literature, Eq. (1) is frequently used when calculating the area within the hysteresis loop to determine the liquefaction energy:

$$W = \frac{1}{2} \sum_{i=1}^n (\tau_n + \tau_{n+1})(\gamma_{n+1} - \gamma_n) \quad (1)$$

W = Cumulative liquefaction energy (J/m^3), τ = Shear stress, γ = Shear strain, n = Number of cycles recorded until liquefaction

In the study by Javdanian *et al.* (2019), cyclic triaxial tests were performed on sandy soil and silty sand samples to check the accuracy of the strain energy model. Comparison of the energy required to initiate liquefaction in the tested soil samples with the values predicted by the developed model showed the high accuracy of the energy-based model. Moreover, in another study by Javdanian (2017), neuro-fuzzy group data processing method (NF-GMDH) was used to estimate the strain energy required to initiate liquefaction. The NFGMDH-based model was developed using particle swarm optimization. It has clearly been demonstrated that the proposed model, derived from laboratory results, can be successfully used for strain energy-based estimation of liquefaction potential. For all these reasons, the results of this study were evaluated using the energy-based approach.

2.2 Soil samples adopted in the present study

The three types of sand used within the scope of the study were obtained from a sand quarry in the Kızılırmak region of Kırıkkale, Türkiye. These sands have the same geological origin but different gradations and are denoted as Krk085, Krk042, Krk025. Their grain-size distribution graph is



Fig. 2 Dynamic simple shear test apparatus used in the study

given in Fig. 3. In addition, two different non-plastic silts, namely CS and BS, were used as fine soil in this study. CS silt was obtained from a sand quarry in Çorum province. BS silt was obtained by grinding from silica. The grain-size distribution graphs of these two silts are illustrated in Fig. 3. SEM images of the silts are given in Fig. 4. The reason for choosing sand in three different grain distributions and non-plastic silt in two different grain distributions is to reveal the effect of silt grain size on seismic liquefaction of silty sands and also to determine how these effects change due to the change in the fines content of sands.

Maximum (e_{max}) and minimum (e_{min}) void ratios of sand and silts, specific gravity (G_s), average grain sizes ($D_{50-sand}$, $D_{50-silt}$), uniformity coefficient and soil classes according to USCS are given in Table 1. Since the methods in the ASTM D4253 and D4254 standards are recommended for the determination of e_{max} and e_{min} ratios of sands with a maximum of 15% fines content, the method proposed by Lade *et al.* (1998) was preferred in the present study for the determination of the void ratios of silty sand samples.

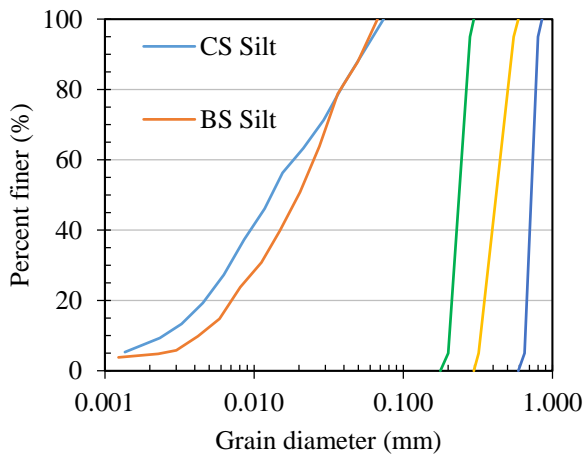


Fig. 3 Grain-size distributions of the sands and silts of the present study

Table 1 Properties of the sand used in the present study

	Krk085	Krk042	Krk025	CS Silt	BS Silt
USCS classification symbol	SP	SP	SP	ML	ML
Median grain size, D_{50} (mm)	0.85	0.42	0.25	0.012	0.02
Specivic gravity, G_s	2.69	2.69	2.69	2.7	2.69
Max. void ratio (e_{max})	0.902	0.945	1.022		
Min. void ratio (e_{min})	0.722	0.738	0.746		

Different methods of determining maximum and minimum void ratio (e.g., ASTM, Japanese standards, etc.) may yield different e_{max} and e_{min} values, and may also include their individual limitations (e.g., applicable up to a certain FC value) (Cubrinovski *et al.* 2002, Lade *et al.* 1998). However, for this study, the consistency and reproducibility of the process is important rather than the absolute values of e_{max} and e_{min} . Therefore, Lade *et al.* The [1998] method has been used considering it has been successfully adopted in various previous research studies involving clean and silty sands (Yamamuro and Lade 1997, Monkul and Yamamuro 2011, Monkul *et al.* 2015, 2016).

In this study, CS and BS silts were added to three different sands (Krk085, Krk042, Krk025) in 5%, 15%, 30% by weight and tests were carried out at 30% and 50% relative densities.

Wet tamping method was used in the preparation of all samples within the scope of the study. Ladd (1978) indicated that this method is good, acceptable and feasible. In this method, the silty sand needed for the desired relative density is mixed with approximately 5% water and is laid inside the mold in seven layers and lightly tamped. Typical specimens are 100 mm in diameter and 46 mm in height. Lateral constraint is achieved by aligning teflon-coated rings around a latex membrane as recommended by ASTM D6528-07. The samples were consolidated under 100 kPa effective stress and tests were performed at 0.1 hz frequency and 1% strain.

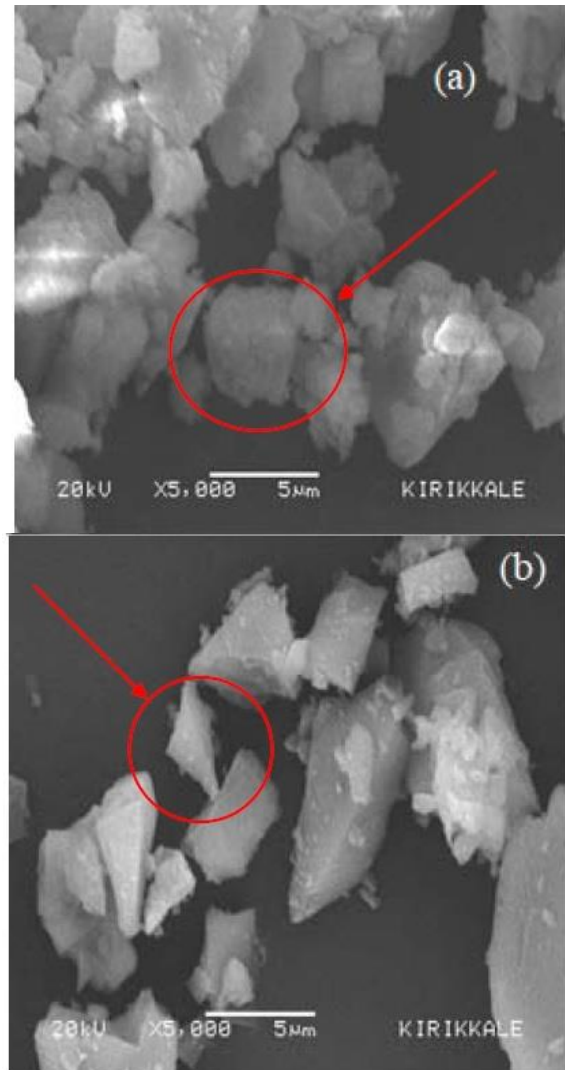


Fig. 4 SEM images of the silts adopted in the present study: (a) CS Silt (b) BS Silt

3. Test results

Within the scope of the study, a total of 48 deformation-controlled cyclic simple shear tests were performed to determine the effect of fines content and grain diameter ratio ($D_{50 \text{ sand}} / D_{50 \text{ silt}}$) on the dynamic response of silty sands. All the results obtained are given in Table 2. As an example, the results of a typical test on Krk042 sand at 30% relative density and 15% CS content are given in Fig. 5. In tests performed under constant-volume conditions, it is accepted that liquefaction occurs at the point where the effective stress reaches zero. In the mentioned test, the effective stress value decreases very much in the 15th cycle (N), in the 18th cycle, the effective stress reaches zero and liquefaction occurs.

The liquefaction behavior of sandy soils is significantly affected by the fines content. The liquefaction behavior of such soils is very complex and the exact mechanism is unknown (Kokusho 2007). Erten and Maher (1995) and Kokusho (2007) stated that the decrease in the liquefaction resistance with the increase in the fines content of the sand

Table 2 The results of the tests conducted within the scope of the present study

Sample Name	Dr	Cumulative Liquefaction Energy (J/m^3)			
		0%	5%	15%	30%
BS silt, Krk085 sand		4624	4107	2668	2139
BS silt, Krk042 sand		3426	2856	3078	3531
BS silt, Krk025 sand	30%	1880	2788	5481	5497
CS silt, Krk085 sand		4624	3123	2466	1813
CS silt, Krk042 sand		3426	2749	2184	1572
CS silt, Krk025 sand		1880	4818	3119	2492
BS silt, Krk085 sand		6435	5726	4651	3528
BS silt, Krk042 sand		4040	3890	4481	6280
BS silt, Krk025 sand	50%	2454	5690	6537	7862
CS silt, Krk085 sand		6435	5807	3509	3145
CS silt, Krk042 sand		4040	3576	3031	2493
CS silt, Krk025 sand		2454	5560	4917	2755

is due to the lubricating effect of the non-plastic fine particles in the mixture and thus their contribution to the rearrangement of the sand grains. In the stress-controlled dynamic triaxial tests performed by Carraro *et al.* (2003) on Ottawa sand containing 5%, 10% and 15% non-plastic silt, the liquefaction resistance of the sand-silt mixtures increased at constant relative density with increasing fines content from zero to 5%, while decreasing with increasing fines content from 5% to 15%. All these explanations show the effect of fines on sandy soil. In this context, the effect of fines on the liquefaction potential of sandy soil was investigated in the tests performed in this study and the results are given in the following section.

