PREDICTING UNDRAINED CYCLIC SIMPLE SHEAR RESPONSE OF SAND-SILT MIXTURES: A CRITICAL STATE APPROACH

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Abstract

This paper presents an experimental program of undrained cyclic simple shear tests on Ticino sand with different percentages of non-plastic fines (f_c=0-40%) along with analysis and interpretation in the framework of critical state soil mechanics. The samples were tested under a wide range of void ratio, vertical effective stress and fines content, and a unified correlation was established between the cyclic resistance *CRR* and the state parameter Ψ. Test results were also interpret by using the equivalent granular void ratio e^* concept and it was found to be an appropriate approach for interpreting the undrained cyclic behavior of sand with different amounts of fines up to a threshold fines content f_{thre}. Because a single trend for critical state data points was observed in the e^*-log(p') plane (*EG-CSL*) for different amounts of fines, the cyclic simple shear test results were analyzed in terms of an equivalent granular state parameter Ψ^* referred to a single *CSL* (*EG-CSL*).

1. Introduction

The behavior of sand under both monotonic and cyclic loading has often been explained or modelled within the critical state framework in terms of a state parameter Ψ (e.g., Jefferies & Been 2006; Rahman & Lo 2014; Rahman et al. 2019).

Experimental evidence addressing the issues of uniqueness of critical state (*CS*) lines for a given sand–fines mix showed that an increase in fines content (f_c) initially shifts the critical state line (*CSL*) downwards in e-log(p') space up to a threshold fines content (f_{thre}), where e is the void ratio and p' the mean effective stress.

To consider the real role of the fines in the force chain of the mixture, the concept of equivalent granular void ratio e^* was introduced by Thevanayagam et al. (2002):

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

where b represents the fraction of fines that is active in force structure of the sand skeleton.

If e^* is used instead of e, the *CSLs* coalesce into a single trend curve in e^*-log(p') plane, irrespective of f_c (e.g., Thevanayagam et al. 2002; Rahman et al. 2008). The single trend of *CSL* is called equivalent granular critical state line, *EG-CSL*, which is used to modify state parameter, Ψ, to equivalent granular state parameter, Ψ^*. Recently, the modified state parameter Ψ^* has been correlated to the key parameters of undrained behavior and cyclic liquefaction resistance (*CRR*) of sand-silt mixtures (e.g., Huang & Chuang 2011; Rahman & Sitharam 2020; Porcino et al. 2021) regardless of f_c. Most of these studies employed cyclic triaxial tests while it is well known that cyclic simple shear tests reproduces better the in-situ ground conditions during seismic loading. The purpose of the present paper is to investigate the combined effect of the void ratio, effective vertical stress, and fines content on the liquefaction resistance of sands by cyclic simple shear tests and clarify whether a *CSSM*-based approach could be used for predicting the type of undrained cyclic behavior and cyclic liquefaction resistance of sand-silt mixtures.

2. Materials, testing program and procedures

The materials used in the experimental program to prepare the soil mixtures were Ticino sand and a non-plastic silt. The host material is a uniform coarse-to-medium natural silica sand with rounded-to-subrounded grains sampled from the Ticino river. The fines are a natural non-plastic silt collected from the same site. The mixtures of Ticino sand with fines were prepared by moist-tamping with fines contents f_c=5%, 10%, 20%, 30%, and 40%, and the grain size distribution curves of each materials were presented in Fig. 1.

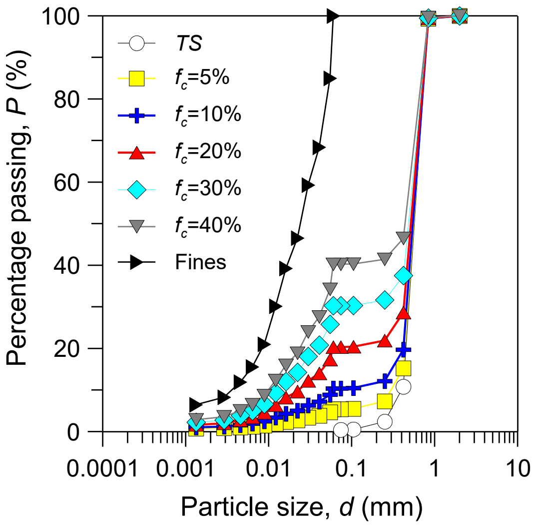


Fig 1. Grading curves of tested materials.

