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Prediction of field sand cyclic resistance in terms of relative state parameter index using numerical experiments

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1 INTRODUCTION

The state-of-practice for evaluating the liquefaction resistance of soil is still the "simplified procedure" (Seed & Idriss 1971, Youd et al. 2001, Idriss & Boulanger 2008). This method evaluates two soil variables: (1) cyclic stress ratio (CSR), which represents soil seismic demands; and (2) cyclic resistance ratio (CRR), which represents the capacity of the soil to resist liquefaction. An ideal approach to evaluate CRR is to carefully retrieve and test soil samples in the laboratory. Even when using the high-cost freezing technique which is considered the best approach to minimize sample disturbance, it is still questionable whether the soil fabric has been altered during freezing and melting. The importance of calibration procedure consistency for geotechnical earthquake engineering is very relevant, and it should not be assumed that laboratory-based parameters are directly applicable to in-situ soil conditions (Cheng 2019). The CRR evaluation is, therefore, generally based on field tests. These field tests include the standard penetration test (SPT), the cone penetration test (CPT), and shear-wave velocity measurements. Using SPT as an example, liquefaction and no liquefaction cases are labeled in the plot of CRR vs $(N_1)_{60}$ (normalized blow-counts to an overburdened pressure of approximately 1 atm (≈ 100 kPa) and hammer efficiency of 60%) from case histories. The standard liquefaction triggering curve is the boundary between liquefication and non-liquefaction domains on the plot that corresponds to an average number of 15 loading cycles, which is equivalent to a magnitude 7.5 earthquake for clean (fine content less than 5%) sands (Youd et al. 2001).

In recent years, practice-oriented constitutive models consistent with this simplified procedure are increasingly appealing to engineers. These models include the UBCSand (Beaty & Byrne 2011) and PM4Sand (Boulanger & Ziotopoulou 2015) for plain-strain conditions and the recently developed P2PSand (Cheng 2018) in *FLAC3D* (Itasca 2019) for general 3D conditions.

This paper uses the P2PSand model with calibrated field sand properties compatible to the standard liquefaction triggering curve to perform numerical cyclic experiments with different initial relative densities and overburden stresses. The results of the numerical experiments are compared with those based on field data.

2 MODELING PROCEDURE

The standard cyclic resistance curve based on the "simplified procedure" does not correspond to a specific field sand but is statistically derived from many field cases. It is possible to simulate numerically a Standard Cyclic Resistance Field sand (SCRF sand) that liquefies exactly in 15 uniform cycles under direct simple shear loading with an initial overburden stress of 100 kPa. The material properties of the simulated SCRF sand should be calibrated with the following procedure:

- Undrained direct simple shear (DSS) element test simulations.
- Initial vertical stress (before cyclic loading) of $\sigma'_{v0} = 100$ kPa, with a typical stress coefficient of $K_0 = \sigma'_{h0}/\sigma'_{v0} = 0.5$ and no static shear stress.
- Applied pressure of 100 kPa on the zone top.

- 15 cycles are required to reach liquefaction when CSR is equal to a selected standard CRR, see e.g., Youd et al. (2001).
- Liquefaction occurs when the peak shear strain first reaches a 3% amplitude.

The P2PSand model has default material properties that have been internally calibrated to represent the SCRF sand using the above procedure. In the calibration, the relative density is related to $(N_1)_{60}$ using the following empirical relationship

