Recent advances in pore water pressure and liquefaction characteristics of low plasticity silty sands subjected to cyclic loading

D D Porcino

Department of Civil, Energy, Environmental and Material Engineering, University Mediterranea of Reggio Calabria, Via Graziella (Feo Vito), 89124, Reggio Calabria, Italy

Email: daniela.porcino@unirc.it

Abstract. Low plasticity sand-silt mixtures are very common in Italy either in natural depositional environment or in man-made earth-fill, hence the knowledge of their behavior is a crucial aspect in many practical applications. Due to higher compressibility features, significant strains and strength loss may be triggered by earthquakes. The results of a laboratory-based investigation undertaken on undisturbed samples of low plasticity silty-sandy soils recovered from a bank stretch after the 2012 Emilia Romagna earthquake in Italy, when serious damages and widespread liquefaction events were observed, are herein presented. Special emphasis was given to susceptibility to liquefaction and pore water pressure response in presence of an initial static shear stress. As part of the present work, the results of undrained cyclic simple shear (CSS) tests carried out on reconstituted specimens of sand-fines mixtures, covering a range of non-plastic fines contents from 0% to 40%, were used for predicting undrained cyclic resistance through the concept of equivalent granular void ratio, $e^*$. The conceptual framework based on $e^*$ appears appropriate for streamlining the effect of fines on cyclic liquefaction resistance of these intermediate soils, provided that fines content is less than a limiting value. Since an important stage in the assessment of liquefaction potential is to predict excess pore water pressure during cyclic loading, the results of CSS tests were also utilized for analysing pore water pressure generation models of silty sands over a wide range of fines contents.

1. Introduction

Many case histories of liquefaction and other problems induced by seismic loading have been involved sand deposits containing various amounts of fines, such as alluvial deposits, hydraulic fills, tailings dams. Recent evidence of ground failures in low-plasticity fine-grained soils during recent earthquakes [1-4] has emphasized that considerable additional research work is needed to fully understand the undrained response to cyclic loading of these “non-text book” soils, which have features intermediate to those of clean sands and pure clays [5]. There are some issues related to the characterization and modeling of silty (intermediate) sands in engineering practice, such as [5-6]: 1) both the amount and the nature (i.e. plastic or non plastic) of fines needs to be accounted for; 2) appropriate selection of density state variables for a logical, consistent treatment of liquefaction; 3) microstructure may significantly affect their mechanical response; 4) intermediate values of hydraulic conductivity may lead to partial drainage; 5) recovery of high quality undisturbed samples is often difficult with...
reasonable costs. It has been recognized that the “threshold or limiting” fines content ($LFC$) is a key parameter representing the maximum amount of silt that can be contained in the void space while maintaining a contiguous sand skeleton (“sand-dominated” behavior) [7-8], implying that the smaller particles may have a secondary role in the force structure [9].

In this context, the author conducted a comprehensive research on undrained response of low plasticity and non plastic silty sands under both monotonic and cyclic loading [10-14]. This paper focuses on the key features of their response under cyclic loading through: 1) A case study involving low plasticity silty sandy soils during the May 2012 earthquake in Italy. 2) Application of the equivalent granular void ratio-based approach for predicting cyclic liquefaction resistance of sand-silt mixtures under simple shear loading. 3) Prediction of seismic pore water pressure generation for silty sands over a wide range of fines (in a range 0%-70%).

2. Evaluating cyclic liquefaction response of low plasticity silty sands during the 2012 earthquake in Italy: the role of initial static shear stress

The performance of low plasticity silty sandy soils after the 2012 Emilia Romagna earthquake sequence ($M_w$=6.1) in Italy offered the opportunity for understanding their susceptibility to liquefaction and their response to cyclic loading. In particular, the case study concerns a river bank which was seriously damaged by the seismic sequence, so that a comprehensive in-situ and laboratory test program [3, 14] was undertaken to identify possible damage causes and effective remedial countermeasures. A typical cross-section of the bank is reported in figure 1.

