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An experimental study of the liquefaction strength of silty sands in terms of the state parameter

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ABSTRACT

An elaborate program of monotonic and cyclic triaxial laboratory tests on mixtures of sand and silt with fines content 0%, 15% and 25% was performed to investigate the effect of density, consolidation stress and non-plastic fines on the liquefaction strength. The monotonic tests illustrated that the critical state lines of all mixtures do not cross each other, and are, approximately, parallel to each other. The results of the cyclic tests illustrated that the relationship between the cyclic strength and the state parameter does not depend on the consolidation stress, the soil density and the silt content. Analysis in terms of the state parameter showed that: (i) as the consolidation stress increases, the cyclic strength decreases and this effect is more pronounced as the specimens become denser, especially as the fines content increases and (ii) the cyclic strength decreases as the fines content increases and this effect is more pronounced as the specimens become denser.

1. Introduction

The cyclic strength of sands, as defined hereunder, is one of the most studied soil parameters in geotechnical earthquake engineering. It determines whether or not a site will liquefy under a given seismic acceleration [1–3]. The cyclic strength of sands has been studied extensively in the laboratory, especially in the triaxial device, but also in the simple-shear and torsional-shear devices. Important factors that affect the cyclic strength of sands are the void ratio, the consolidation stress and the content of fines.

The effect of void ratio on liquefaction susceptibility has been previously studied extensively for clean sands. A large number of tests have been performed in the sands of Toyoura [3], Ottawa [4], Monterey [5]. The results show a considerable increase in the cyclic strength as the sand void ratio decreases. The effect of consolidation stress on cyclic strength of sands has also been studied. It has been observed that as the consolidation stress increases, the cyclic strength at similar void ratio decreases [6,7]. The effect of consolidation stress on the cyclic strength is usually described by the factor $K\sigma$ that is defined as the ratio of the cyclic strength at the current consolidation stress and the cyclic strength at a consolidation stress equal to 100 kPa and similar void ratio. Based on laboratory test results, different expressions have been proposed for the factor K_σ [8,9].

The effect of non-plastic fines on the cyclic strength of sands has also been studied in the laboratory. The majority of laboratory tests show that at similar void ratio, the presence of fines up to at least about 30% of the total weight decreases the cyclic strength [10–15]. However, other test results indicate an increase of the cyclic strength with the fines content [16]. In addition, most empirical correlations from in situ tests show that the presence of fines increases liquefaction resistance (e.g. [2]). Thevanayagam et al. [17] recommend the use of the intergranular void ratio, defined hereunder, for the interpretation of the experimentally observed effect of non-plastic fines on the liquefaction resistance.

It has been observed recently that thru the state parameter, defined hereunder, the effects of both the consolidation stress and void ratio on the cyclic strength can be simulated. Chen and Liao [18] related the cyclic strength of a sand measured in the triaxial device to the state parameter. Pillai and Muhunthan [19] validated based on published cyclic simple-shear test results of two sands that thru the state parameter the effects of both the consolidation stress and void ratio on the cyclic strength can be simulated. Stamatopoulos et al. [20] studied the effect of both the void ratio and the consolidation stress in two silty sands in the direct-shear device and observed that both effects can be simulated thru the state parameter for given soil.

The relationship between cyclic strength and the state parameter has recently been used to study the effect of consolidation stress and fines content on the cyclic strength of

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Nomenclature

AUTH	Aristotle University of Thessaloniki
a_σ	factor defined by Eq. (8)
CPT	cone penetration test
Dr	relative density
Dr_{sand}	the relative density of the clean sand corresponding to the void ratio of the mixture
Dr_{cs}	the relative density at the critical state
e_0	initial (prior to consolidation) void ratio
e	void ratio
e_f	final (critical-state) void ratio
fc	fines content
NTUA	National Technical University of Athens
Num	number of tests
I_f	factor defined by Eq. (9)
N_f	number of cycles to liquefaction
K_σ	factor defined by Eq. (7)
p'	octahedral effective stress defined by equation (1)
p'_o	octahedral effective stress prior to the application of cyclic loading
p_a	atmospheric pressure (equals about 100 kPa)
p'_f	final (critical state) octahedral effective stress
q	deviatoric stress defined by Eq. (2)
R^2	coefficient of correlation
STAM	Stamatopoulos and Associates Co.
SR_{15}	cyclic strength, or the cyclic stress ratio (SR) causing liquefaction in 15 uniform cycles
SR_{10}	cyclic stress ratio (SR) causing liquefaction in 10 uniform cycles
SR	cyclic stress ratio (Eq. (7))
$SR_{15\text{-}p'o=100\,kPa}$	cyclic strength at p'_o=100 kPa
$X'_{Pred/Meas}$	average value of the ratio of predicted by measured values
u_p	permanent excess pore water pressure
Γ, λ, ξ	parameters of the critical state line (Eq. (3)
$\varepsilon_{a\text{-}cyc}$	double-amplitude cyclic axial strain
$\varepsilon_{a\text{-}p}$	permanent axial strain
$\sigma'_{Pred/Meas}$	standard deviation of the ratio of predicted by measured values
σ'_h	effective horizontal stress
σ'_v	effective vertical stress
$\sigma'_{v\text{-}cyc}$	cyclic vertical stress applied in cyclic triaxial tests
$\sigma'_{v\text{-}o}$	effective vertical stress prior to the application of dynamic loading
ψ	state parameter defined by Eq. (4)