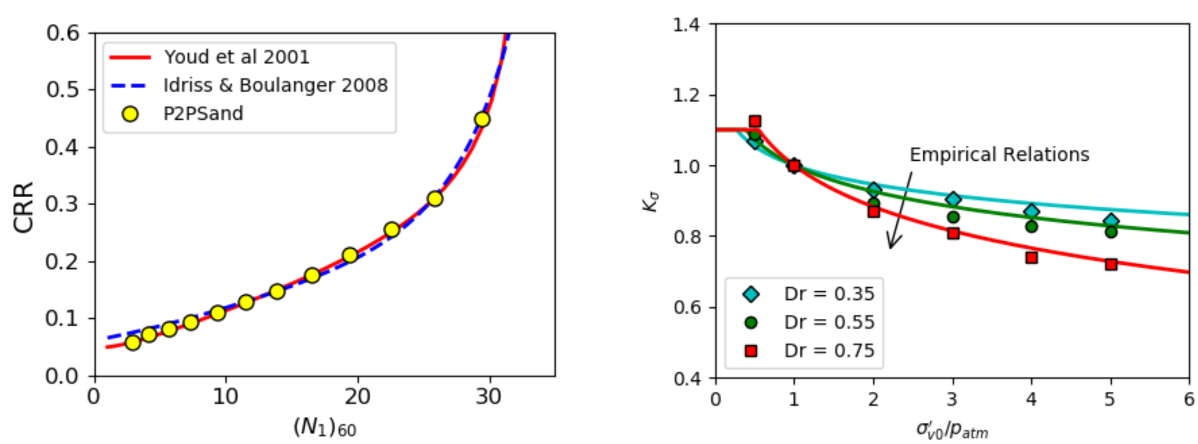
$$D_r = \sqrt{\frac{(N_1)_{60}}{46}} \tag{1}$$

The P2PSand model was exercised for different $(N_1)_{60}$ (or D_r, see Eq. 1) values and a fixed initial overburden stress at 100 kPa. The CRR numerical predictions show a very good fit with the cyclic resistance curves proposed by Youd et al. (2001) and Idriss & Boulanger (2008). The plot of CRR versus $(N_1)_{60}$ predicted by the P2PSand model is quite smooth (Fig. 1a), and the predicted CRR increases nonlinearly with $(N_1)_{60}$.

Additional numerical tests with different combinations of initial relative densities ($D_r = 35, 55, 75\%$) and initial overburden stresses (σ'_{v0}/P_{atm} = 0.5, 1.0, 2.0, 3.0, 4.0 and 5.0) were performed to test the effect of initial overburden stress (or confining stress). The factor K_σ is defined as follows:

$$K_\sigma = \frac{CRR_{\sigma'_{v0}}}{CRR_{\sigma'_{v0} = 100\,kPa}} \tag{2}$$

The $K_\sigma$values estimated from these simulations are compared to the empirical relationships proposed by Idriss & Boulanger (2008) in Figure 1b. The simulated effects of overburden stress are in good agreement. The P2PSand simulation results are consistent with the well-known finding from experimental testing that K_σ decreases with increasing overburden stresses and that the decrease is nonlinear. Also, compared to loose sands, the cyclic strengths for dense sands are more sensible to the value of overburden stress.



(a) (b)

Figure 1. (a) CRR vs $(N_1)_{60}$ simulated by P2PSand model and by empirical correlations by Youd et al. (2001) and Idriss and Boulanger (2008). (b) Predicted K_σ by P2PSand model (dots) and by empirical relation from Idriss & Boulanger 2008 (lines).

The satisfactory P2PSand model prediction of CRR vs $(N_1)_{60}$ (Fig. 1a) and of the K_σ effect (in Fig. 1b) as well as the model overall good performances show that the calibrated (default) properties correctly represent the essential cyclic characteristics of the SCRF sand. Once the material properties of SCRF sand have been correctly estimated, they can be used confidently in numerical experiments, thus overcoming the sampling disturbance arising in laboratory tests.

After analyzing extensive field data, Boulanger (2003) and Jafarian et al. (2010) have showed that CRR can be correlated with the relative state parameter index $\xi_R = D_{rc} - D_r$, where D_{rc} is relative density at critical state. The relative state parameter index ξ_R includes the combined effects of sand density and confining stress.