3.1 Effect of fines content

In some studies, it has been reported that an increase in fines content up to the threshold fines content (FC_{th}) leads to a decrease in liquefaction resistance (Boominathan 2010, Papadapoulou 2008). However, in the study by Amini and Qui 2000, it was reported that an increase in fines content causes an increase in liquefaction resistance. On the other hand, results of some other studies indicate an initial increase in cyclic liquefaction resistance up to low fines content (e.g., 5%) followed by a decrease in liquefaction resistance with further increase in FC (Carraro 2003). Interestingly, after decades of research, there is still no direct or perhaps simple answer to whether fine grain content increases or decreases the cyclic liquefaction resistance of sands. The relationship is complex and needs to be explored.

The effect of CS silt mixed with Krk085, Krk042, Krk025 sand at the rates of 5%, 15% and 30% on liquefaction resistance, liquefaction energy and the number of cycles are given in Figs. 6(a)-6(c). In Fig. 6(a) the liquefaction energy of the base sand (Krk085) decreases with increasing fines content. As will be explained in the

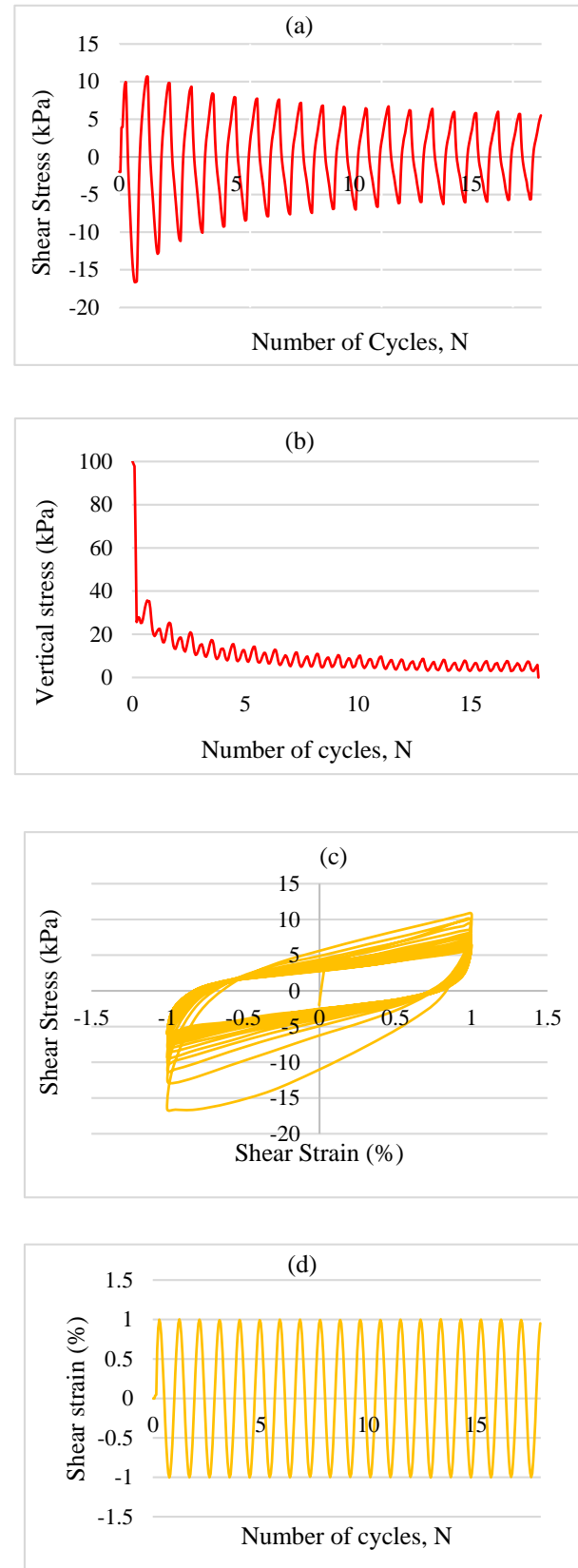


Fig. 5 The sample of Krk042 sand at 100 kPa effective stress, 30% relative density, 15% CS content, (a) shear stress and N variation, (b) vertical effective stress and N variation, (c) shear stress and shear strain and (d) shear strain and N variation

next sections, the liquefaction resistance of silty sand decreases as the average grain size ratio ($D_{50\text{sand}}/d_{50\text{silt}}$) increases. Similarly, as the grain diameter of the base sand (Krk042) decreases the liquefaction energy also decreases with increasing fines content (Fig. 6(b)). However, the amount of decrease is not as pronounced as in Krk085 sand. In Fig. 6(c), as the grain diameter of the base sand (Krk025) gets smaller, the liquefaction energy first increases and then decreases slowly with increasing fine grain content. Similar views have been reported by other researchers (Cho *et al.* (2006), Yang and Wei (2012)). An investigation conducted by Yang and Wei (2012) reported the importance of the effect of particle shape on the instability of loose sands through undrained triaxial compression tests on two basic sands (Toyoura and Fujian) mixed with two different fines [crushed silica fines (angular) and glass beads (round)] types. In their study, they also observed an increase in the critical state internal friction angle (ϕ_{cs}) of clean sands as they became more angular. But more importantly, Yang and Wei (2012) reported that at a given fines content, a sand containing round glass particles has greater susceptibility to static liquefaction than a sand containing angular crushed silica fines.

The changes in BS silt content and liquefaction energy of Krk085 sand at 30% and 50% relative densities under 100 kPa effective stress are given in Fig. 7(a), and the respective changes in CS silt content and liquefaction energy are given in Fig. 7(b). In both types of silt mixed with Krk085 sand, the liquefaction resistance decreases continuously with the increasing silt content for the studied range of fines ($\leq 30\%$). This conclusion is valid for both 30% and 50% relative densities. In other words, the liquefaction potential of the samples increases with increasing silt content for both relative densities. However, when the influence of the Krk085 sand with identical relative density on the liquefaction resistance is examined for increasing content of fines in BS and CS silts (Fig. 7(c)), the liquefaction resistance of the sand can be seen to decrease slightly more in the presence of CS silt as compared to the BS silt. While there is no significant decrease in the liquefaction resistance with increasing fines content for both silt types at 30% relative density, the respective decrease in CS silt at 50% relative density is more pronounced at 15% silt content compared to 5% and 30% silt contents.

While the liquefaction potential of silty sands can be said to increase with increasing fines content for in Krk085 sand, the situation is slightly different for Krk042 sand. In Fig. 8(a), the liquefaction resistance of Krk042 sand mixed with BS silt under 100 kPa effective stress and 30% relative density decreases slightly at first and then slightly increases with increasing content of fines. However, at 50% relative density, the liquefaction resistance increases continuously with increasing fines content. In Fig. 8(b), the liquefaction resistance of Krk042 sand mixed with CS silt decreases continuously at both 30% and 50% relative densities with increasing fine content. In Fig. 8(c), when the effects of BS and CS silts on the liquefaction resistance of Krk042 sand are compared, the mean grain size ratio ($D_{50\text{-sand}} / D_{50\text{-silt}}$) of