Undisturbed samples of silty sandy soils were recovered up to 10 m in depth by Osterberg sampler at site in correspondence of the upper soil layer of the bank. This layer includes two sublayers labeled as Unit $R$ and $B$ in figure 1. Layer $B$ overlies a thin layer of clayey material (Layer $C$). All of these soils are founded on a base Unit ($\approx 40$ m thick) consisting of medium-coarse clean sands of the so-called “Padana Aquifer” (Unit $A$). The fines contents ($FC$) of the tested samples were in the range 40% to 70%. A first step was to apply and verify the most relevant criteria introduced in the literature based on index properties of soils (i.e. plasticity index, $PI$; liquid limit, $LL$; water content, $w_c$, etc.) for assessing liquefaction susceptibility of the silty soils. Since fine-grained soils of Units $R$ and $B$ met the conditions $PI<12$, $w_c/LL>0.85$ and $LL<37$, they were considered potentially liquefiable according to Seed et al. [15] and Bray and Sancio [16]. Further, for the samples of layer $B$ ($PI<8$), it is very likely they exhibit a “sand-like” behavior or eventually an “intermediate” behavior (between “sand-like” and “clay-like”) for which specific laboratory tests are required [17]. With the aim of clarifying the role of an initial static shear stress deriving from sloping ground of the bank before earthquake, a finite element code (PLAXIS, 8.2 [18]) was used to evaluate the initial stress conditions within the embankment, and the results obtained are shown in figure 1 in terms of shadings of shear stress ($\tau_{stat}$).

![Figure 1](image_url)
The preshearing constant $\alpha = \tau_{stat}/\sigma_{v0}'$, where $\sigma_{v0}'$ is the initial vertical effective stress, resulted in an average value close to 0.1 near the crest of the slope (section a-a' in figure 1). Further, a seismic response analysis was conducted by using a linear elastic equivalent approach by QUAD4M 2D code [19]. The maximum shear stresses gathered from the analysis were then used for the liquefaction susceptibility assessment of the silty soils. Undrained cyclic tests were performed by using a modified Norwegian Geotechnical Institute (NGI) simple shear apparatus capable of applying both stress and strain-controlled conditions. More details regarding the tested materials, apparatus and test procedure are described in Porcino and Diano [10]. Both symmetrical ($\tau_{stat} = 0$) and non-symmetrical ($\tau_{stat} \neq 0$) cyclic simple shear tests were performed at different values of cyclic stress ratios ($CSR = \tau_{cyc}/\sigma_{v0}'$) on silty sands and some typical results are depicted in figure 2. In non-symmetrical CSS tests ($\alpha=0.1$) (figure 2b) the sample experienced reversed shear stress loading conditions and “cyclic ratcheting” with a progressive accumulation of shear strains in the directions of the driving shear force. The development of 3.75% single-amplitude shear strain ($\gamma_{SA}$) was assumed as a yardstick to recognize a state of cyclically induced liquefaction for all CSS tests presented in this paper. It is apparent that the generation of excess pore pressure and shear strains during undrained cyclic loading of the silty samples are significantly affected by the presence of an initial static shear stress.

The undrained cyclic simple shear strength $CRR_{SS,\sigma=0}$ of the silty soils was evaluated from liquefaction curves shown in figure 3a while figure 3b reports the adjustment factor for the effects of static shear stresses on CRR (i.e. $K_{\alpha}$) [20] versus number of cycles to failure ($N_f$). $K_{\alpha}$ parameter was drawn upon the results of CSS tests considering the expression: $K_{\alpha} = CRR_{\alpha,0}/CRR_{\sigma=0}$.

![Figure 2](image_url)  
*Figure 2.* Typical effective stress paths and stress-strain relationships from (a) symmetrical and (b) nonsymmetrical undrained CSS tests of low plasticity silty samples ($FC=70\%, \sigma_{v0}'=100$ kPa, $CSR=0.21$).
Figure 3. Liquefaction resistance curves of low plasticity silty samples obtained from CSS tests ($\alpha=0$) (a) and $K_\alpha$ correction factor of the cyclic resistance ratio for the effect of sloping ground conditions ($\alpha=0.1$) (b).

For $N_f=6-1/4$ which is relevant for the considered case study, $K$ values for the silty soils are less than 1 (ranging from 0.81 to 0.93) (figure 3b), implying a negative effect of the initial static shear stress on undrained cyclic resistance. Using these values of $K_\alpha$, the factor of safety against liquefaction ($FS$) for sloping ground conditions, expressed as the ratio between cyclic resistance ratio of soil ($CRR_{\alpha>0}$) and cyclic stress ratio ($CSR$) induced by the earthquake, was calculated through the expression:

$$FS = \frac{CRR_{\text{field,} \alpha>0}}{CSR} = \frac{CRR_{SS, \alpha=0} \cdot K_\alpha \cdot r_c}{CSR}$$

where only a correction factor $r_c$, ranging between 0.90 and 1.00, was applied to $CRR_{SS}$ to account for the effect of multidirectional loading which occurs during a seismic event [21].

