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The influence of non-plastic fines on pore water pressure generation and undrained shear strength of sand-silt mixtures

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ABSTRACT

An extensive experimental study was undertaken to investigate the influence of non-plastic fines on pore water pressure generation and undrained cyclic shear strength of sand–silt mixtures. For this purpose, stress-controlled undrained cyclic simple shear (*CSS*) tests were carried out on reconstituted specimens of Ticino silica sand under different combinations of fines content (*FC*) and global void ratios (*e*). The applicability of several models suggested in literature for predicting cyclic residual excess pore water pressure generation in non-plastic silty soils was analyzed, and revised correlations for assessing model parameters were proposed. Finally, the study confirmed that the equivalent granular void ratio (e^*) is an effective and appropriate parameter for characterizing the behavior of sand with fines up to a threshold value of fines content of sand-silt mixtures, and cyclic resistance ratio (*CRR*) of the mixtures can be well correlated with e*, irrespective of their fines contents and void ratios.

1. Introduction

Natural sand deposits often contain various amounts of fines (silt and clay size particles). The effect of fines on the response of sands to monotonic and cyclic loadings has been one of the most challenging topics in geotechnical engineering. In addition to the void ratio and stress level, the value of fines content (FC), as another state related variable, controls the behavior of sand-silt mixtures. Various parameters such as void ratio, relative density, intergranular void ratio were used in previous research in order to compare the liquefaction behavior of clean sands vs. sands with fines (e.g. the influence of *FC*) [1]. Perhaps the most commonly used parameter is the global void ratio for such a comparison [2–8], since it is one of the key parameters in geotechnical engineering [1].

Numerous laboratory studies have shown that the undrained cyclic shear strength of the mixtures decreases as silt content increases at a constant void ratio and stress level, until it reaches a certain threshold fines content. After this threshold, undrained cyclic shear strength then increases with increasing silt content [2,6,9,10]. The transition fines content range is about 20–30% for non-plastic fines [4,6,9].

It has been recognized that the microstructure of a granular mix, which can be constituted in many different ways with different types of intergrain contacts, significantly affects its mechanical response. The definition of intergranular void ratio, e_g, [2,11,12] is based on the assumption that all of the fines in sand-fine mixtures can be approximated as void space, i.e. their contribution to the force structure can be neglected. The work of Pitman et al. [13], among others, unambiguously demonstrated that e_g can function as an alternative to *e,* provided that *FC* is low relative to the void space formed by the host sand. At higher fines contents (relative to the void space), the fines begin to participate in the force structure [14]. Therefore, Thevanayagam [15,16], proposed the use of equivalent granular void ratio, e^*, defined by Eq. (1), as a better alternative state to *e:*

$$e^* = \frac{e + (1 - b)\cdot FC}{1 - (1 - b)\cdot FC} \quad (1)$$

where, *b* represents the fraction of fines that are active in force structure; $b = 0$ would mean that none of the fine grains actively participate in supporting the coarse-grain skeleton; $b = 1$ would mean that all of the fine grains actively participate in supporting the coarse grains skeleton (Thevanayagam et al. [17]). The selection of appropriate means of comparison of samples with different fines contents, (*e*, e^*, relative density, or simply creating samples by similar methods, whatever their densities then turn out to be) is still a relevant issue in geotechnical literature. Some researchers have attempted to apply the most recent e*-based approach to predict several void ratio dependent soil behaviours, such as cyclic liquefaction resistance (*CRR*) [18–22],instability behavior [23–25] and small strain shear modulus [15,26,27], irrespective of fines contents. By considering the simultaneous role of void ratio, stress level, and fines content in characterizing the behavior,

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a key question to be answered is how to combine the effect of these variables. Critical state soil mechanics (*CSSM*) provides an effective and convenient framework to describe the monotonic and cyclic behavior of sands [28] but other efforts are needed to reach definitive conclusions on the applicability of this approach. In the present research, undrained cyclic simple shear (*CSS*) tests were conducted to investigate the undrained cyclic liquefaction resistance and pore water pressure response of silty sands with non-plastic fines in a range of *FC* from 0% to 40%. Test results were interpreted by using the equivalent granular void ratio concept for predicting the undrained cyclic shear strength of silty sands. The main advantage of this approach is that one can predict the undrained cyclic shear strength of sand-silt mixtures in a unique way for various fines contents, stress levels and densities, without the need of performing tests at different fines contents but using only the clean sand data. The manner in which pore water pressure generation varies as the quantity of fines in the sand increases, is also an important aspect of the present research. Most of the previous studies on excess pore water pressure generation of sand-silt mixtures and model predictions were based on the results of cyclic triaxial tests (*CTX*) [6,29–34] and some revisions or modifications of the models originally proposed for clean sands were made to account for the effect of fines [35–38]. However, there is a need to enlarge the existing data-base to derive model parameters, possibly from *CSS* tests, in order to use them in practical applications.

2. Experimental investigation

2.1. Testing program and materials

The host sand used in this study is Ticino sand (*TS*), a clean uniform size quartz sand with a mean grain size (D_{50}) equal to 0.56 mm. Specific gravity G_s was 2.68 and the minimum and maximum void ratios according to ASTM D 4253, 4254 [39,40], resulted 0.58 and 0.93, respectively.