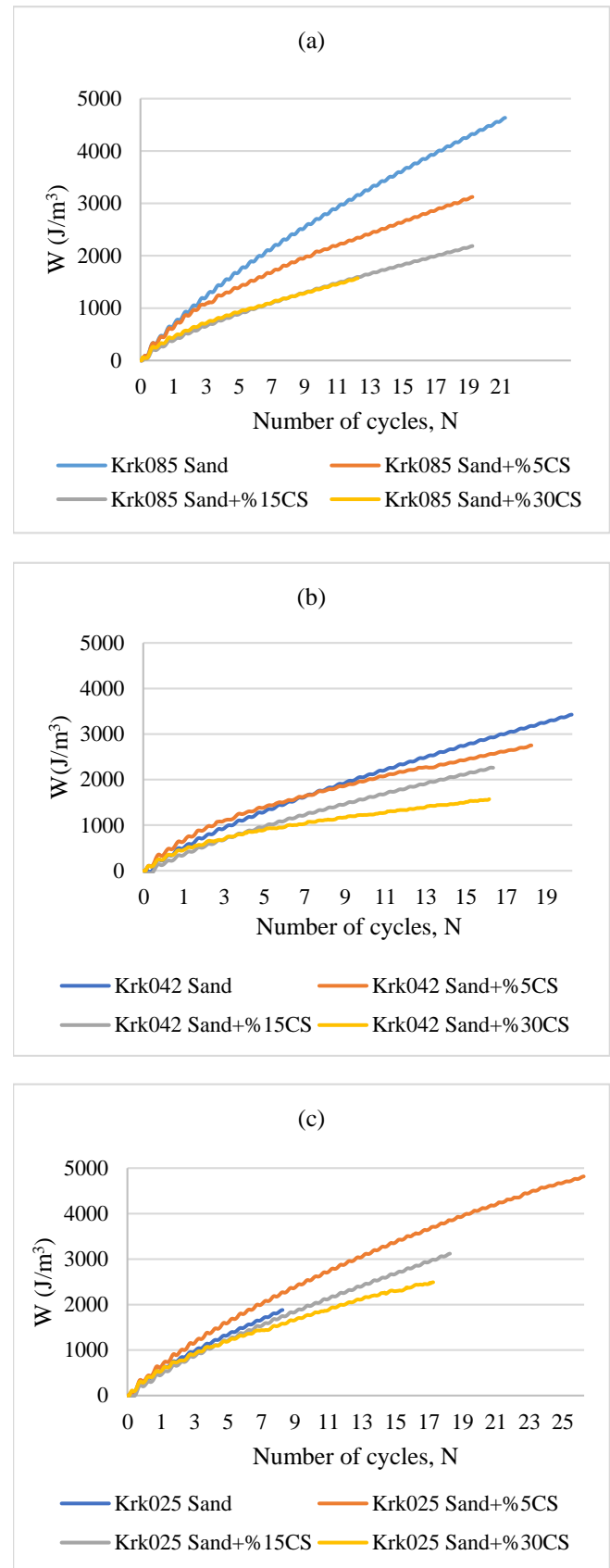


Fig. 6 The relationship between the number of cycles for liquefaction energy of silty sand samples prepared at 100 kPa effective stress and 30% relative density. (a) Krk085 sand, (b) Krk042 and (c) Krk025

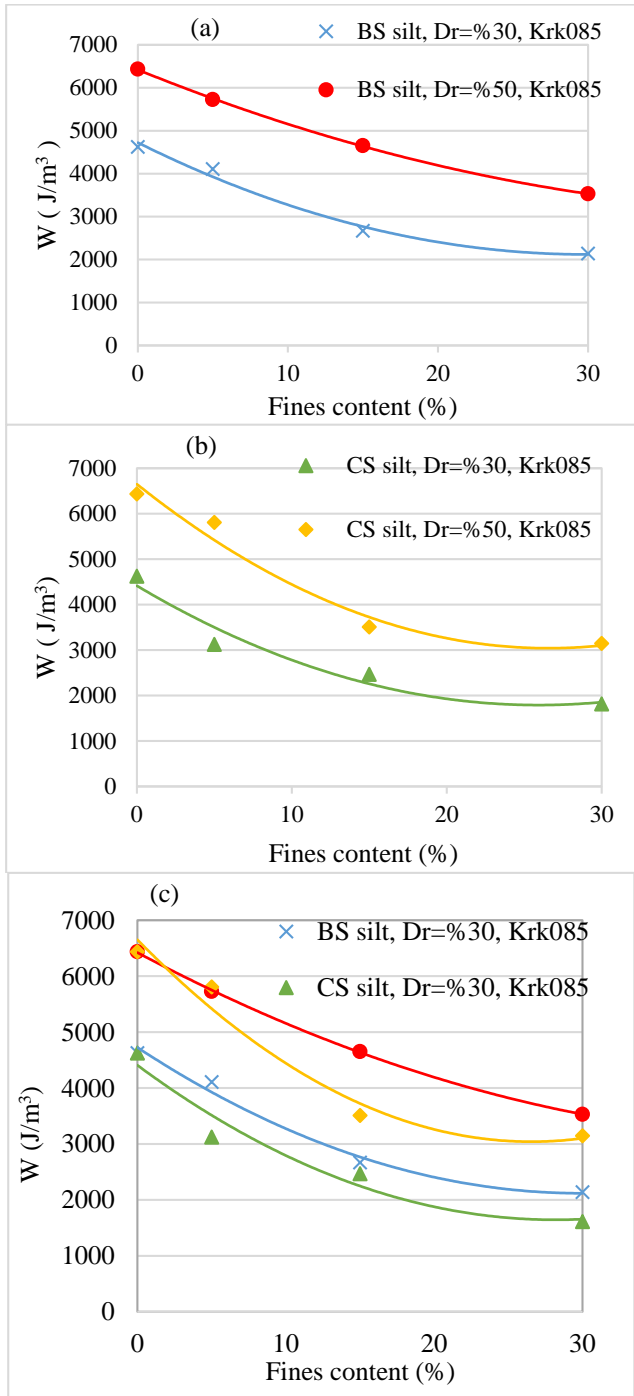


Fig. 7 The fines content vs liquefaction energy relationship of the Krk085 sand at 100 kPa effective stress (a) BS silt (b) CS silt (c) BS and CS silt

the Krk042 sand-BS silt mixture can be seen to have a value of 21 while the respective value of the Krk042 sand-CS silt mixture is 35%. This shows that as the mean grain size ratio decreases, the liquefaction resistance gradually increases. In Fig. 9, the variation of the liquefaction energies of the samples prepared by adding BS and CS silts to Krk025 sand under 100 kPa effective stress and 30% and 50% relative densities with increasing content of fines are given. In Fig. 9(a), the liquefaction resistance of Krk025 sand mixed with BS silt can be seen to continuously increase with increasing fines

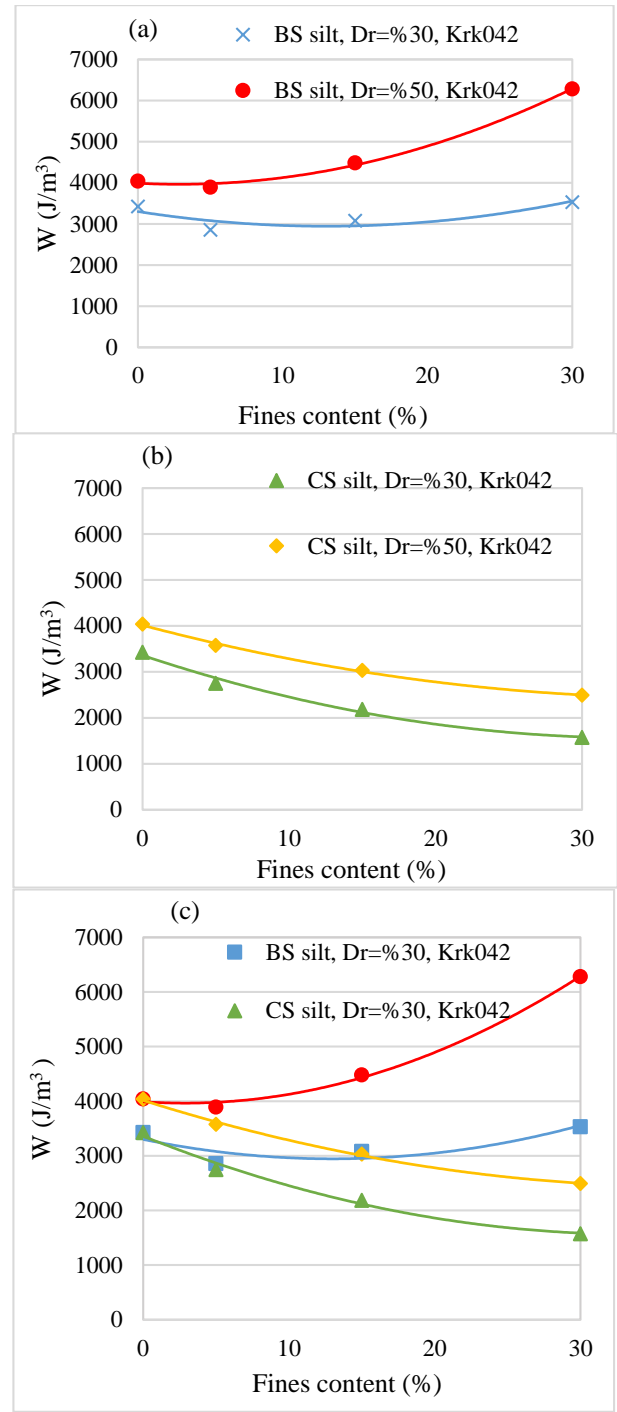


Fig. 8 The fines content vs liquefaction energy relationship of the Krk042 sand at 100 kPa effective stress (a) BS silt (b) CS silt (c) BS and CS silt

up to a fine content of 15%. However, in the range of 15-30% fines content, while the energy remains constant at 30% relative density, it slightly increases at 50% relative density. In Fig. 9(b), the liquefaction resistance of Krk025 sand mixed with CS silt was shown to increase with increasing fines up to a fine content of 5% and then decrease up to 30% fines content. In Fig. 9(c), the change in liquefaction resistance is given comparatively for the addition of BS and CS silts to Krk025 sand. With the decrease in the mean grain size ratio