Testing was performed using a modified automated cyclic simple shear (*CSS*) apparatus (*NGI* type). In this type of apparatus, undrained tests are of the constant volume type. The stress path imposed by a simple shear test better represents actual soil response under vertically propagating waves. Test program comprised 78 *CSS* tests. For the purpose of describing the triggering of liquefaction, a criterion of 3.75% shear strain (in single amplitude) was adopted.

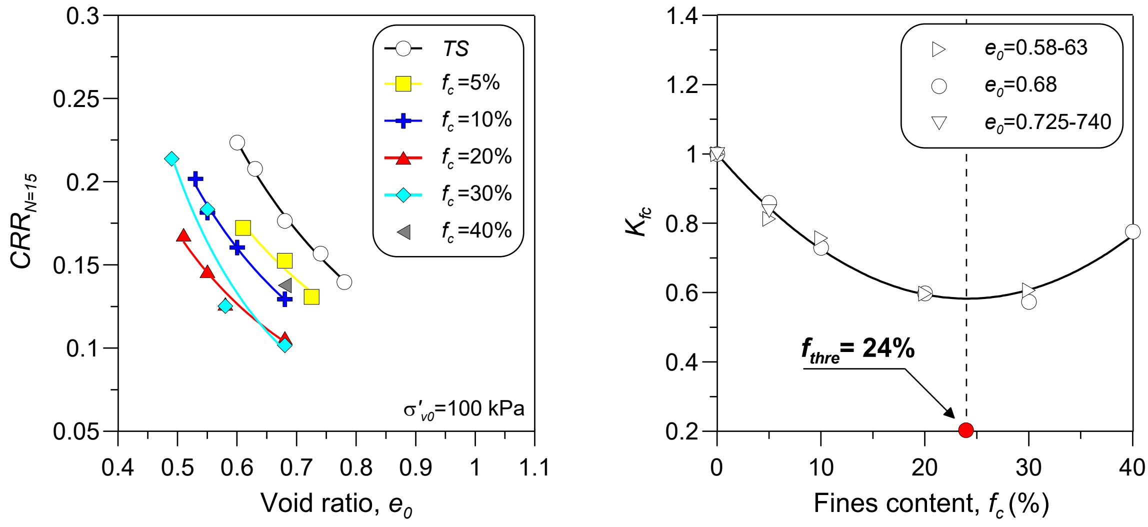
3. Test results

3.1 Effect of Initial (Global) Void Ratio

The effect of initial (global) void ratio on the *CRR* of *TS*-fines mixtures is provided in Fig. 2(a), where the liquefaction resistance, expressed in terms of cyclic stress ratio (*CSR*) for a number of cycles to liquefaction (N_f) equal to 15 ($CRR_{N=15}$), is depicted against the initial (global) void ratio (e_0). The $CRR_{N=15}$-e_0 trend curves shift downwards with increasing f_c up to f_{thre}, while a reincrease is observed at larger fines content. The f_{thre} is the specific value of the fines content at which the behavioral properties of the mixture are reversed (Mohammadi & Qadimi 2015). In Fig. 2(b) are reported the results of Fig. 2(a) in terms of the scaling factor of fines ($K_{fc}=CRR_{fc\neq0}/CRR_{fc=0}$, at the same initial state) (Bouckovalas et al. 2003), with the aim to identify a specific value of the f_{thre} for *TS*-fines mixtures. The values of K_{fc} are found to decrease with f_c up to a minimum value around 24%; at higher fines contents, the trend is reversed and, for this reason, a value of f_{thre} equal to 24% was assessed.

