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Coupled influence of content, gradation and shape characteristics of silts on static liquefaction of loose silty sands

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ABSTRACT

Static liquefaction is a challenging problem of geotechnical engineering as its consequences are generally catastrophic when they occur on site. Previous laboratory studies focused on various factors that could influence the static liquefaction potential of silty sands. Most popular of those investigated factors are stress conditions, deposition method and fines content. The purpose of the present study is to investigate the other possible factors, of which very little is known, mainly focusing on the silt characteristics including grain size distribution, relative size, and shape effects of the silt grain matrix within the sand. Undrained monotonic triaxial compression tests were conducted on thirty sands with varying fines contents, which were prepared by mixing three base sands (Sile Sands 20/30, 50/55, 80/100) with same geologic origin but with different gradations and three different non-plastic silts (IZ, SI and TT silts) with different gradations and shape characteristics. The experimental results revealed that each of the mentioned factors had their own influence on static liquefaction behavior of sands. The static liquefaction potential of all the three sands in this study was observed to increase with decreasing coefficient of uniformities of the silt grain matrix (CU_{silt}) in sands. For a particular base sand, static liquefaction potential was observed to increase with decreasing mean grain diameter ratio ($D_{50\text{-}sand}/d_{50\text{-}silt}$) due to change of silt gradation. However, shape characteristics of the silt grains are also found to be another important factor, in certain cases observed to have a greater influence than mean grain diameter ratio criterion. As an example, it was shown that at the same FC, base sand, depositional energy and consolidation stress, angular nature of TT silt potentially caused more meta-stable contacts (weaker grain contacts that promote excess pore pressure generation during shearing) within the specimens than sub-rounded SI silt, which caused specimens with TT silt to be more liquefiable than their counterparts with SI silt. Moreover, it was found that there is a coupled relationship between the fines content and investigated silt characteristics (gradation, mean size, shape effects) on the static liquefaction behavior of sands. The unexpected trend regarding the last finding is that the mentioned influence of silt characteristics (i.e. gradation, size and shape) on static liquefaction of sands becomes more considerable with decreasing fines content at loose states.

1. Introduction

Static liquefaction is a phenomenon where a significant decrease in the load carrying capacity of the soil occurs well inside the effective stress failure envelope under undrained conditions (i.e. significant drop in the deviator stress occurs before the effective stress failure envelope is reached). Laboratory studies are still quite important to understand the role of various factors on static liquefaction behavior of sands. The effect of fines content (FC) was perhaps the most studied one among those factors. But still, it is difficult to say that there is consensus about whether the silt content increases or decreases the liquefaction resistance of a sand. According to the results of some studies, increasing non-plastic silt content had increased the static liquefaction resistance of sands [15,25,27], while others showed a decrease of static liquefaction resistance with increasing non-plastic silt content [1,17,21,44]. In fact, both conclusions are valid considering that different comparison bases (i.e. same void ratio (e), relative density (D_r), intergranular void ratio (e_s), loosest possible density after deposition, etc.) and initial conditions (i.e. depositional methods influencing initial soil fabric) were employed for different studies.

Among the other factors that could influence the static liquefaction behavior of sands are initial stress conditions, grain size distribution,

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and shape characteristics. Yamamuro and Lade [39] ran monotonic undrained triaxial compression tests on Nevada Sand with silt and clean Ottawa sand at various confining stresses and for both soils static liquefaction potential was shown to increase with decreasing confining stress. More explicitly, static liquefaction is a low-stress phenomenon; therefore both clean and silty sands are more liquefiable at considerably low confining stress (e.g. σ_{3c} = 30 kPa). Thevanayagam [33] also conducted monotonic undrained triaxial tests and stated that undrained shear strength of silty sands became sensitive to the magnitude of the initial confining stress especially when the intergranular void ratio (void ratio of the sand matrix alone) of the specimens were greater than or equal to the maximum void ratio of the base sand.

Effect of grain size distribution on undrained shear strength of sands was generally investigated mostly focusing on the clean sand response. Monkul et al. [23] gave a detailed literature review regarding the gradation influence on the drained/undrained shear strength of sands and investigated the influence of coefficient of uniformity (CU) and base sand gradation on the static liquefaction behavior of clean sands and sand-silt mixtures. However, the knowledge about how the static liquefaction response or undrained shear strength of a sand are affected by the gradation of the silt matrix within the sand is quite limited. This is perhaps due to the presumption that the role of the silt gradation in a sand dominated soil is not expected to be considerable. Monkul and Yamamuro [21] did monotonic undrained triaxial compression tests on Nevada Sand mixed with three different non-plastic silts. They showed that, when other factors (i.e., deposition method, initial confining stress, relative density, fines content, base sand gradation, shape and mineralogy) were kept the same, static liquefaction resistance of Nevada Sand had increased as the mean grain diameter ratio ($D_{50\text{-sand}}/d_{50\text{-silt}}$) of the specimens increased. In other words, the static liquefaction resistance of a particular base sand increases, as the mean size of the silt matrix in it decreases. There are studies on undrained shear strength of silty sands considering other density index parameters as well. For instance, Thevanayagam et al. [34] proposed a modified version of intergranular void ratio, where the contribution of the silt matrix on the force carrying mechanism of sands during shearing is represented by a parameter named as "b". In physical terms; when b = 0, silt grains within a base sand are considered as voids, whereas when b = 1, silt grains within a base sand are considered similar to sand grains and fully contribute to the load carrying skeleton. In later studies, Ni et al. [25] reported that b would increase with decreasing ($D_{10\text{-sand}}/d_{50\text{-silt}}$). Kanagalingam and Thevanayagam [13] mentioned that b is a function of coefficient of uniformities of sand and silt matrix, as well as the mean grain diameter ratio. Rahman and Lo [30] proposed an equation from which b could be predicted as a function of FC, transition fines content and $D_{10\text{-sand}}/d_{50\text{-silt}}$ ratio. All of the mentioned studies imply that grain size distribution of silt matrix has a potential to influence the undrained shear strength of sands and therefore could also play a role on the static liquefaction of sands.