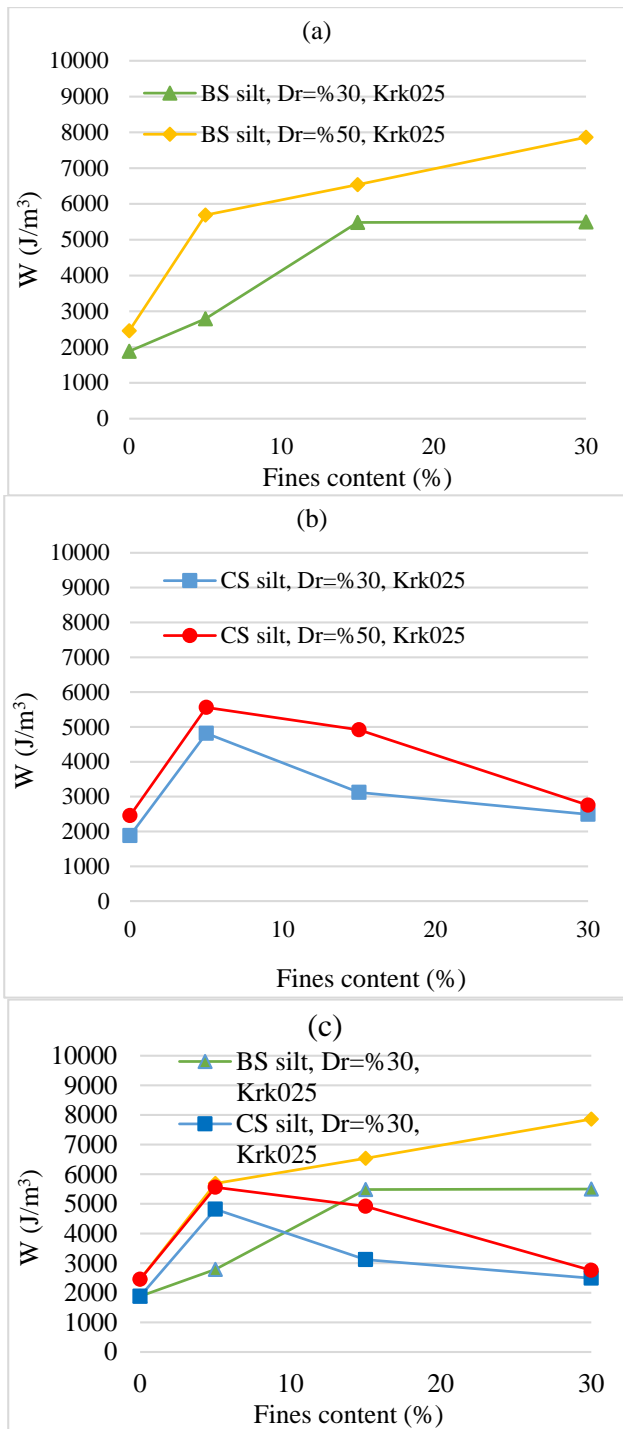


Fig. 9 The fines content vs liquefaction energy relationship of the Krk025 sand at 100 kPa effective stress (a) BS silt (b) CS silt (c) BS and CS silt

($D_{50-sand} / D_{50-silt}$) of the Krk025 sand-BS silt mixture, the liquefaction resistance increases up to 15% fines content. Yet, at 15-30% fines content, this resistance remains constant at 30% relative density and increases slightly at 50% relative density. Krk025 sand-CS silt mixture, on the other hand, liquefaction resistance increases up to 5% fines content with decreasing mean grain size ratio at both relative densities, while liquefaction resistance starts to decrease in fine content

between 5-30%.

Silt grains have two main positional tendencies during the deposition process: 1) They can settle in the spaces between adjacent sand grains 2) They can settle between the contact points of the sand grains and separate them. Both of these trends are often present simultaneously during the process of preparing silty sand samples. The ratio and balance between these two main trends are thought to be highly influential on the liquefaction behavior of silty sands. At low fine contents, when there are silt grains between the sand grains, relatively weak grain contacts called "metastable" contacts occur, while the sand-sand grain contacts are called "stable" contacts (Yamamuro and Lade 1997, Wood *et al.* 2008a). In undrained shear of loose silty sands, seismic liquefaction behavior is significantly affected by the destruction of existing metastable contacts where silt grains move into the spaces between the sand grains. Meanwhile, the sand skeleton is reconstructed with more stable contacts (Monkul 2012, Wood *et al.* 2008b). Such a mechanism contributes to the increased production capacity of excess pore pressure and hence the liquefaction potential of the samples.

As can be seen from the graphics and explanations above, there are significant changes in the liquefaction behavior of silty sands with the variation in fines content and mean grain diameter ratio. This situation is observed in both BS silt and CS silt. In coarse-grained sand (Krk085), liquefaction resistance generally decreases with increasing fines content for the same silt. It is thought that this is due to the fact that silt grains form weaker "metastable" contacts between the sand grains at both low (5%) and high (30%) fine contents during the shearing process and consequently the sand grain contacts decrease.

As the grain diameter of the base sand decreases (Krk042 and Krk025), silt grains in low fine contents (5%) fill the smaller spaces between the sand grains and increase the liquefaction resistance by forming "stable" contacts. In high fines contents (30%), the contacts between the sand grains decrease due to the increase in the silt grain content. However, this situation differs between CS and BS silts. Although being beyond the scope of this study, this difference is thought to stem from the shape of the silt grains. That is, when the SEM images in Figure 3 are examined, the CS silt can be seen to consist of more rounded grains, while BS silt consists of grains with more angular and pointy ends. Therefore, it can be said that BS silt, which is more angular, increases the liquefaction resistance slightly more than CS silt.

In the study conducted by Baziar and Sharafi (2011) in the literature using the energy-to-energy method, as seen in Fig.10, in cases where the fines content is less than 30%, the liquefaction energy decreases with increasing fines content. Even though the liquefaction energy values are high, a similar situation is seen in the tests performed with CS silt in this study in terms of showing the general tendency. The difference in liquefaction energy values is thought to be due to reasons such as sample preparation method and different test device. However, in tests with BS silt, the liquefaction energy decreases by 5% and then increases. It is thought that this situation is caused by the grain structure of silts and the difference in the average grain diameter ratio. Therefore, in the following sections,

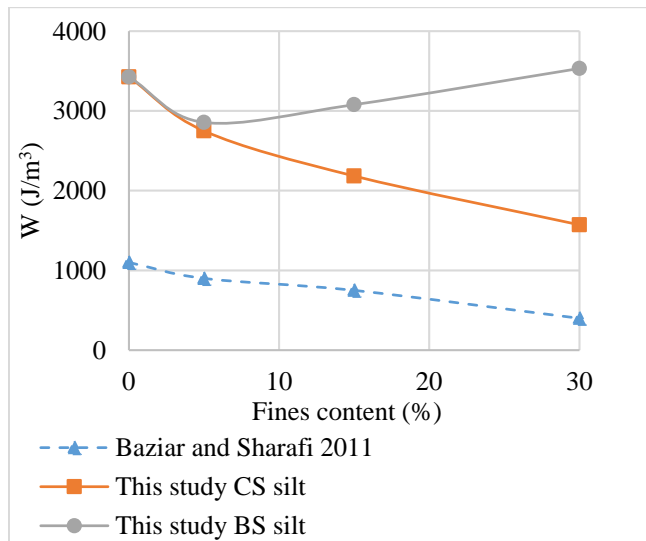


Fig. 10 The relationship between liquefaction energy and cycle numbers of the tests performed in Baziar and Sharafi (2011) and this study

the possible causes and mechanisms of these behavioral changes are emphasized and the study was expanded in this scope.

3.2 Effect of the mean grain size ratio ($D_{50-sand} / D_{50-silt}$)

Monkul and Yamamuro (2011) defined the ratio of the mean grain size of the sand matrix ($D_{50-sand}$) to the mean grain size of the silt matrix ($D_{50-silt}$) as the mean grain size ratio in loose sandy soils, and investigated how this parameter ($D_{50-sand} / D_{50-silt}$) affects the liquefaction behavior of the silty sands under static loads. As a result of the mentioned study, it was found that the static liquefaction potential of silty sands increased with the decreasing $D_{50-sand} / D_{50-silt}$ ratio, if various factors such as confining pressure, sample preparation method, grain distribution and mineralogy of the sand matrix, relative density of the samples, etc. were kept constant. However, the effect of this situation on seismic liquefaction has not been specified yet.

In this study, the effect of $D_{50-sand} / D_{50-silt}$ ratio on the seismic liquefaction potential of silty sands was investigated and the results were explained. Considering that the factors including the effective stress (100 kPa), sample preparation method (wet tamping) and silt gradation remain constant, increasing the fines content reduces the liquefaction resistance of the sand consistently at a sufficiently large mean grain size ratio of the Krk085 sand-CS silt mixture ($D_{50-sand} / D_{50-silt} = 70.8$), as shown in Figs. 11(a) and 11(b). In Krk025 sand-CS silt mixture ($D_{50-sand} / D_{50-silt} = 20.8$), increasing the fines content up to 5% increases the liquefaction resistance of the sand with a sufficiently small mean grain size and decreases it between contents of 5-30%. In Figs. 11(c) and 11(d), the liquefaction resistance can be seen to decrease with increasing fines content for sufficiently large mean grain size ratios as in Krk085 sand-BS silt mixture ($D_{50-sand} / D_{50-silt} = 42.5$). Yet, for smaller mean grain size ratios as as in Krk025 sand-BS

silt mixture ($D_{50-sand} / D_{50-silt} = 12.5$) the tendency immediately reverses and liquefaction resistance increases with increasing fines content as the mean grain size ratio decreases.