3.2 Effect of Initial Effective Vertical Stress

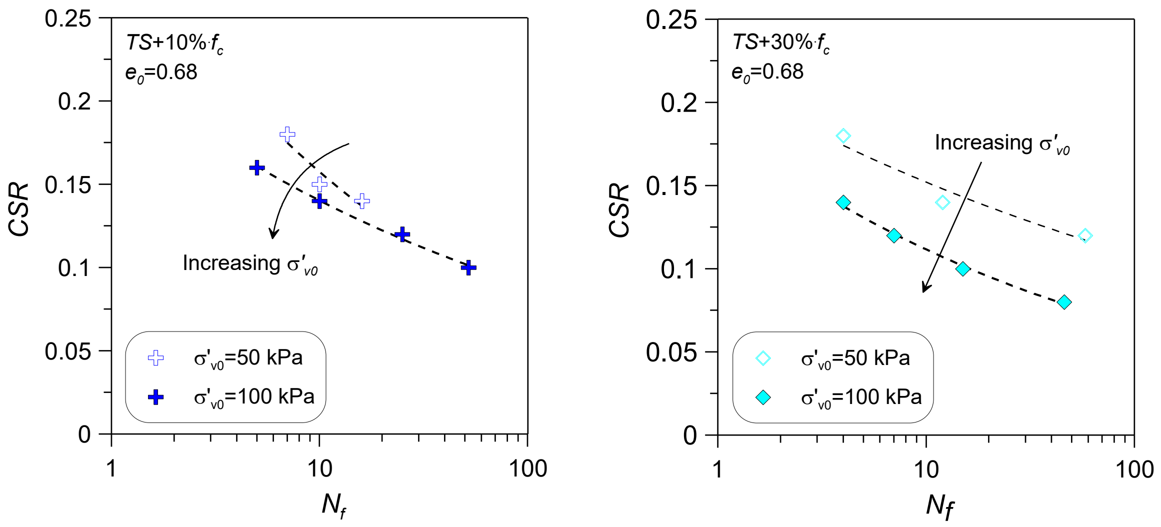
In the context of the critical state theory, the combination of stress level (p') and density state, not density state alone, determines the soil behavior. Figs. 4(a and b) show the curves of cyclic liquefaction resistance *CRR* versus N_f for *TS* with 10% and 30% fines contents, respectively. Specimens were prepared at the same void ratio e_0=0.68. Consistently with previous studies (e.g., Stamatopoulos 2010; Baziar et al. 2011; Montgomery et al. 2014), the undrained cyclic resistance decreased with an increase in σ'_{v0}.



(a) *(b)*

Fig 2. (a) Effect of non-plastic fines on cyclic liquefaction resistance; and (b) scaling factor of cyclic liquefaction resistance K_{fc} at constant initial vertical stress (σ'_{v0}=100 kPa).

The differences are more pronounced for f_c=30%, thereby suggesting that the effect of σ'_{v0} can additionally depend on f_c (Stamatopoulos 2010).