sands. The effect of consolidation stress on the cyclic strength depends on the form of the relationship between the cyclic strength and the state parameter [21]. Chen and Liao [18] and Stamatopoulos et al. [20] data show that the relationship between the state parameter and the cyclic strength is approximately linear. Boulanger [21] defines an empirical index, ξ_R, that has a functional form consistent with critical state concepts. The index ξ_R can be estimated directly from the relative density of the soil (Dr), the consolidation stress and the soil type (as described by the factor Q). He studies the relationship of the cyclic strength with the parameter ξ_R, based on published results of laboratory tests (Fig. 1a), as well as CPT data and empirical relationships from field data (Fig. 1b). It is observed that the relationship between the cyclic strength and ξ_R (a) is not unique but depends on soil type and type of test and (b) in all cases the cyclic strength decreases as ξ_R increases at a rate that progressively decreases. Based on Figs. 1a and b, Boulanger [21] estimates the K_σ factor and observes that at similar consolidation stress, K_σ increases as sand density increases (Fig. 1c and d).

Bouckovalas et al. [22], assume that (a) for different fines contents all critical state lines in the logarithm of octahedral effective stress-void ratio space (i) are linear, (ii) pass thru a unique point at consolidation stress of 60 kPa approximately and (iii) their slope increases with fines content and (b) the relationship between the state parameter and the cyclic strength does not depend on the fines content. Thru these assumptions they conclude that the effect of fines on the cyclic strength is affected drastically by the consolidation stress.

From the above it is inferred that even though the effects of void ratio, consolidation stress and fines content on cyclic strength have been studied by many researchers in the laboratory, many aspects are not clear: The effect of consolidation stress on the cyclic strength is described by different empirical expressions. Only recently, expressions indicating that this effect depends on sand density were proposed. The effect of fines content on these relationships has not been investigated. On the other hand, for the effect of fines on the cyclic strength conflicting data (e.g. [10] versus [16]) and different theories ([17] versus [22]) exist. A laboratory study of the effect of the fines content over a considerable range of consolidation stresses and void ratios was not found in the literature. Furthermore, recently the critical state theory has been used to analyze the effects of void ratio, consolidation stress and fines content on the cyclic strength of sands. Such analyses need the relationship between the state parameter and the cyclic strength. Different shapes of this relationship have been observed. In addition, the effect of the fines content on this relationship has yet to be studied experimentally.

The purpose of this paper is to investigate comprehensibly the effect of void ratio, consolidation stress and fines content on the cyclic strength of sands. Investigation was performed by an elaborate program of cyclic triaxial tests at different cyclic stress ratios, initial void ratios, initial consolidation stresses and fines content. Monotonic tests were also performed to define the critical state line of the mixtures. Consistently with modern practice, analysis is in terms of the state parameter. It should be noted that the applicability of relationships predicting the effect of void ratio, consolidation stress and fines content on the cyclic strength is considerable, and they can lead to improved relationships giving the cyclic strength in terms of the fines content and the SPT or CPT resistance measured in situ [21,22].

The tests performed were part of a research program that was coordinated by Prof. Bouckovalas of the National Technical University of Athens (NTUA) and included three laboratories: The laboratory of the author (STAM), the laboratory of the Aristotle University of Thessaloniki (AUTH) under the direction of Prof. Tika and the laboratory of NTUA under the direction of Prof. Georgiannou. The same soils were used by all three laboratories. First common tests were performed by all three laboratories and it was ensured that they produce compatible results. Then, tests proposed by Prof. Bouckovalas, as well as additional tests were performed by each laboratory. Tests by STAM and AUTH were performed in the triaxial device, while tests by NTUA in the torsional-shear device. In this paper, the test results of the STAM laboratory are presented. Then, analysis of the test results is given. As the AUTH data were on the same sand–silt mixtures and using the same preparation method in the triaxial device, in the analyses of the laboratory results below, all data were combined in a single database, and data regression was performed at this much larger and thus more reliable database.