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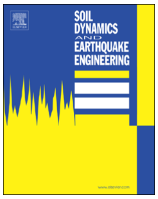

The effect of preloading on the liquefaction cyclic strength of mixtures of sand and silt

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ABSTRACT

The paper studies the effect of preloading on the liquefaction cyclic strength of silty sands in the free field condition. This effect first is investigated by cyclic shear tests where horizontal shear stress oscillated about a zero mean value. Samples with varying fines content and at varying pre-stress ratios, densities and vertical stresses are tested. Test results show a marked increase of the liquefaction cyclic strength with the pre-stress ratio. The effect is more pronounced for tests with less liquefaction cyclic strength without pre-stress. Using critical state soil mechanics concepts, factors simulating the effect of preloading on the liquefaction cyclic strength are identified and based on the results of the laboratory program an empirical expression is proposed predicting the increase in the liquefaction cyclic strength induced by pre-stress. This expression is validated by numerical simulation of the relevant laboratory tests using an elastoplastic multi-mechanism model. In addition, based on the derived expression, a methodology is proposed predicting the increase in liquefaction cyclic strength as a result of preloading in the field in the case of the free field condition. This methodology is validated by the comparison with field measurements on liquefaction-susceptible soils before and after the field application of preloading. Last but not least, the increase in liquefaction cyclic strength which the proposed methodology predicts for typical soil profiles and embankment preloads is predicted and discussed.

1. Introduction

The liquefaction cyclic strength, as defined hereunder, determines whether or not saturated sandy layers in the free field condition run the risk of earthquake-induced liquefaction [1,2]. The factor of safety against liquefaction below horizontal ground surfaces is defined, versus depth, as the ratio of the in-situ liquefaction cyclic strength by the cyclic stress ratio resulting from the design earthquake [2]. In cases where this factor takes values close to, or less than, unity, soil improvement is an effective way to mitigate the liquefaction risk by increasing the liquefaction cyclic strength. Preloading is a temporary loading, usually an embankment, applied at a construction site to improve subsurface soils primarily by increasing density and horizontal stress [3,4]. Preloading requires simpler equipment than other methods of soil improvement and is often less expensive [3].

The liquefaction 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 which affect the liquefaction cyclic strength of sand samples are the void ratio, the consolidation stress and the content of fines: Tests in the sands of Toyoura [2], Ottawa [5,6] and Monterey [6] show a considerable increase in the cyclic strength as the sand void ratio decreases. In addition, it has been observed that as the consolidation stress increases, the cyclic strength at similar void ratio decreases [7]. Furthermore, laboratory tests show that at similar void ratio and confining stress, the presence of fines up to at least about 25% of the total weight decreases the liquefaction cyclic strength [8,9]. Recently, the effects of both the consolidation stress and void ratio on the liquefaction cyclic strength has been simulated by only one parameter, the state parameter, defined hereunder [10,11]. Furthermore, for sand–silt mixtures it has been observed that the relationship between the state parameter and the liquefaction cyclic strength for soil samples with different fines content tested in the triaxial device (a) is unique for the same sample preparation method [12] and (b) differs for different sample separation methods [13].

In addition to the effect of density, consolidation stress and fines content on the liquefaction cyclic strength of sand samples prepared in a similar manner, described above, the liquefaction cyclic strength measured in the laboratory depends also on the preloading (over-consolidation or pre-stress) of the soil sample before the application of cyclic loading [14–23]. Also, using a totally different technique, dynamic geotechnical centrifuge testing, Adalier and Elgamal [24] studied the preloading effect on

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Nomenclature

$a1$, $a2$	Fitting parameters of Eq. (9)
Dr	Relative density
e_o	Initial (prior to consolidation) void ratio
f1, f2, f3, f4	Functions
fc	Content of fines = Weight of fines per total weight of mixture
Mea., Pred.	Measured, predicted
N_f	Number of cycles to liquefaction
N_{60}	Blow count number measured in the Standard Penetration Test
PR	Pre-stress ratio of samples prepared in the laboratory (Eq. (2))
PR_{field}	Field pre-stress ratio (Eq. (15b))
p'	Octahedral effective stress
p'_o	Octahedral effective stress prior to the application of cyclic loading
Pa	Atmospheric pressure (equals about 100 kPa)
qc	Resistance measured in the cone penetration test
R^2	Coefficient of correlation
R_{PR}	$SR_{15\text{-PR}}/SR_{15\text{-1}}$
R_{field}	$SR_{15\text{-after}}/SR_{15\text{-bef}}$
SR	Stress ratio ($=\tau_{cyc}/\sigma'_{vo}$) under Ko consolidation (Eq. (1))
SR_{15}	Liquefaction cyclic strength, or the cyclic stress ratio (SR) causing liquefaction in 15 uniform cycles of loading.
$SR_{15\text{-1}}$	SR_{15} at PR=1
$SR_{15\text{-I}}$	SR_{15} at PR=i
$SR_{15\text{-bef}}$	SR_{15} in the field before the application of preloading
$SR_{15\text{-after}}$	SR_{15} in the field after the application of preloading
V_s	Shear wave velocity
$\Delta\sigma'_\nu$	The maximum additional effective vertical stress applied during the preload process
Γ, λ, ξ	Parameters of the critical state line (Eq. (12))
ΔU	Excess pore pressure
ε_i (i=1–3)	Principal Strains
Ko	Earth pressure coefficient at rest
θ, A	Factors given by Eqs. (A2) and (A3)
ν	Poisson Ratio
σ'_h	Effective horizontal stress
σ'_v	Effective vertical stress
σ'_{vo}, σ'_{ho}	Effective vertical and horizontal stress prior to the application of cyclic loading
$\sigma'_{v\text{-c}}$	Maximum past effective vertical stress
σ'_i (i=1–3)	Principal effective stresses
τ_{cyc}	Cyclic shear stress (half peak-to-peak)
φ'	Friction angle at the critical state
ψ	State parameter defined by Eq. (11)