Monkul and Yamamuro (2011) conducted an experimental study to investigate the static liquefaction behavior of a single base sand (Nevada Sand-B) mixed with three different non-plastic silts (Loch Raven, Sil-CoSil 125 and Potsdam silt). In the aforementioned study, it was reported that for the same D_r , fines content and initial stress conditions, the lower the $D_{50-sand} / D_{50-silt}$ ratio, the more liquefiable the sand. However, if the grain size of the base sand increases or decreases, the effect of this change on the liquefaction potential of silty sand has not been reported.

When the gradation distribution of three sands and two silts are examined in Fig. 3, the particle size (D_{50}) of CS silt can be seen to be smaller than the size of BS silt. In this sense, the mean grain size ratios (D_{50} / D_{50}) of CS silt samples prepared by mixing with three base sands (Krk085, Krk042, Krk025) are greater than the respective ratios of the BS silt samples. For the same base sand, the liquefaction resistance of the sand decreases relatively more slowly in BS as compared to CS silt, since the mean grain size ratio of BS silt is smaller than the CS silt.

These observations yield to the following results. As the mean grain size ratio increases for the same base sand, the liquefaction resistance of the sand decreases. As the grain size of the base sand decreases, the effect of CS silt on the increase of the resistance of samples against liquefaction is limited, while the effect of BS silt becomes much more pronounced. As stated before, this difference is thought to be due to the shape of the silt grains.

It is thought that mean grain size ratio ($D_{50-sand} / D_{50-silt}$) is one of the important factors affecting the effect of fine content on the liquefaction potential of sands. However, it is seen that the liquefaction potential of silty sand is not affected only by the fines content ratio and the mean grain size ratio. Other factors affecting the liquefaction behavior are assumed to be present. For this reason, within the scope of the study, the effect of the void ratio range and the soil fabric effect were thought to be effective in this and the study was carried out in this direction and the results are discussed below.

3.3 Effect of void ratio range

The concept of intergranular void ratio proposed by Kuerbis *et al.* (1988) can be simply defined as the fine grains filling the spaces between the coarse grains, assuming fines content volume as void. The void ratios of the tested samples for different fine grain contents are shown in Fig. 12(a). The global void ratio decreases with the increasing fines content in all samples. In other words, fine grains fill the spaces between the base sand and reduce the gaps. Especially in low fine contents where fine grains fill the intergranular spaces the amount of reduction in void ratio increases. However, as seen in Fig. 12(b), the intergranular void ratio increases for all samples with increasing fines content. This is because, with its increasing fines content, the fine grains (silt) fill the spaces between

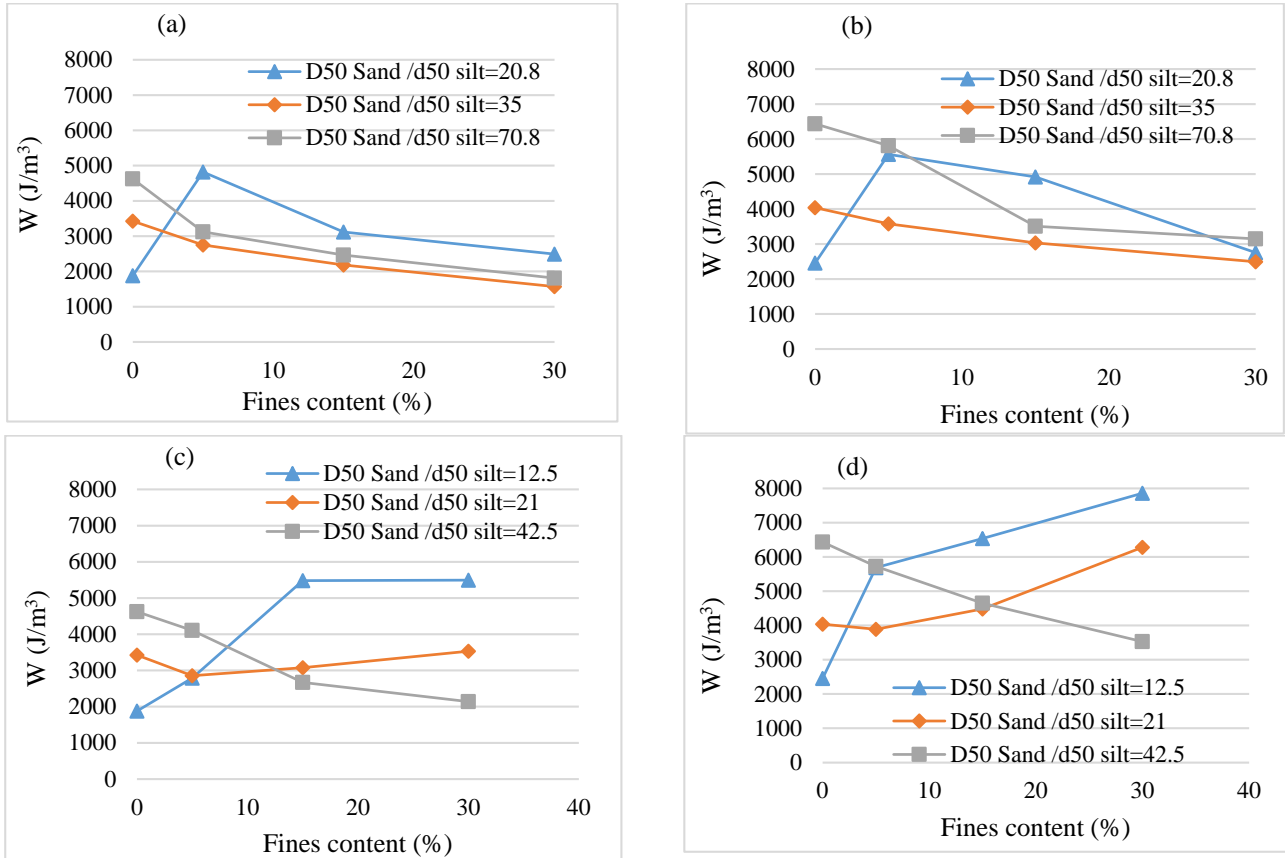


Fig. 11 The liquefaction energy - fines content relationship according to the mean grain size ratio under 100 kPa effective stress (a) Base sand and CS silt, $D_r = 30\%$, (b) Base sand and CS silt, $D_r = 50\%$, (c) Base sand and BS silt, $D_r = 30\%$ and (d) Base sand and BS silt, $D_r = 50\%$

the sand grains while at the same time loosening the sand skeleton significantly.

In general, as the $D_{50-sand} / D_{50-silt}$ ratio decreases, silty sands tend to have larger intergranular void ratios for the same amount of fine content. This is actually due to silt grains that do not fit into intergranular spaces. These silts mostly separate the sand grains from each other, which increases the intergranular void ratio. However, it is seen from Fig. 12(b) that the intergranular void ratio alone cannot be a consistent comparison basis for the effect of fine content on the liquefaction potential of sand. That is, an increase in the intergranular void ratio does not mean an increase in the liquefaction potential of the soil. This is actually due to the modified soil fabric for the same base sand and silt, although it is used at different rates (Monkul and Yamamuro 2011). On this subject, Yang *et al.* (2015) presented a study of several state variables, including void ratio (e), skeleton void ratio (e_{sk}), and equivalent intergranular void ratio (e_{eq}). In their study, they suggested that when compared to skeletal void ratio and equivalent intergranular void ratio, global void ratio remains a simple and useful state variable suitable for critical state soil mechanics framework and geotechnical applications.

For example, as seen in Fig. 11, when fines are added up to 30% to Krk085 sand-CS silt or Krk085 sand-BS silt mixtures with the highest mean grain size ratio, intergranular void ratio increases with increasing fines ratio and liquefaction resistance decreases. A similar trend is observed in Krk045 sand-CS silt,

while in Krk045 sand-BS silt, the liquefaction resistance decreases slightly with increasing fines ratio up to 5% content and slightly increases between 5-30% fines contents. However, in Krk025 sand-CS silt, liquefaction resistance increases with increasing intergranular void ratio up to 5% fines ratio, while it decreases between 5-30% fines content. In addition, in Krk025 sand-BS silt, liquefaction resistance in all fines contents (<30%) increases with increasing intergranular void ratio. Considering the study by Yang *et al.* (2015), it is clear that the intergranular void ratio will not be a stand-alone criterion for determining the liquefaction potential of silty sands, as mentioned before.

Cubrinovski and Ishihara (2000) proposed the void ratio range ($e_{max} - e_{min}$) as an indicator, since the gradation for the liquefaction potential of sandy soils includes the combined effect of grain shape and fines content. Accordingly, the high void ratio range ($e_{max} - e_{min}$) is an indication of the high liquefaction potential. The relationship between the void ratio range and fines content is shown in Fig. 13(a) for the samples prepared by mixing Krk085, Krk042, Krk025 sands with BS silt and in Fig. 13(b) with CS silt.

The void ratio range of Krk085 and Krk042 sands gradually increases until they reach 30% fines content for BS and CS silts. However, the void ratio range of Krk025 sand decreases up 5% fines content when BS and CS silts are added, and then increases. This is consistent with the observed change in liquefaction potential of samples prepared at 30% and 50%

relative densities. In fact, this change in liquefaction potential correlates highly with the change in the void ratio range of Krk085-BS and Krk085-CS silty sands and with the void ratio range of Krk042-CS silty sand and Krk025-CS silty sand, as can be seen in Figs. 13(a) and 13(b).