It seems natural to ask if the curve of CRR vs ξ_R derived from field data can also be obtained from numerical experiments with an advanced constitutive model. In tentative response to this question, the P2PSand model was exercised using a total of 30 combinations of different relative densities and confining stresses. As suspected, the numerical results, plotted in Figure 2a, show a strong correlation between CRR and ξ_R. For the range of initial relative densities and confining stresses considered in the analysis, it appears that the relationship between CRR and ξ_R can be approximated by the following power law:

$$CRR = 0.048\exp\left(-3.184\xi_R\right) \tag{3}$$

The overall fit between the numerical experiments and the simple power law given in Equation (3) is excellent, except for some discrepancy observed near $\xi_R = -0.6$, where the curve predicted numerically has a vertical asymptote.

(a)

(b)

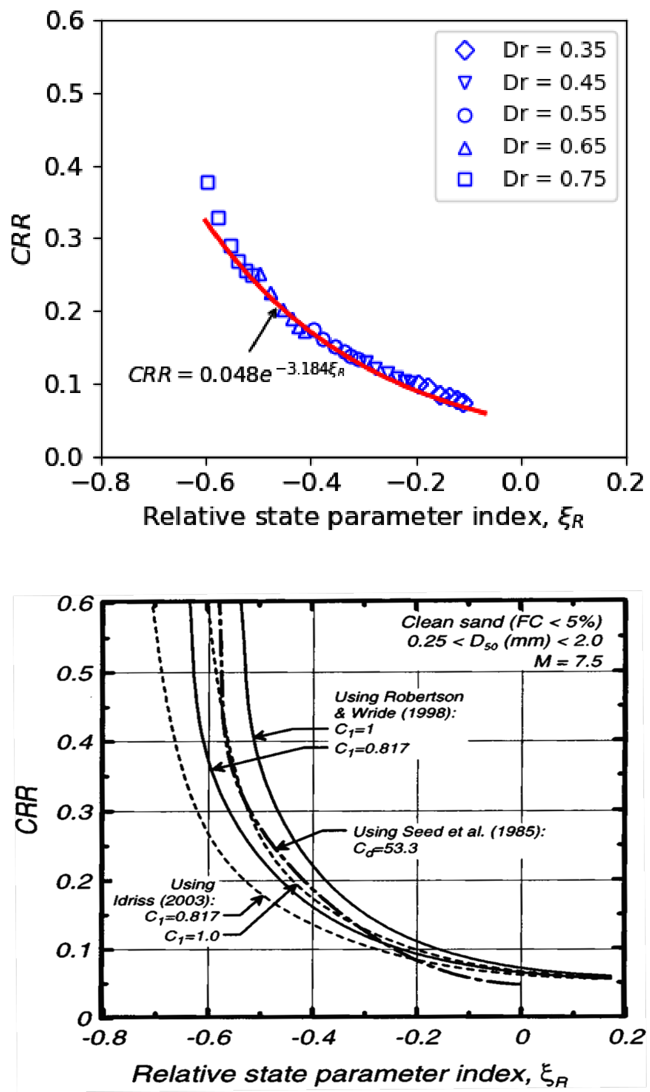


Figure 2. (a) Predicted CRR vs ξ_R from numerical experiments using P2PSand model. (b) Derived CRR vs ξ_R for field conditions (after Boulanger 2003).

The CRR vs ξ_R curve, derived for field conditions by Boulanger (2003) was plotted in Figure 2b. The similar curve predicted from numerical experiments using the P2PSand model (Fig. 1a) is in the middle of the range derived from field conditions.

3 CONCLUSIONS

This paper uses the P2PSand model with field sand properties compatible to the state-of-practice liquefaction triggering curve to perform purely numerical cyclic experiments with various combinations of initial sand densities and confining stresses. The results suggest a simple power correlation between cyclic resistance for clean field sands and relative state parameter index. The numerical experiment results are consistent with the results derived from field conditions. This comparison validates the default material properties used in the P2PSand model for the standard cyclic resistance field sand (SCRF sand).

Because the result is based on the state-of-practice liquefaction triggering relations in the simplified procedure, any limitation of this procedure also applies to the proposed relation in Equation 3 or the presented curve in Figure 1a. In particular, the applicability is limited to sites on level to gently sloping terrain underlain by sediment less than 15 meters.

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