cyclic liquefaction and subsequent ground subsidence in clean saturated sand deposits based on much larger soil models.

Cyclic laboratory tests performed on samples of the same soil, consolidated at different pre-stress ratios, can illustrate the effect of pre-stress on the liquefaction cyclic strength. Based on results of such tests, empirical equations predicting the effect of pre-stress on the liquefaction cyclic strength of sandy soils have been proposed [15,19,20]. However, these equations were based on tests performed on specific sands. As the liquefaction cyclic strength greatly depends on fines content [8,9], the effect of pre-stress on the liquefaction cyclic strength may depend on the fines content of the soil.

Sophisticated elasto-plastic analyses predicting the response of liquefaction-susceptible soils under earthquake loadings,, have been developed and extensively validated [25,26]. Such analyses can be used to validate equations predicting the effect of pre-stress on liquefaction-susceptible soils measured in the laboratory. Furthermore, a number of case studies are reported in the bibliography where field data exists, which allows the estimation of the in-situ liquefaction cyclic strength both prior and after the field application of preloading in the free field condition [3,4,27–30]. These case studies can provide additional data to validate the equations predicting the effect of preloading on liquefaction-susceptible soils measured in the laboratory.

The purpose of the paper is to propose and validate a simple equation and associated methodology simulating the effect of preloading on the liquefaction cyclic strength of any liquefaction-susceptible soil in the free field condition. In order to achieve this, the paper below (a) defines the liquefaction cyclic strength of sands and illustrates that the constant-volume cyclic shear tests are suitable to investigate the effect of preloading on this strength, (b) performs in the shear device constant-volume tests in samples where the fines content in combination with the soil density, the consolidation stress and the prestress ratio vary, (c) identifies factors simulating the effect of pre-stress on the liquefaction cyclic strength using critical state soil mechanics concepts and, based on the results of the laboratory program, proposes an empirical expression predicting the increase in the liquefaction cyclic strength induced by pre-stress, (d) performs numerical runs simulating the effect of pre-stress on constant-volume cyclic laboratory tests to validate the proposed empirical expression, (e) proposes a methodology predicting the increase in the liquefaction cyclic strength as a result of preloading in the field based on the proposed empirical expression, (f) validates the proposed methodology by the comparison with measurements found in the literature on liquefaction-susceptible soil layers before and after the field application of preloading and (g) discusses the increase in liquefaction cyclic strength which the proposed methodology predicts in the field for typical soil profiles and embankment preloads.

2. Appropriate laboratory tests measuring the effect of preloading on the liquefaction cyclic strengthin the free field condition and previously proposed empirical expressions

2.1. Appropriate laboratory tests

As described by Seed and Peacock [14], below horizontal ground surfaces prior to the application of cyclic loading, the shear stresses are zero. In addition, the effective vertical stress, denoted as σ'_{vo}, equals the overburden effective pressure. Furthermore, the ratio of the effective horizontal stress, denoted as σ'_{ho}, to σ'_{vo}, is given by the coefficient of earth pressure at rest, Ko. As a result of an earthquake, dynamic loading is applied primary in the horizontal direction. When harmonic shear horizontal loading is applied, a cycle of loading is defined as the complete change of the horizontal shear stress (i) from zero to τ_{cyc}, (ii) from τ_{cyc} to $-\tau_{cyc}$ and (iii) from $-\tau_{cyc}$ back to zero. In this case, the cyclic stress ratio SR is defined as

$$SR = \tau_{cyc}/\sigma'_{vo} \tag{1}$$

In addition, cyclic shear strain during a loading cycle is defined as the maximum value of shear strain attained. Permanent strain, or permanent pore water pressure, is the part of the strain, or pore water pressure, which accumulates at the end of each cycle of loading.