Experiments conducted in this study show that the void ratio range ($e_{max} - e_{min}$) for laboratory samples prepared at 30% and 50% relative densities provides a good insight into the variation of the liquefaction potential with fines content. However, the numerical values of the void ratio range do not allow a direct comparison for liquefaction potential between clean sands and silty sand samples at relatively higher fines contents (i.e., 30%).

3.4 Soil fabric in the presence of low or high contents of fines and the mean grain size ratio

The effect of the mean grain size ratio ($D_{50-sand} / D_{50-silt}$) on many parameters discussed in the literature up to now, and most importantly, on the liquefaction potential of sands with different fines content is believed to be closely related to the first soil fabric obtained before shearing process. At low fines contents, when there are silt grains between the sand grains, relatively weak grain contacts called "metastable" contacts occur, while grain contacts from sand to sand are called "stable" contacts (Yamamuro and Lade 1997, Wood *et al.* 2008a). Previous research has shown that silty sands can have significant "metastable" grain contacts before shearing (Yamamuro and Wood 2004, Wood *et al.* 2008a).

When a small amount of fine grains (i.e. 5%) such as CS or BS silt is added to Krk085 sand and the mean grain size ratio ($D_{50-sand} / D_{50-silt}$) is high enough, the silt grains can often form a "metastable" contact between the sand grains. In fact, this situation can be confirmed by increasing the intergranular void ratio when 5% CS silt or 5% BS silt is added to Krk085 sand as seen in Fig. 12(b). This situation significantly increases the liquefaction potential of silty sand compared to clean sand (Fig. 8).

When a small amount of fine grains (i.e., 5%) is added to Krk025 sand, such as 5% CS silt or BS silt, and as the mean grain diameter ratio ($D_{50-sand} / D_{50-silt}$) decreases, silt grains tend to fill the intergranular voids rather than forming "metastable" between the sand grains. This originates from the fact that as the sand grains get smaller and the mean grain size ratio decreases, the silt grains cannot settle between the contact points of the small grains of sand due to the mobility during consolidation and (or) deposition, that is, they cannot form a "metastable" contact. Instead, they settle in intergranular spaces. This different mechanism increases the resistance to liquefaction and decreases the liquefaction potential (Fig. 9). When more fines (i.e., 30%) are added to Krk085 sand, such as CS and BS silts, and when there is a relatively large mean grain size ($D_{50-sand} / D_{50-silt}$), the silts first fill the intergranular spaces and then loosen the sand skeleton. Therefore, when compared to clean sand, the intergranular void ratio increases significantly (Fig. 12(b)). Silty sands with high fines content have a higher liquefaction potential than clean sands, as the voids sand. However, the liquefaction potential increases further due to the loosened sand skeleton compared to silty sand (e.g., 5%) with less fines content (Fig. 7).

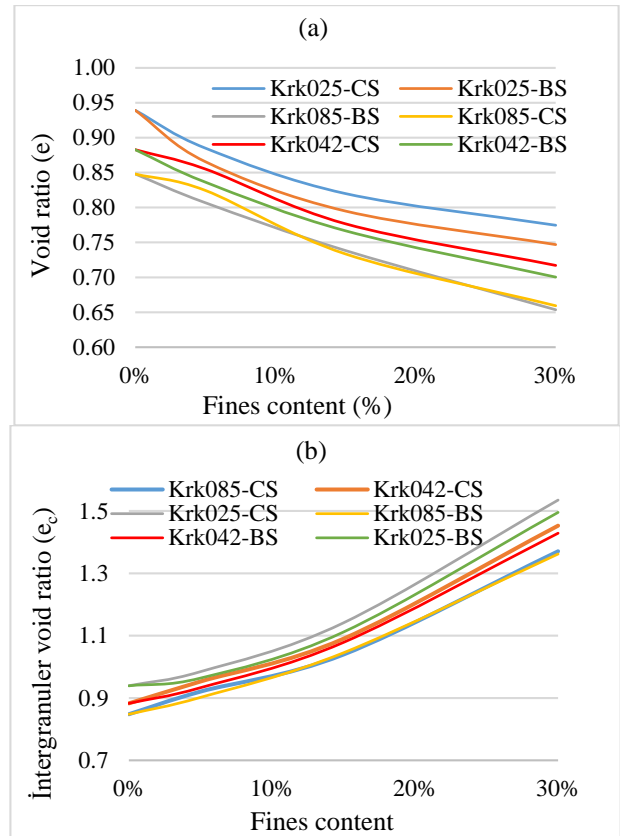


Fig. 12 (a) Void ratio - fines content relationship ($D_r = 30\%$) and (b) Intergranular void ratio - fines content relationship ($D_r = 30\%$)

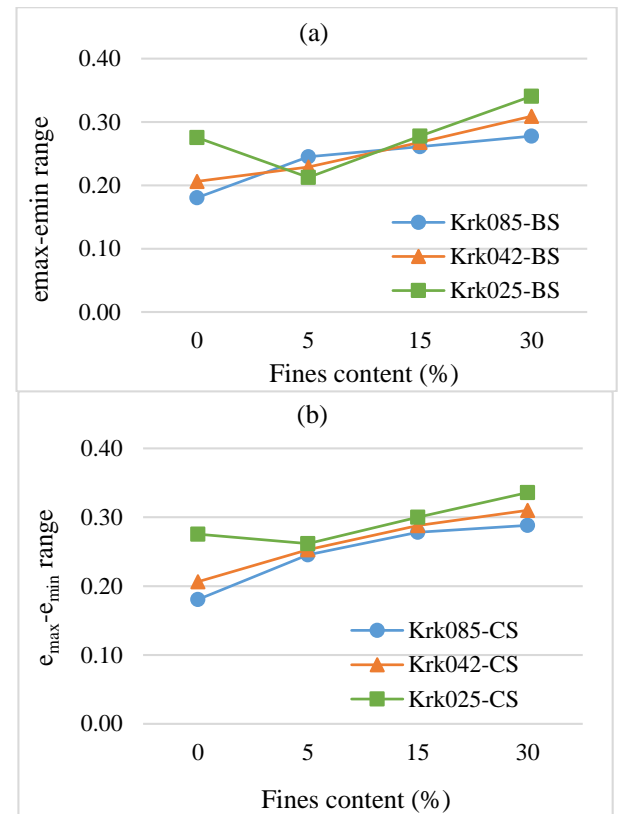


Fig. 13 $e_{max} - e_{min}$ interval - fines content relationship of the silt-sand mixtures for (a) BS silt and (b) CS silt

On the other hand, when a large amount of fine-grained CS and BS silt is added to Krk025 sand (i.e., 30%) and the mean grain size ratio ($D_{50\text{-sand}} / D_{50\text{-silt}}$) is sufficiently small, the silts increase the intergranular space ratio and loosen the sand skeleton (Fig. 12(b)). In this case, silty sand tends to create more metastable grain contact compared to silty sand containing both clean sand and a smaller amount of fine grains (e.g., 5%), which increases the potential for liquefaction.

4. Conclusions

In this study, the effect of non-plastic silt content and silt grain size on the liquefaction potential of sands with different mean grain sizes was investigated. For this purpose, deformation-controlled dynamic simple shear tests were carried out on samples prepared by mixing two different non-plastic silts with three sand of different mean grain sizes. In the tests, factors such as effective stress (100 kPa) and sample preparation method (wet tamping) were kept constant. The mean grain diameter ratio ($D_{50\text{-sand}} / D_{50\text{-silt}}$) and silt content were found to have a significant effect on the liquefaction potential of the sands. The most significant findings of the present study are summarized as follows:

- The liquefaction potential of Krk085 sand is constantly increasing with increasing fines content ($FC \leq 30\%$) for both types of silt (CS, BS). This situation is thought to be due to the fact that silt grains at both low (5%) and high (30%) fines contents create “metastable” weak grain contacts between the sand grains during the shearing process. As the grain diameter of the base sand decreases (Krk042 and Krk025), in low fine contents (5%) silt grains fill the smaller spaces between the sand grains, forming “stable” contacts and increasing the liquefaction resistance. In high fine grain contents (30%), the contact between the sand grains decreases and the liquefaction potential increases due to the decreasing sand grain diameter and increasing fines content. However, it can be said that this situation varies according to the grain structure of the silt.
- If the mean grain size ratio ($D_{50\text{-sand}} / D_{50\text{-silt}}$) for the same silt is large enough, the increase of non-plastic silt content increases the seismic liquefaction potential of silty sand. In this case, the seismic liquefaction potential of clean sand is less than the liquefaction potential of silty sand under the same conditions.
- If the mean grain size ratio ($D_{50\text{-sand}} / D_{50\text{-silt}}$) for the same silt is sufficiently small, the increase of non-plastic silt content decreases the seismic liquefaction potential of silty sand up to a content of 5%. For silt contents between 5-30%, on the other hand, the CS silt increases the liquefaction potential while the BS silt decreases. This difference is thought to be due to the silt grain structure.
- The experiments conducted in this study showed that the void ratio range ($e_{\max} - e_{\min}$) provides a good insight into the change in liquefaction potential with fines content. However, the numerical values of the void ratio range do not allow a direct comparison for liquefaction potential between clean sands and silty sand samples at relatively higher fine contents (i.e., 30%). The intergranular void ratio was also determined not to be a stand-alone criterion for determining the liquefaction potential of silty sands.