The fine material (D_{50} = 0.025 mm) added to host sand is a natural non-plastic silt collected from Ticino river bank deposits. Six different fines contents ranging from 0% to 40% were used in the experimental investigation. Grading curves of original Ticino sand and added fines are shown in Fig. 1. Index properties including specific gravity, and maximum and minimum index void ratios were determined for each soil mixture (Table 1).

Over the entire investigated range of silt contents, ASTM D 4253 [39] and ASTM D 4254 [40] were used to define the minimum and maximum void ratios, respectively. A plot of the maximum and

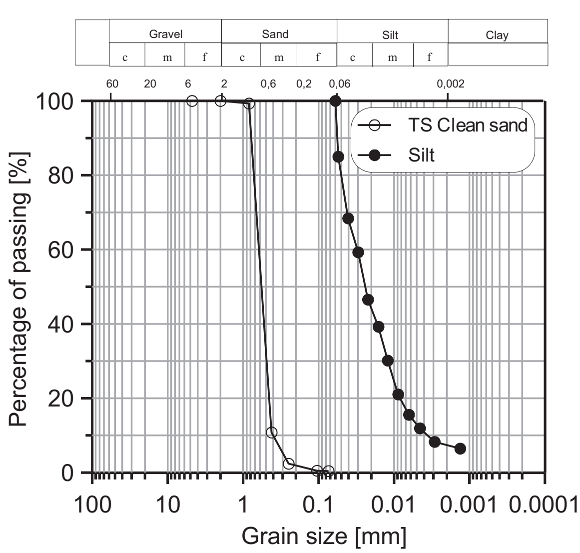

Fig. 1. Grain-size distribution curves of component materials.

Table 1
Index properties for Ticino sand with non-plastic silt mixtures.

Index properties	Percent silt (% by weight)				
	5	10	20	30	40
G_s	2.66	2.67	2.68	2.69	2.7
e_{max}	0.84	0.81	0.79	0.80	0.95
e_{min}	0.53	0.47	0.37	0.37	0.48

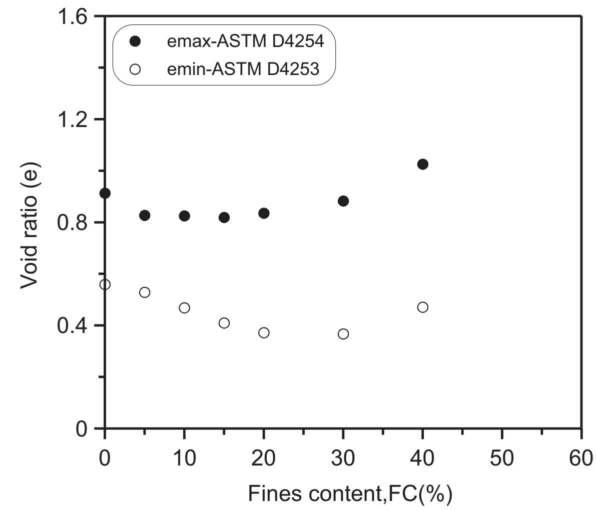

Fig. 2. Variation of minimum and maximum void ratio with fines content for Ticino sand-silt mixtures.

minimum index void ratios vs. silt content for the investigated mixtures is presented in Fig. 2. The void ratio decreases with fines content until it reaches a certain threshold value, beyond which a further increase in FC leads to an increase in void ratio. This trend is consistent with the concept of limiting or threshold fines content (*TFC* or *LFC*) predicted on the basis of binary packing considerations [41,42].

Cyclic simple shear tests (*CSS*) were performed by using a modified NGI *SS* apparatus [43] to investigate the liquefaction behavior of tested soils. The objective of laboratory tests is to replicate actual loading conditions as closely as possible: in fact, cyclic simple shear tests provide one of the best representations of field conditions before and during earthquakes (with or without initial static shear stress). In this apparatus, the lateral restraint provided by the reinforced membrane assures a condition of zero horizontal extension on the vertical boundary. Undrained tests were carried out under constant volume conditions by an automatic control system developed at University Mediterranea of Reggio Calabria (Italy). Therefore, the reduction or increase in vertical stress required to maintain constant sample height are equivalent to the pore water pressures that might be developed in an undrained test under constant vertical load [44,45]. Tests at different equivalent granular void ratios, e^*, can be produced by different combinations of fines contents and global void ratio (e) using Eq. (1). The testing program covered a wide range of initial conditions: (i) e (after consolidation) ranging from 0.49 to 0.74; (ii) e^* in the range from 0.63 to 1.07. All tests were conducted at a vertical effective stress σ'_{vo} = 100 kPa. When analyzing test results, it is essential to use the post consolidation void ratios. Ignoring changes in void ratio during consolidation can lead to unpredictable errors and some confusion in the evaluation of fines content effects. A total of about 60 *CSS* tests were carried out, as tabulated in Table 2.

SS specimen dimensions were 20 mm in height and 80 mm in diameter. A modified moist tamping method was used for specimen preparation to ensure uniformity conditions of the specimen. This technique can produce specimens over a large range of void ratios relative