The values of CSR induced by the earthquake along the vertical axes a-a' have been calculated through the expression proposed by Seed and Idriss [22] providing values from 0.183 to 0.192. Finally, the analyses based on appropriate laboratory undrained CSS testing revealed values of $FS\leq1$ and, consequently, the occurrence of liquefaction in correspondence to the silty layers of Unit B.

3. Equivalent-granular void ratio based approach for predicting undrained cyclic simple shear resistance of sand with non plastic fines

Selecting appropriate density state variables for comparison and analyses of low plasticity silty soils is a relevant issue in geotechnical engineering and it is a matter of discussion until now. An extensive laboratory investigation based on undrained cyclic simple shear tests was carried out on reconstituted specimens of mixtures of Ticino clean sand ($TS$) with different amounts of non plastic fines below a threshold (or limiting) value. Such limiting $FC$ value was pinpointed to be 30% based on the analysis of the experimental CSS data [11]. The diameter ratio ($D_{10}/d_{50}$) of the host coarse sand grains to that of the fine grains was equal to 17. All specimens were prepared by moist tamping method at different (post-consolidation) global void ratios ($\varepsilon$) and consolidated at different effective vertical stresses. Figure 4a presents selected CSS tests at a constant $\sigma'_{vo}=100$ kPa. The concept of equivalent granular void ratio ($e^*$) was herein introduced as an alternative parameter to $\varepsilon$ for streamlining the effect of fines on undrained cyclic strength of silty sands and unifying their cyclic strength response. It should be noted that the available studies reported in the literature on this approach have mostly been conducted by cyclic triaxial apparatus; nevertheless, the loading condition in the CSS apparatus is considered more representative of field conditions. The parameter $e^*$ was defined as [7]:
where \( b \) represents the fraction of the active fine particles in a mixture system (i.e. participating to the force structure of the solid skeleton). The values of \( b \), depending on both fines content and grading characteristics of the mixture, was carefully assessed for a given mixture (equation (2)) by a back-analysis procedure based on trial and error calculation, using the clean sand cyclic resistance curve as a benchmark response in CRR-\( e \) plane. It was found \( b \) ranging between 0 (clean sands) and 0.496 (sand with 30\% FC). The CRR producing a 3.75\% single amplitude shear strain in 15 uniform loading cycles was plotted against \( e \) (figure 4a) and \( e^* \) (figure 4b) for different fines contents. The main findings which can be drawn are: 1) for specimens with the same \( e \), CRR decreases with FC indicating a more contractive behavior under undrained cyclic loading; 2) a unified \( e^* \) based CRR line referred to as EG-CRRL (\( R^2=0.93 \)) was obtained for the five types of fines and it was close to that of the clean sand for which \( e=e^* \); 3) from a practical point of view, the advantage of using a single linear CRR-\( e^* \) correlation is that CRR may be predicted for every fines content by performing a limited number of tests on a given mixture or using the clean sand data.

The \( e^* \)-based approach was applied successively also for interpreting the undrained response of these silty sands under monotonic loadings in the context of the theoretical critical state soil mechanics (CSSM) framework [13].

4. An insight into the prediction of seismic pore water pressure of low plasticity silty sands over a wide range of fines

A soil may or may not liquefy, but the amount of excess pore water pressure (PWP) generation during cyclic loading considerably affects its strength and stiffness (for example in post-seismic stability of dams, slopes, dikes). The pore pressure generation in silty soils is dependent on the deformational characteristics of silty sands which are quite different from those of clean sands.

To clarify the effect of non plastic/low plasticity fines among the parameters (i.e. cyclic stress ratio, relative density, initial effective vertical stress and static shear stress, fabric) influencing cyclically-induced PWP of silty soils [12], test results are herein presented for soils over a wide range of fines contents namely FC\( \leq35\% \) (figure 5) and FC\( >35\% \) (figure 6) through stress-controlled undrained CSS tests.
Figure 5. Residual pore water pressure build-up for Ticino sand-fines mixtures (\(FC\leq 35\%\)) and comparison with upper and lower bounds proposed for clean sands.

Following the two methods generally adopted in the literature to analyze PWP response, figure 5a presents the PWP build-up against cycle ratio (i.e. the ratio of cycles of loading to the cycles required to cause liquefaction) while figure 5b in terms of strains required to generate them, as suggested by Dobry et al. [23]. Excess pore water pressure ratio \((R_u)\) is defined as the excess of pore water pressure \((\Delta u)\) to the initial effective vertical stress \((\sigma'_v)\). For comparison purposes, the upper and lower bound curves suggested in the literature by Seed et al. [24] for clean sands are also superimposed.