• In studies conducted to evaluate the liquefaction potential of silty sands and in the correlations derived, mostly plasticity index and/or fines content are taken into consideration. This study depicted that the effect of fines content and mean grain size ratio on the liquefaction potential of sand can be influenced by the nature of the fine grains and the liquefaction resistance of the resulting sand may differ significantly for the same stress conditions depending on the silt gradation.

References

- Alavi, A.H. and Gandomi, A.H. (2012), “Energy-based numerical models for assessment of soil liquefaction”, *Geosci. Front.*, **3**(4), 541-555. <https://doi.org/https://doi.org/10.1016/j.gsf.2011.12.008>.
- Alberto, Y., Towhata, I., Gunji, K. and Yamada, S. (2015), “Laboratory tests on cyclic undrained behavior of loose sand with cohesionless silt and its application to assessment of seismic performance of subsoil”, *Soil Dyn. Earthq. Eng.*, **79**, 365-378. <https://doi.org/10.1016/j.soildyn.2015.09.004>.
- Altun, S., Göktepe, B. and Akgüner, C. (2005), “Cyclic shear strength of silts and sands under cyclic loading”, *Geo-Frontiers Congress*, Austin, USA, January.
- Amini, F. and Qi, G. (2000), “Liquefaction testing of stratified silty sands”, *J. Geotech. Geoenviron. Eng.*, **126**(3), 208-217. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2000\)126:3\(208\)](https://doi.org/10.1061/(ASCE)1090-0241(2000)126:3(208)).
- ASTM D4253-16 (2018), *Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table*, Annual Book of ASTM Standards, ASTM International.
- ASTM D4254-16 (2018), *Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density*, Annual Book of ASTM Standards, ASTM International.
- ASTM D6528-07 (2007), *Standard Test Method for Consolidated Undrained Direct Simple Shear Testing of Cohesive soils*, Annual Book of ASTM Standards, ASTM International.
- Baziar, M.H. and Sharafi, H. (2011), “Assessment of silty sand liquefaction potential using hollow torsional tests—An energy approach”, *Soil Dyn. Earthq. Eng.*, **31**(7), 857-865. <https://doi.org/https://doi.org/10.1016/j.soildyn.2010.12.014>.
- Baziar, M.H. and Jafarian, Y. (2007), “Assessment of liquefaction triggering using strain energy concept and ANN model: Capacity Energy”, *Soil Dyn. Earthq. Eng.*, **27**, 1056-1072. <https://doi.org/10.1016/j.soildyn.2007.03.007>.
- Baziar, M.H., Jafarian, Y., Shahnazari, H., Movahed, V. and Tutunchian, M. (2011), “Prediction of strain energy-based liquefaction resistance of sand-silt mixtures: An evolutionary approach”, *Comput. Geosci.*, **37**. <https://doi.org/10.1016/j.cageo.2011.04.008>.
- Baxter, C.D.P., Bradshaw, A.S., Ochoa-Lavergne M. and Hankour R. (2010), “DSS test results using wire-reinforced membranes and stacked rings”, *Proceedings of the advances in analysis modeling and design*, ASCE. *Geotechnical Special Publication* **199**, 600-607. [https://doi.org/10.1061/41095\(365\)57](https://doi.org/10.1061/41095(365)57).
- Bjerrum, L. and Landva, A. (1966), “Direct Simple-Shear Tests on a Norwegian Quick Clay”, *Géotechnique*, **16**(1), 1-20. <https://doi.org/10.1680/geot.1966.16.1.1>.
- Boominathan, A. and Rangaswamy, K., Rajagopal. (2010), “Effect of non-plastic fines on liquefaction resistance of Gujarat sand”, *Int. J. Geotech. Eng.*, **4**(2), 241-253.
- Bouferra, R. and Shahrour, I. (2004), “Influence of fines on the resistance to liquefaction of a clayey sand”, *Ground Improvement*, **8**, 1-5. <https://doi.org/10.1680/grim.8.1.1.36366>.
- Carraro, J. Bandini, P., and Salgado, R. (2003), “Liquefaction resistance of clean and nonplastic silty sands based on cone

- penetration resistance”, *J. Geotech. Geoenviron. Eng.*, **129**.
[https://doi.org/10.1061/\(ASCE\)1090-0241\(2003\)129:11\(965\)](https://doi.org/10.1061/(ASCE)1090-0241(2003)129:11(965)).
- Castelli, F., Cavallaro, A., Grasso, S. and Lentini V., (2019), “Undrained cyclic laboratory behaviour of sandy soils”; *Geosciences*, **9**(12), 1-27.
<https://doi.org/10.3390/geosciences9120512>.
- Chang, W.J. and Hong, M.L. (2008), “Effects of clay content on liquefaction characteristics of gap-graded clayey sands”, *Soils Found.*, **48**, 101-114. <https://doi.org/10.3208/sandf.48.101>.
- Cho, G.C., Dodds, J. and Santamarina J.C.(2006), “Particle shape effects on packing density, stiffness, and strength: Natural and crushed sands”, *J. Geotech. Geoenviron. Eng. ASCE.*, **132**(5), 591-602. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2006\)132:5\(591\)](https://doi.org/10.1061/(ASCE)1090-0241(2006)132:5(591)).
- Cubrinovski, M. and Ishihara, K. (2000), “Flow potential of sandy soils with different grain compositions”, *Soils Found.*, **40**, 103-119. https://doi.org/10.3208/sandf.40.4_103.
- Cubrinovski, M., Ishihara, K. (2002), “Maximum and minimum void ratio characteristics of sands”, *Soils Found.*, **42**(6), 65-78. https://doi.org/10.3208/sandf.42.6_65.
- Cubrinovski, M., Rees, S. and Bowman, E. (2010), “Effects of non-plastic fines on liquefaction resistance of sandy soils”, *Geotech. Geol. Earthq. Eng.*, **17**, 125-144. https://doi.org/10.1007/978-90-481-9544-2_6.
- Dash, H.K. and Sitharam, T.G. (2011), “Cyclic liquefaction and pore pressure response of sand-silt mixtures”, *Geomech. Eng.*, **3**(2), 83-108. <https://doi.org/10.12989/gae.2011.3.2.083>.
- Dezfulian, H. (1984), “Effects of silt content on dynamic properties of sandy soils”, *Proceedings of the 8th World Conference on Earthquake Engineering*, San Francisco, July.
- Dyvik, R., Berre, T. and Lacasse, S. (1987), “Comparison of truly undrained and constant volume direct simple shear tests”, *Geotechnique*, **37**(1), 3-10. <https://doi.org/10.1680/geot.1987.37.1.3>.
- Erten, D. and Maher, M.H. (1995), “Cyclic undrained behavior of silty sand”, *Soil Dyn. Earthq. Eng.*, **14**, 115-123. [https://doi.org/10.1016/0267-7261\(94\)00035-F](https://doi.org/10.1016/0267-7261(94)00035-F).
- Eseller-Bayat, E., Monkul, M., Akın, Ö. and Yenigun, S. (2017), “The coupled influence of relative density, CSR, plasticity and content of fines on cyclic liquefaction resistance of sands”, *J. Earthq. Eng.*, **23**(6), 909-929. <https://doi.org/10.1080/13632469.2017.1342297>.
- Finn, W.D.L. and Vaid, Y.P. (1977), “Liquefaction potential from drained constant volume cyclic simple shear tests”, *Proceedings of the 6th World Conference on Earthquake Engineering*, NewDelhi, January.
- Finn, W., Ledbetter, R. and Wu, G. (1994), “Liquefaction in silty soils: Design and analysis”, *Geotechnical Special Publication, ASCE*, **44**, 51-76.
- Ghahremani, M. and Ghalandarzadeh, A. (2006), “Effect of plastic fines on cyclic resistance of sands”, *Proceedings of the GeoShanghai International Conference*, Shanghai, China, June.
- Gomez, F.M., Caidedo, B. and Da Fonseca, A.V. (2019), “Physical modelling of soil liquefaction in a novel micro shaking table”, *Geomech. Eng.*, **19**(9), 229-240. <https://doi.org/10.12989/gae.2019.19.3.229>.
- Green, R.A. (2001), “Energy-based evaluation and remediation of liquefiable soils”, Ph.D. Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, U.S.A.
- Javdanian, H., Heidari, A. and Kamgar, R. (2017), “Energy-based estimation of soil liquefaction potential using GMDH algorithm”, *Iran J. Sci. Technol. T. Civil Eng.*, **41**(3), 283-295. <https://doi.org/10.1007/s40996-017-0061-4>.
- Javdanian, H. (2019), “Evaluation of soil liquefaction potential using energy approach: experimental and statistical investigation”, *Bull. Eng. Geol. Environ.*, **78**(3), 1697-1708. <https://doi.org/10.1007/s10064-017-1201-6>.
- Kokusho, T. (2007), “Liquefaction strengths of poorly-graded and well-graded granular soils investigated by lab tests”, *Geotech., Geol. Earthq. Eng.*, **6**, 159-184. https://doi.org/10.1007/978-1-4020-5893-6_8.
- Kokusho, T. (2013), “Liquefaction potential evaluations: energy-based method versus stress-based method”, *Can. Geotech. J.*, **50**(10), 1088-1099. <https://doi.org/10.1139/cgj-2012-0456>.
- Kuerbis, R., Negusse, D. and Vaid, Y.P. (1988), “Effect of gradation and fines content on the undrained response of sand”, *Geotech. Spec. Publication*, **21**, 330-345.
- Ladd, R.S. (1978), “Preparing test specimens using undercompaction”, *Geotech. Test. J.*, **1**(1), 16-23. <https://doi.org/10.1520/GTJ10364J>.
- Lade, P.V. and Yamamuro, J. (1997), “Effects of nonplastic fines on static liquefaction of sands”, *Can. Geotech. J.*, **34**, 918-928. <https://doi.org/10.1139/cgj-34-6-918>.
- Lade, P.V., Liggio, C.D. and Yamamuro, J. A. (1998), “Effects of non-plastic fines on minimum and maximum void ratios of sand”, *Geotech. Test. J.*, **21**(4), 336-347. <https://doi.org/10.1520/GTJ11373J>.
- Lade, P.V., Yamamuro, J.A. and Liggio, C.D. (2009), “Effects of fines content on void ratio, compressibility, and static liquefaction of silty sand”, *Geomech. Eng.*, **1**(1), 1-15. <https://doi.org/10.12989/gae.2009.1.1.001>.
- Law, K. and Ling, Y. (1992), “Liquefaction of granular soils with non-cohesive and cohesive fines”, *Proceedings of the 10th World Conference on Earthquake Engineering*, Madrid, July.
- Law, K.T., Cao, Y.L. and He, G.N. (1990), “An energy approach for assessing seismic liquefaction potential”, *Can. Geotech. J.*, **27**(3), 320-329. <https://doi.org/10.1139/t90-043>.
- Liang, L. (1995), “Development of an energy method for evaluating the liquefaction potential of a soil deposit”, Ph.D. Dissertation, Case Western Reserve University, Cleveland, Ohio, U.S.A.
- Liu, Y., Li, G., Yin, Z.Y., Dano, C., Hicher, P.Y., Xia, X.H. and Wang, J. (2013), “Influence of grading on undrained behavior of granular materials”, *Comptes Rendus Mécanique*, **342**. <https://doi.org/10.1016/j.crme.2013.11.001>.
- Mohan, A., Kodi, R. and Sankar, N. (2019), “Effect of non-plastic fines on undrained response of fine sand”, *Int. J. Geomate*, **16**, 170-175. <https://doi.org/10.21660/2019.54.8325>.
- Monkul, M., Etminan, E. and Senol, A. (2016), “Influence of coefficient of uniformity and base sand gradation on static liquefaction of loose sands with silt”, *Soil Dyn. Earthq. Eng.*, **89**, 185-197. <https://doi.org/10.1016/j.soildyn.2016.08.001>.
- Monkul, M., Gültekin, C., Gülver Gültekin, M., Akın, Ö. and Eseller-Bayat, E. (2015), “Estimation of liquefaction potential from dry and saturated sandy soils under drained constant volume cyclic simple shear loading”, *Soil Dyn. Earthq. Eng.*, **75**. <https://doi.org/10.1016/j.soildyn.2015.03.019>.
- Monkul, M.M. (2012), “On some of the factors influencing the fines’ role on liquefaction of silty sands”, *Geo Congress*, Oakland, USA, March.
- Monkul, M. and Yamamuro, J. (2011), “Influence of silt size and content on liquefaction behavior of sands”, *Can. Geotech. J.*, **48**, 931-942. <https://doi.org/10.1139/t11-001>.
- Nemat-Nasser, S. and Shokoh, A. (1979), “A unified approach to densification and liquefaction of cohesionless sand in cyclic shearing”, *Can. Geotech. J.*, **16**(4), 659-678. <https://doi.org/10.1139/t79-076>.
- Papadopoulou, A. and Tika, T. (2008), “The effect of fines on critical state and liquefaction resistance characteristics of non-plastic silty sands”, *Soils Found.*, **48**, 713-725. <https://doi.org/10.3208/sandf.48.713>.
- Polito, C.P. and Martin II, J.R. (2001), “Effects of nonplastic fines on the liquefaction resistance of sands”, *J. Geotech.*