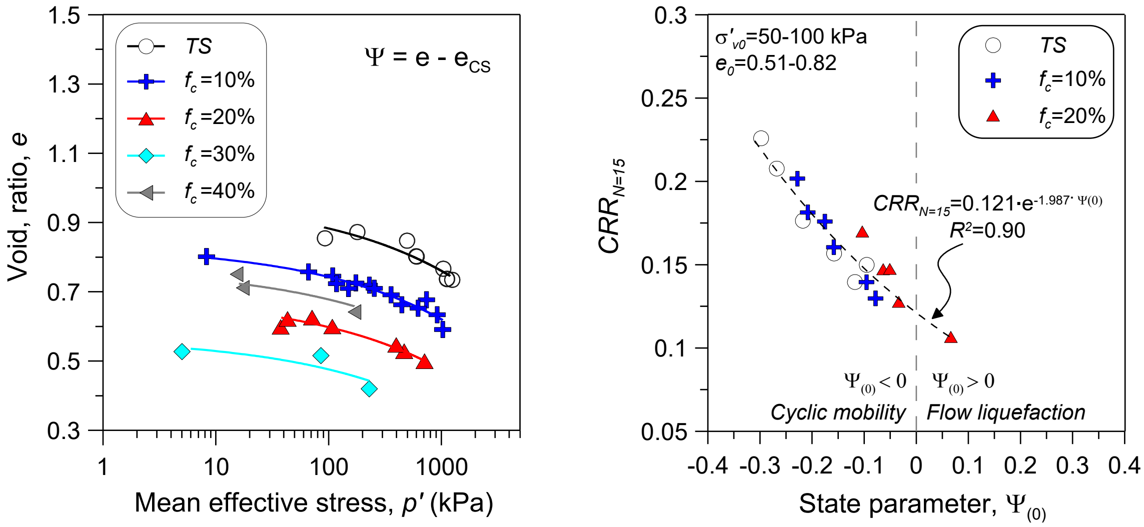


(a) *(b)*

Fig 3. Influence of initial vertical effective stress on cyclic liquefaction resistance for TS with two different percentages of non-plastic fines: (a) f_c=10 %; and (b) f_c=30 %.

3.3 Critical state-based interpretation

The results gathered from the present study and previous investigations in the literature indicate that the undrained cyclic strength *CRR* of a silty sand is a function of several factors, including the void ratio, vertical effective vertical stress, and fines content. Nevertheless, the characterization of the effects of these parameters on *CRR* is not straightforward because the impact of a certain factor can be affected by the other ones. *CSSM* framework can be useful to overcome this issue: the critical state lines (*CSLs*) have been used in the present study to predict the behavior of silty sands under undrained cyclic loading. The effect of fines content on the location of the critical state line (*CSL*) for *TS*-fines mixtures was firstly investigated by undrained monotonic triaxial compression tests. *CSL* data were extracted from Porcino et al. (2019) where the test procedures and results are described in detail. Fig. 4(a) presents the critical state lines (*CSLs*) for each *TS*-fines mixture in the *e-p'* plane. As evident in Fig. 4(a), the common shape *CSLs* are shifted downwards with increasing f_c up to f_c=30%, after which the trend is reversed, and the *CSL* moves upwards again at higher fines contents. The observed tendency in undrained monotonic tests is consistent with that observed from the K_{fc}-f_c relationship from *CSS* tests.



(a) *(b)*

Fig 4. (a) Effect of fines content on critical state lines in e-p' plane, and (b) correlation between undrained cyclic strength and state parameter Ψ_0 for TS-fines mixtures.

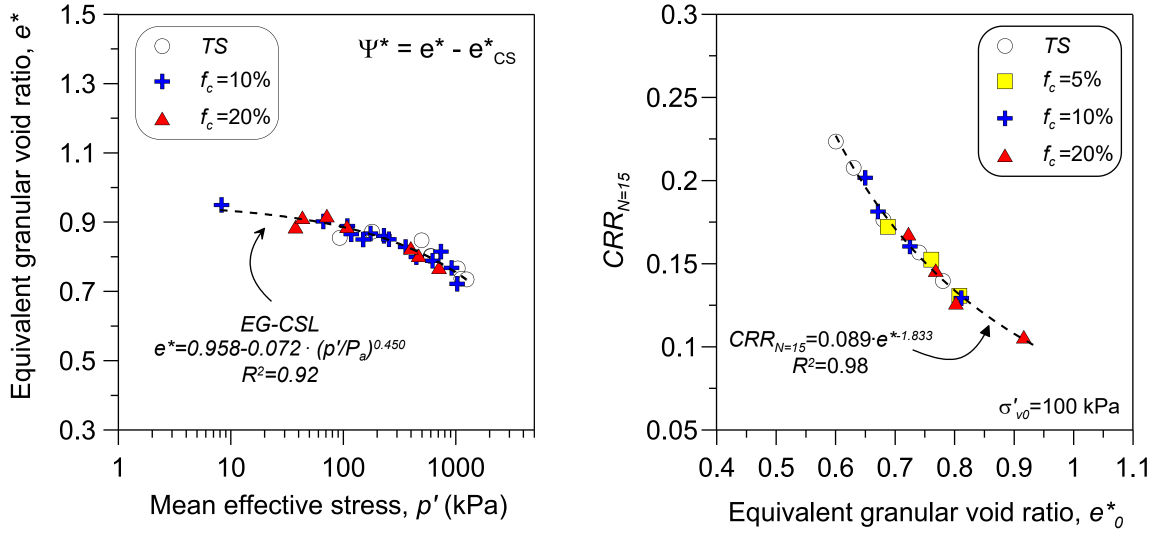
It is well known that liquefaction of clean sands under undrained cyclic loading can occur in two different forms, cyclic mobility and cyclic instability, the latter being also termed flow liquefaction. In silty sands, the type of behavior can be affected by the presence of fines. The state parameter Ψ defined by the following equation (Been & Jefferies 1985):