When a global void ratio-based approach is used for the analysis, the following key features for silty sands with \(FC\leq 35\%\) (figure 5a) were observed: 1) the specimens experienced zero, or near zero, vertical effective stress conditions during cyclic loading; 2) the higher fines content soils are more contractive, causing a faster rate of excess PWP generation; 3) the shape of Seed’s model [24] for clean sands agrees well with experimental data but only data points for \(FC\leq 20\%\) fall inside the band suggested for clean sands (0.6≤\(\beta\)≤1) (see figure 5a) while for higher \(FC\) values a proposed expansion of the upper bound is necessary (i.e. \(\beta=1.50\) for the tested soils).

Figure 6. Residual pore water pressure versus normalized number of cycles for undisturbed samples of low plasticity silty sands (40\%≤\(FC\)≤70\%) and prediction of the PWP generation model (equation 4).
The clear dependence of the calibration parameter $\beta$ of Seed’s model [24] on fines content (FC) can be expressed through the expression:

$$\beta = c_1 \cdot FC + c_2 \cdot D_r + c_3 \cdot CSR + c_4$$

(3)

where fines content (FC) and relative density ($D_r$) are expressed as a percentage, CSR is the cyclic stress ratio imposed in CSS loading, and $c_1$, $c_2$, $c_3$, and $c_4$ are regression constants (dimensionless). The regression coefficients for Ticino sand with silt mixtures ($FC<35\%$, $D_r<65\%$, $N_r>4$) resulted: $c_1=0.027$, $c_2=0.00012$, $c_3=6.25$, $c_4=-0.627$ (correlation coefficient $R^2=0.65$). When the results obtained for the tested mixtures at various values of void ratio and CSR are compared with the upper and lower boundary curves for clean sands proposed by Dobry [25] from strain-controlled tests (figure 5b), it may be identified a relatively narrow band with a tendency of data points to fall to the right of the lower Dobry’s curve [25] for clean sands. This comparison should take into account also possible differences between the two test types (i.e. strain and stress-controlled tests), actually.

The key features inferred from the interpretation of PWP measurements for undisturbed samples of low plasticity silty sandy soils from Emilia Romagna (Italy) ($FC>35\%$ in CSS tests (figure 6), were the following: 1) samples with $FC>35\%$ experienced a cumulative increase in PWP’s during cyclic loading with values of residual $R_u$ generally less than 0.95 (in the range 0.88-0.94 for the tested soils); 2) a different pattern of PWP response was observed compared to sands with $FC<35\%$ so that the model proposed by Seed et al. [24] is not appropriate. A new simple relationship was suggested for predicting PWP build-up in a more reliable way by the expression (figures 6a and 6b):

$$R_u = a \cdot \left(\frac{N}{N_f}\right)^b$$

(4)

where $a$ and $b$ are two empirical parameters controlling the shape of the curve. It was also verified that the proposed model reflects well the development law of the pore water pressure of clean sands and silty sands when the initial shear stress exists. A successful application of the proposed relationship for predicting seismic PWP generation is reported in Porcino et al. [12] through the use of “damage” concept to provide a simple link between laboratory and field.

5. Conclusions

- The liquefaction analysis for the investigated case-study concerning a damaged bank after the 2012 Emilia Romagna earthquake in Italy evidenced the negative role exerted by initial static shear stress on seismic (cyclic) liquefaction of low plasticity silty sandy soils ($FC=40\%-70\%$), with factors of safety against liquefaction based on laboratory cyclic simple shear tests less than unity, supporting the post-earthquakes field observations.
- The use of $e^*$ is effective in capturing the role of fines contents of Ticino sand-silt mixtures and a single unified $CRR-e^*$ correlation would apply to a wide range of fines up to 30%.
- Marked differences are expected to be in undrained cyclic pore pressure generation characteristics of low plasticity silty soils when fines content is less or greater than 35%. This aspect requires careful consideration in adopting suitable PWP generation models for practical applications.

