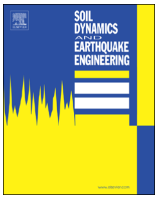
Soil Dynamics and Earthquake Engineering 77 (2015) 137–151

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn



Engineering behavior and correlated parameters from obtained results of sand–silt mixtures

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ARTICLE INFO

Article history:
Received 30 October 2014
Received in revised form
30 March 2015
Accepted 8 May 2015

Keywords:
Cyclic resistance ratio
Shear strength parameters
Hydraulic conductivity
Coefficient of consolidation
Sand–silt mixtures

ABSTRACT

The results of an experimental study on sands with low-plastic silt content are presented. Flexible wall permeameter tests, drained and undrained triaxial compression tests, one-dimensional consolidation tests, and undrained cyclic triaxial tests were performed on specimens with a low plastic silt content of 0%, 15%, 30%, 40%, 50% and 60% by weight. The soil specimens were tested under three different categories: (1) at a constant void ratio index; (2) at the same peak deviator stress in a triaxial test; and (3) at a constant relative density. The results were observed to be somewhat different from previous studies with non-plastic silt content and plastic fine content. Cyclic triaxial tests showed that an increase in silt content causes a decrease in the cyclic resistance ratio with a silt content up to 40–50% and thereafter causes an increase in the cyclic resistance ratio with further increases in silt content. The results of triaxial tests indicated that the value of the peak deviator stress changed with different types of specimens, and the greater internal friction an angle has, the stronger is the liquefaction resistance. Flexible wall permeameter tests concluded that the saturated hydraulic conductivity slowly decreases with an increase in silt content in the range from 0% to 30% and considerably decreases with a silt content greater than 30%. A one-dimensional consolidation test postulated that increasing silt content decreases the coefficient of consolidation. In addition, the global void ratio did not appear to be a pertinent parameter in explaining the behavior of sand–silt mixtures, while fine content and intergranular void ratio were suitable parameters for explaining the behavior of sand–silt mixtures. Finally, correlated parameters from obtained results were also presented in this study.

1. Introduction

For the past many years, the liquefaction of saturated granular soil during earthquakes has been one of the most interesting and complex phenomena studied in the field of geotechnical earthquake engineering. In common usage, liquefaction refers to the loss of strength in saturated, cohesionless soils due to the build-up of pore water pressures during dynamic loading. Sladen et al. [1] defined liquefaction as a phenomenon wherein a mass of soil loses a large percentage of its shear resistance when subjected to monotonic, cyclic, or shock loading and flows in a manner resembling a liquid until the shear stresses acting on the mass are as low as the reduced shear resistance. At the initial liquefaction, the behavior of the soil mass is similar to a liquid, which causes severe damages to soil conditions and earthwork, such as sand boils, settlements, tilting of structures, failure of earth dams and slopes, lateral spreading of bridge foundations, and ground failure [2]. In fact, there are various factors that influence the soil liquefaction phenomenon, such as the type of soil, soil parameters (i.e., grain size distribution, void ratio, density, plasticity, and hydraulic conductivity), testing parameters, and sample preparation methods [3,4]. Most previous scholars have focused on relatively clean sand [5,6]. However, natural sand commonly consists of fines (passing sieve no. 200, particle size less than 0.075 mm) and sand particles with different proportions. The existence of fines significantly influences and plays an important role in liquefaction behavior as well as on the engineering properties of sands [2,7–11]. The plasticity of fines also leads to many complicated phenomena under undrained behavior and liquefaction resistance [12–17]. Additionally, the role of non-plastic silt or silt content on the liquefaction behavior of sands has been a topic of debate for some time [7].

As most experimental laboratory testing is done to evaluate liquefaction susceptibility, the behavior of undrained and drained triaxial test appears to be different in terms of the effect of plastic fine, non-plastic and low-plastic silt content. Lade [18] revealed that loose fine sand became unstable even before the stress reaches failure undrained conditions. For medium loose to dense sand, Chu et al. [19]

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http://dx.doi.org/10.1016/j.soildyn.2015.05.005
0267-7261/

also found unstable behavior under strain path controlled conditions. Pitman et al. [20] observed that when silt was added to Ottawa sand, it became less collapsible during undrained triaxial tests. Yamamuro and Lade [21,22] and Lade and Yamamuro [23] concluded that increasing the non-plastic silt content in Nevada sand increased the volumetric contractive parameter of specimens in both drained and undrained triaxial tests. In addition, other studies found that the existence of non-plastic silt appeared to decrease the undrained shear strength depending on the intergranular void ratio of sand–silt mixtures [24].

Numerous scholars have conflicting conclusions about the effects of fines content on the liquefaction behavior of sand and have not yet reached a consensus. Hazirbaba and Rathje [25] tested the specimens under three different categories, including at a constant relative density, at a constant sand skeleton void ratio, and at a constant overall void ratio; in addition, they concluded that pore water pressure appears to increase when enough fines were present to create a sand skeleton void ratio greater than the maximum void ratio of clean sand. Ural and Gunduz [26] showed that in soils with clay content equal to or less than 10%, the excess pore pressure ratio build up was quicker, with an increase in different cyclic stress ratios, and when fines and clay content increases, excess pore water pressure decreases at a constant cyclic stress ratio in non-plastic silty soils.