$$\Psi = e - e_{CS} \tag{2}$$

where e = void ratio at the current state, and e_{CS} = critical state void ratio corresponding to the current mean effective stress p', enables one to predict the expected type of behavior under cyclic loading. In fact a cyclic mobility behavior (*CM*) was observed for the samples tested when the initial state prior to cyclic shearing is below *CSL* (Ψ_0<0, Fig. 4(b)), whereas a flow liquefaction type behavior (*FL*) was observed for initial states above the *CSL* (Ψ_0>0, Fig. 4(b)). Furthermore the data points reported in Fig. 4(b) evidence clearly that a strong correlation between $CRR_{N=15}$ and Ψ_0 can be obtained, regardless of initial states and fines content.

3.4 Application of the Equivalent State Theory

The results presented in the previous sections demonstrated that the *CSL* curves are dependent on fines content. This leads unavoidably to some practical difficulties in applying the *CSSM* framework in case of sand with fines content because each fines content requires its own *CSL*. To overcome this problem, the equivalent granular void ratio e^* (Eq. 1), instead of void ratio e, is applied in the following for any f_c<f_{thre}. Data points from Fig. 4(a) are re-plotted in Fig. 5(a) in *e*-p'* plane. The biggest challenge using e^* is to get a physically and theoretically reasonable value of the fines influence factor b (Eq. 1). In the present study, the b values were determined for a given f_c by back-analysis of the *EG-CSL* data in the *e*-p'* plane assuming the *CSL* of the clean sand as a benchmark soil response curve. It is apparent that the data points are scattering around a single *CSL* relationship. This single relationship is referred to as the equivalent granular critical state line (*EG-CSL*). Therefore the drawback of requiring a separate critical state curve for each f_c can be avoided by using a unified critical state curve based on the e^*.



(a) (b)

Fig 5. (a) Unique equivalent granular critical state line for f_c<f_{thre} in e^*-p' plane; and (b) cyclic resistance ratio for N_f=15 cycles versus equivalent granular void ratio e^*.

The same procedure was applied to the experimental results reported in Fig. 2(a) to seek a unique correlation between the *CRR* and e^*, at the same vertical effective stress (σ'_{v0}=100 kPa). Fig 5(b) suggests that similar values of e^* correspond to similar *CRR* for the *TS*-silt mixtures, regardless of fines content and global void ratio. In this case, the *b* factor for *CSS* results was determined by back-analysis of the data available for each fines content by using the cyclic resistance curve for the clean sand as a reference in the *CRR*-e_0 plane. It should be noted that useful empirical relationships for predicting *b* (to be considered constant with fines content of and-silt mixtures) were also proposed in the literature (Rees 2010; Mohammadi & Qadimi 2015).