References

[1] Rees S D 2010 Effects of fines on the undrained behaviour of Christchurch sandy soils PhD thesis (New Zeland: University of Canterbury)
[2] Lee W F, Ishihara K and Chen C-C 2012 Liquefaction of silty sand-preliminary studies from recent Taiwan, New Zealand and Japan earthquakes Proc. Int. Symp. Eng. Lessons learned from the 2011 Great East Japan Earthquake (Tokyo) pp 747-58
[3] Tonni L et al. 2015 Interpreting the deformation phenomena triggered by the 2012 Emilia seismic sequence on the Canale Diversivo di Burana banks Ital. Geotech. J. 45 28-58
[4] Sharma K, Deng L and Khadka D 2019 Reconnaissance of liquefaction case studies in 2015...
Gorkha (Nepal) earthquake and assessment of liquefaction susceptibility Int. J. Geotech. Eng. 13 326-38
[5] Carraro J A H and Salgado R 2004 Mechanical behavior of non-textbook soils Final Report FHWA/IN/JTRP-2004/5 (Indiana: Pardue University)
[6] Huang A B 2016 The seventh James K. Mitchell lecture: characterization of silt/sand soils Geotechnical and Geophysical Site Characterisation 5 ed Lehane et al. (Sydney: 2016 Australian Geomechanics Society) pp 3-18
[7] Thevanayagam S, Shenthan T, Mohan S and Liang J 2002 Undrained fragility of clean sands, silty sands, and sandy silts J. Geotech. Geoenviron. Eng. 128 849-59
[8] Yang S, Lacasse S and Sandven R 2006 Determination of the transitional fines content of mixtures of sand and non-plastic fines Geotech. Testing J. 29 1-6
[9] Rahman M M and Lo S R 2008 The prediction of equivalent granular steady state line of loose sand with fines Geomechanics and Geoengineering: An International Journal 3 179-90
[10] Porcino D and Diano V 2016 Laboratory study on pore pressure generation and liquefaction of low-plasticity silty sandy soils during the 2012 earthquake in Italy J. Geotech. Geoenviron. Eng. 142 1-10
[11] Porcino D D and Diano V 2017 The influence of non-plastic fines on pore water pressure generation and undrained shear strength of sand-silt mixtures Soil Dyn. Earthquake Eng. 101 311-21
[12] Porcino D D, Tomasello G and Diano V 2018 Key factors affecting prediction of seismic pore water pressures in silty sands based on damage parameter B. Earthq. Eng. 16 5801-19
[13] Porcino D D, Diano V, Triantafyllidis T and Wichtmann T 2019 Predicting undrained static response of sand with non-plastic fines in terms of equivalent granular state parameter Acta Geotech. 2019 1-16
[14] Porcino D D, Monaco P and Tonni L 2019 Evaluating seismic behavior of intermediate silty sands of low plasticity from Emilia Romagna, Italy Geo-Congress 2019 GSP 308 (ASCE) pp 341-351
[15] Seed R B et al. 2003 Recent advances in soil liquefaction engineering: a unified and consistent framework Reporto No. EERC-2003-06 (Berkley: Earthquake Eng. Research Center)
[16] Bray J D and Sancio R B 2006 Assessment of the liquefaction susceptibility of fine-grained soils J. Geotech. Geoenviron. Eng. 132 1165-77
[17] Boulanger R W and Idriss I M 2006 Liquefaction susceptibility criteria for silts and clays J. Geotech. Geoenviron. Eng. 132 1413-26
[18] Brinkgreve R B J and Vermeer P A 2002 PLAXIS -finite element code for soil and rock analysis (Rotterdam)
[19] Hudson M, Idriss I M and Beikae M 1994 User’s manual for QUAD4M - A computer program to evaluate the seismic response of soil structures using finite element procedures and incorporating a compliant base Center for Geotech. Modeling Department of Civil and Env. Eng. (Davis: University of California)
[20] Seed H B 1983 Earthquake resistant design of earth dams Proc. Symp. on Seismic Design of Embankments and Caverns (Reston: ASCE) pp 41-64
[21] Seed H B, Martin G R and Pyke R M 1978 Effect of multidirectional shaking on pore pressure development in sands J. Geotech. Eng. Div. 104 27-44
[22] Seed H B and Idriss I M 1971 Simplified procedure for evaluating soil liquefaction potential J. Soil. Mech. Found. Div. 97 1249-73
[23] Dobry R, Ladd R S, Yokel F Y, Chung R M and Powell 1982 Prediction of pore-water pressure buildup and liquefaction of sands during earthquakes by the cyclic strain method Building Science Series 138 (Washington D C: National Bureau of Standards)
[24] Seed H B, Martin P P and Lysmer J 1975 The generation and dissipation of pore-water pressures during soil liquefaction Geotech. Rep. no. EERC 75-26 (Berkeley)
[25] Dobry R 1985 Liquefaction of soils during earthquakes Rep. no. CETS-EE-001 (Washington)