Some results showed that the liquefaction resistance either increased with increasing fine content in the mixture [20,27–29] or decreased with increasing fine content [10,14,21,23,30–33]. Other studies have found that the resistance of sand to liquefaction initially decreased as the silt content increased until some minimum resistance was reached and then increased as the silt content continued to increase [13,29,34,35]. Mokul and Yamamuro (2011) [36] concluded that 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 in the range of 0–20%. However, as $D_{50\text{-sand}}/d_{50\text{-silt}}$ increases, the liquefaction potential of the silty sand becomes less than the liquefaction potential of clean sand.

Considering the compression behavior of sandy soil, some models are proposed for the compression behavior of cohesionless soils, such as that by Pestana and Whittle [37]. The effects of initial void ratio, relative density, particle shape, mineralogy, structure and applied stress conditions on the compression behavior of sandy soil were also realized and prominent in experimental studies related to the compression of sands [38,39]. As was done for other parameters, the influence of fines on compression behavior does not seem to have been systematically considered in past publications [40]. Yin[41] found a limitation in the correlations between consolidation parameters, such as compression index, swelling index, coefficient of secondary consolidation with plasticity index and clay content, for reconstituted Hong Kong marine deposits. Martins et al. [42] revealed that the fines do not yield a unique compression line for a particular coarse grained soil, and a new framework behavior is essentially proposed for this sandy soil. Monkul and Ozden [40] concluded that the initial condition, percentage of fines, and stress conditions significantly influence compression behavior; up to a fraction of fines, which is named the transition fines content (FCt), the compression behavior of the mixtures is mainly controlled by the sand grains. When the concentration of fines exceeds FCt, kaolinite controls the compression.

Hydraulic conductivity is an important indicator parameter in the generation and redistribution of excess pore water pressure of sand–silt mixture soil deposits during earthquakes. However, hydraulic conductivity is significantly influenced by sand conditions, such as the percentage of fines, sand gradation, void ratio, confining pressure, and density. To date, literature reviews showed that very few studies have been published on the effect of fine content on hydraulic conductivity in laboratory tests [2,43–45]. Bandini and Sathiskumar [44] showed that the saturated hydraulic conductivity and the coefficient of consolidation of sands with 25% non-plastic silt can be, on average, two orders of magnitude smaller than those of clean sands. For a given silt content, k varies mostly within one order of magnitude, depending on the void ratio of the soil. On the other hand, factors such as changes in void ratios, silt content, and effective confining stress have relatively less effect. Belkhatir et al. [2] revealed that hydraulic conductivity decreased with increasing fines content and initial relative density; additionally, at a fines content of up to 50%, there was a relatively high degree of correlation between fines content (FC) and the logarithm of saturated hydraulic conductivity and a decreased linear relationship with decreasing hydraulic conductivity and increasing fines content.

The objective of this study is to systematically investigate the behavior and engineering properties of sand–silt mixtures from the perspective of fine content, global void ratio, and intergranular void ratio. The test program employed flexible wall permeameter, one-dimensional consolidation, static triaxial, and cyclic triaxial tests on various sand–silt mixtures with three types of specimens, i.e., a constant void ratio index of 0.582 (type 1), the same peak deviator stress of 290 kPa (type 2), and a constant relative density D_r of 30% (type 3). In a previous study, Hsiao and Phan [46] focused on the effects of silt content on the static and dynamic properties of sand–silt mixtures. This expanded study aims not only to investigate engineering properties but also to clearly elucidate the behavior of drained and undrained triaxial tests and correlations between obtained results. For example, the relationships between internal friction angles and cyclic resistance ratios, hydraulic conductivity and cyclic resistance ratios, and hydraulic conductivity and the coefficient of consolidation were also established. The findings obtained are expected to contribute to the understanding of the engineering properties and behavior of sand–silt mixtures. The experimental data are also expected to provide a quantitative basis for further design recommendations in Kaohsiung city, Taiwan.

2. Materials used

Soil specimens were taken from Liouguei District, located in Kaohsiung city, Taiwan. A quantity of natural sandy soil was carefully sieved to separately obtain clean sand and pure silt. The silt particles are defined as the grain size of soil that is able to pass through a No. 200 (0.075 mm) sieve. According to the AASHTO classification system, the fraction passing the No. 200 U.S. sieve is called silt and clay; however, the term silty is applied when the fine fractions of the soil have a plasticity index (PI) of 10 or less [47]. The sand–silt mixtures were prepared from these two materials for the following combinations.

All tests were conducted with six sand–silt mixtures defined by dry weight: 100% sand plus 0% silt (0% FC), 85% sand plus 15% silt (15% FC), 70% sand plus 30% silt (30% FC), 60% sand plus 40% silt (40% FC), 50% sand plus 50% silt (50% FC), 40% sand plus 60% silt (60% FC). Based on the ASTM D422 [48] method, the results of the grain size distribution curve for all of the sand–silt mixtures are shown in Fig. 1. The specific gravity test G_s of natural sand was conducted in accordance with ASTM D854 [49] and yielded a value of 2.7, and this value is assumed for all the sand–silt mixtures. It should be noted that no applicable ASTM procedure exists for determining the maximum void ratio over the entire range of silt contents investigated. The ASTM 4254 [50] method was limited to the determination of maximum void ratios with a maximum silt content of 15% in the mixture. Despite this limitation, the maximum void ratio was still tested according to this specification. Similar to the maximum void ratio, there was also no applicable