To incorporate the concept of e^* into *CSSM* framework, the state parameter, as originally proposed by Been & Jefferies (1985) in terms of void ratio *e*, is generalized to an equivalent granular state parameter, Ψ^*, defined by the expression:

$$\Psi^* = e^* - e^*_{CS} \tag{4}$$

where e^*_{CS} = corresponding e^* value at the same p' on the *EG-CSL*.

Fig. 6 shows $CRR_{N=15}$ versus Ψ^*_0 starting from the data reported in Fig. 5.

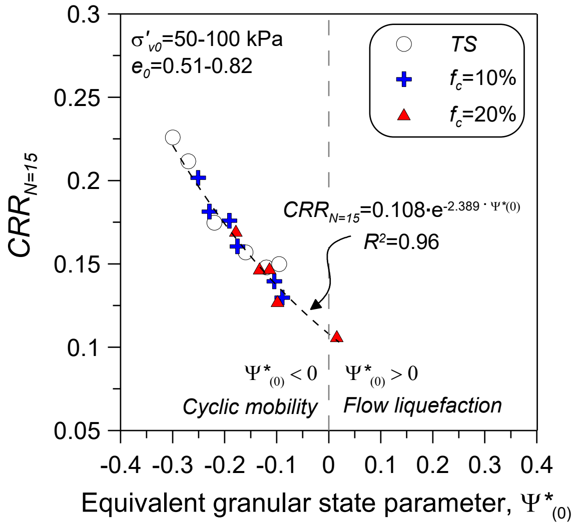


Fig 6. Correlation between CRR and equivalent granular state parameter Ψ^*_0 for TS-fines mixtures.

A clear trend between $CRR_{N=15}$ and Ψ^*_0 can be observed, which shows even less scatter of the data for the different fines contents compared to $CRR_{N=15}$-$\Psi_{(0)}$ relationship in Fig. 4(b). Furthermore, from a practical point of view, the advantage of a relationship between *CRR* and Ψ^*_0 is that it allows one to assess the undrained cyclic strength of a sand with a given non-plastic fines content on the basis of the undrained cyclic strength of the clean sand without needing to know the *CSLs* for all the mixtures.

4. Conclusions

A unified *CSSM* framework was applied to sand-silt mixtures for predicting *CRR* by undrained cyclic simple shear tests in a manner similar to clean sands. For this purpose, the capability of two different state indices, namely, the state parameter Ψ, and a modified state parameter Ψ^*, was evaluated for sand-silt mixtures with different percentages of non-plastic fines. The main conclusions which can be drawn are the following:

- The cyclic liquefaction resistance of *TS*-silt mixtures was found strongly dependent on f_c, *e* and initial vertical effective stress. In particular, at any given number of cycles to liquefaction and void ratio, the *CRR* decreased with the increase in the f_c up to a f_{thre}, which was estimated around 24% based on the experimental results, while, thereafter, the behavior reversed.
- When *CSLs* of each mixtures from undrained monotonic triaxial test results were used as reference lines to define the state parameter Ψ, a unique strong correlation (correlation coefficient R^2=0.90) between cyclic resistance of sand-silt mixtures and Ψ was derived, regardless of initial state and fines content of the mixtures. Further, the application of the *CSSM* framework was shown to be an effective tool for predicting the type of undrained cyclic simple shear behavior of sand-silt mixtures to be expected under seismic loading.
- An equivalent granular critical state line (*EG-CSL*) for all *TS*-fines mixtures was identified when equivalent granular void ratio (*e*)* concept was used in place of *e* in the *e**-log(*p'*) plane. This approach enables the behavior at the critical state of silty sands to be unified, regardless of f_c and *e*.
- When the equivalent state parameter Ψ^* was used instead of Ψ, the cyclic strength was well correlated with Ψ^* (R^2=0.96) and data points coalesced into a single trend line which was practically coincident with the trend line relative to clean sand alone providing that the *b* value is selected correctly.

Main reference

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