When shape characteristics is considered as another factor that could have an influence on the static liquefaction behavior, previous studies once again focused on shape effects of sand grains (i.e., influence of grain shape on drained/undrained clean sand response). Cho et al. [3] investigated the influence of grain shape effects on extreme void ratios (e_{max}, e_{min}), small strain stiffness and critical state parameters. They conducted oedometer, bender element and drained triaxial compression tests on 33 different sands, and found that increasing angularity and/or decreasing sphericity of sand grains caused an increase in extreme void ratios, compression index (C_c), and critical state friction angle (ϕ_{cs}) of sands. Rouse et al. [32] also depicted that increasing angularity of sand grains resulted an increase in extreme void ratios and internal friction angle based on the data of various sands in literature. Guo and Su [10] conducted drained triaxial compression tests on two clean sands with different grain shapes and mentioned that increasing angularity tends to increase the shear strength and influences the dilatancy of sands. Georgiannou and Tsomokos [9] discussed the influence of grain shape effects on undrained behavior of sands. They performed torsional hollow cylinder and undrained triaxial compression tests on four uniform clean sands with similar grading curves but having different shape characteristics. In that study, angular sands had shown a stronger undrained response compared to rounded sands at similar relative densities, and angularity of sand grains were shown to be as influential as gradation on the undrained behavior of clean sands. Yang and Wei [42] conducted an important study regarding the influence of particle shape on the instability of loose sands via undrained triaxial compression tests on two base sands (Toyoura and Fujian) mixed with two different fine types: crushed silica fines (angular) and glass beads (rounded). Similar to Cho et al. [3], Yang and Wei [42] also observed an increase in ϕ_{cs} of clean sands as they become more angular. But more importantly, Yang and Wei [42] reported that at a particular fines content a sand involving rounded glass beads had more susceptibility to static liquefaction than a sand involving angular crushed silica fines.

As could be seen from the mentioned studies, fines content, grain size distribution and grain shape characteristics are among the major factors that affect the shear strength and liquefaction response of sands. However, many of the previous studies have focused on the properties and characteristics of sand grain matrix. This was perhaps a reasonable approach with the assumption that it is the dominating matrix for both clean and silty sands. Nevertheless, relatively little is known about how and to what extent the gradation and shape characteristics of silt grain matrix (e.g., mean size, coefficient of uniformity, angularity) in a silty sand influence the static liquefaction behavior of those soils. Furthermore, it is unclear whether some effects of the mentioned factors are independent of each other or coupled, as most of the previous studies investigated the effects of mentioned factors individually. In this study, monotonic undrained triaxial compression tests were performed on three base sands with same geologic origin and on twenty seven silty sands obtained by mixing the base sands with three different non-plastic silts at various fines contents (i.e. FC ≤ 25%). The results were analyzed based on several aspects including the effects of content, grain size distribution and shape characteristics of the silts on static liquefaction of silty sands.

2. Soils tested and experimental program

Three clean sands were obtained from a sand quarry in Şile region of Istanbul. These sands, which have the same geologic origin but different gradations, are named Sile Sand 20/30, Sile Sand 50/55 and Sile Sand 80/100. Their grain size distributions are shown in Fig. 1. Three different non-plastic silts: IZ silt, SI silt and TT silt, obtained from three cities of Turkey, were used in the experimental program as fine grained soils. TT silt was obtained from a stone quarry in Şile region of Istanbul. It was produced by wet sieving of stone dust through the No 200 standard sieve (0.075 mm). SI silt was obtained from a sand quarry in Lüleburgaz region at the city of Kırklareli. IZ silt is a naturally formed

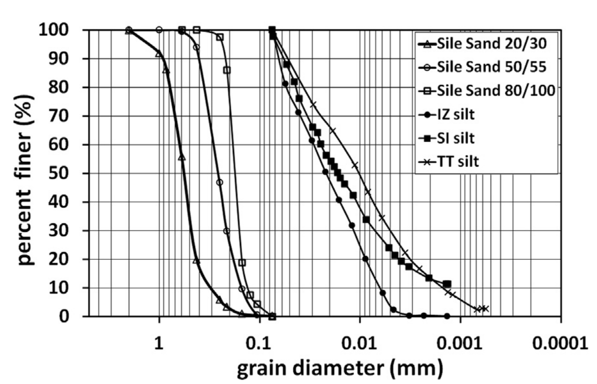

Fig. 1. Grain size distribution of the soils used in the experimental program.