- Geoenviron. Eng.*, **127**(5), 408-415. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2001\)127:5\(408\)](https://doi.org/10.1061/(ASCE)1090-0241(2001)127:5(408)).
- Raadim, B., Dyvik, R., Berre, T. and Lacasse, S. (1987), "Comparison of truly undrained and constant volume direct simple shear tests", *Geotechnique*, **37**, 3-10. <https://doi.org/10.1680/geot.1987.37.1.3>.
- Sonmezer, Y.B. (2019), "Energy-based evaluation of liquefaction potential of uniform sands", *Geomech. Eng.*, **17**(2), 145-156. <https://doi.org/10.12989/gae.2019.17.2.145>.
- Sonmezer, Y.B., Akyuz, A. and Kayabali, K. (2020), "Investigation of the effect of grain size on liquefaction potential of sands", *Geomech. Eng.*, **20**(3), 243-254. <https://doi.org/10.12989/gae.2020.20.3.243>.
- Suits, L., Sheahan, T., Sadrekarimi, A. and Olson, S. (2009), "A new ring shear device to measure the large displacement shearing behavior of sands", *Geotech. Test. J.*, **32**. <https://doi.org/10.1520/GTJ101733>.
- Taiba A.C., Belkhatir M., Kadri A., Mahmoudi Y. and Schanz T. (2016), "Insight into the effect of granulometric characteristics on the static liquefaction susceptibility of silty sand soils", *Geotech. Geol. Eng.*, **34**(1), 367-382. <https://doi.org/10.1007/s10706-015-9951-z>.
- Thevanayagam, S. and Mohan, S. (2000), "Intergranular state variables and stress-strain behavior of silty sands", *Geotechnique*, **50**, 1-23. <https://doi.org/10.1680/geot.2000.50.1.1>.
- Vaid, Y.P. (1994), "Liquefaction of silty soils", In Ground failures under seismic conditions. GSP 44. Edited by S. Prakash and P. Dakoulas, ASCE, New York.
- Wang, Y. and Wang, Y. (2010), "Study of effects of fines content on liquefaction properties of sand", *Proceedings of the GeoShanghai International Conference*, Shanghai, China, June
- Wei, X. and Yang, J. (2019), "Characterizing the effects of fines on the liquefaction resistance of silty sands", *Soils Found.*, **59**(6), 1800-1812. <https://doi.org/10.1016/j.sandf.2019.08.010>.
- Wei, X. and Yang, J. (2021), "Characterising the effect of particle size disparity on liquefaction resistance of non-plastic silty sands from a critical state perspective", *Géotechnique*, Ahead of Print, <https://doi.org/10.1680/jgeot.21.00145>.
- Wood, F., Yamamuro, J. and Lade, P. (2008a), "Effect of depositional method on the microstructure of silty sand", *Can. Geotech. J.*, **45**, 1538-1555. <https://doi.org/10.1139/T08-080>.
- Wood, F., Yamamuro, J. and Lade, P. (2008b), "Effect of depositional method on the undrained response of silty sand", *Can. Geotech. J.*, **45**, 1525-1537. <https://doi.org/10.1139/T08-079>.
- Xenaki, V. and Athanasopoulos, G. (2003), "Liquefaction resistance of sand-mixtures: An experimental investigation of the effect of fines", *Soil Dyn. Earthq. Eng.*, **23**, 1-12. [https://doi.org/10.1016/S0267-7261\(02\)00210-5](https://doi.org/10.1016/S0267-7261(02)00210-5).
- Yamamuro, J. and Lade, P. (1977), "Static liquefaction of very loose sands", *Can. Geotech. J.*, **34**, 905-917. <https://doi.org/10.1139/t97-057>.
- Yamamuro, J. and Wood, F. (2004), "Effect of depositional method on the undrained behavior and microstructure of sand with silt", *Soil Dyn. Earthq. Eng.*, **24**, 751-760. <https://doi.org/10.1016/j.soildyn.2004.06.004>.
- Yang, J. and Wei, L.M. (2012), "Collapse of loose sand with the addition of fines: the role of particle shape", *Geotechnique*, **62**(12), 1111-1125. <https://doi.org/10.1680/geot.11.P.062>.
- Yang, J., Wei, L.M. and Dai, B.B. (2015), "State variables for silty sands: Global void ratio or skeleton void ratio?", *Soils Found.*, **55**(1), 99-111. <https://doi.org/10.1016/j.sandf.2014.12.008>
- Zhang, W., Goh, A., Zhang, Y., Chen, Y.M. and Xiao, Y. (2015), "Assessment of soil liquefaction based on capacity energy concept and multivariate adaptive regression splines", *Eng. Geol.*, **188**. <https://doi.org/10.1016/j.enggeo.2015.01.009>.
- Zhou, J., Lee W. and Zhou, K. (1995), "Dynamic properties sand liquefaction potential of silts", *Proceedings of the 1st International Conference on Earthquake Geotechnical Engineering*, Tokyo, November.

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