Prediction of earthquake-induced liquefaction for level and gently sloped ground

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ABSTRACT

This paper presents a simplified procedure for predicting earthquake-induced level and sloped ground failure, namely liquefaction and shear failure. It consists of a framework where cyclic stress ratio (CSR), static stress ratio (SSR) and undrained shear strength (USS) are formulated considering simple shear conditions, which simulate field stress during earthquakes more realistically. The occurrence or not of ground failure is assessed by means of a plot η_{max} (= [SSR+CSR]/USS) vs. η_{min} (= [SSR-CSR]/USS), where a liquefaction zone, a shear failure zone and a safe zone (i.e. no-liquefaction and no-failure) are defined. Using this procedure, a soil column was examined and failure assessment was obtained for various soil elements, located at different depths beneath ground level. A total of 6 cases were generated by considering 2 slope inclination levels (i.e. i=0% and 5%) and 3 relative density states (i.e. D_r=25%, 50% and 75%). The 2012 Emilia Earthquake (M_w=5.9 and a_{max}=0.26g), that produced an extensive liquefaction scenario in Northern Italy, was used as seismic input. For the case study examined, the prediction confirmed that soil was likely to experience severe liquefaction, except for the case of dense sand in level ground conditions. In addition, it clearly appears that gentle sloped conditions significantly decrease the resistance of soil against liquefaction. Based on past case histories, such a prediction is rational and, thus, the proposed procedure may represent a useful tool to assess earthquake-induced failure mechanisms for both level and sloped ground.

1 INTRODUCTION

Liquefaction of level and sloped ground is a major natural phenomenon of geotechnical significance associated with damage during earthquakes. In the last few decades, in most seismic events with a magnitude greater than 6.5-7 which usually produce also very strong ground acceleration (PGA > 0.15g), the extensive damage to infrastructures, buildings and lifeline facilities have been associated with the occurrence of lateral spreading and/or flow (i.e. ground failure) of liquefied soils. Prediction of ground failure involving earthquake-induced liquefaction of sandy sloped deposits is vital for researchers and practising engineers to understand comprehensively the triggering conditions and consequences of liquefaction, and to develop effective countermeasures against liquefaction.

Aimed at investigating the role which static shear stress (i.e. slope ground conditions) plays on the liquefaction behaviour and large deformation properties of saturated sand, Chiaro et al. (2012) performed a series of undrained cyclic torsional simple shear tests on loose fully-saturated Toyoura sand specimens (Dr = 44-50%) under various combinations of static and cyclic shear stresses. From the study of failure mechanisms, three types of failure (i.e. cyclic liquefaction, rapid flow liquefaction and shear failure) were identified based on the difference in effective stress paths and the modes of development of shear strain during both monotonic and cyclic undrained loadings. The study confirmed that to achieve full liquefaction state the reversal of shear stress during cyclic loading is essential. Alternatively, when the shear stress is not reversed, large shear deformation may bring sand to failure although liquefaction does not take place. Following these findings, Chiaro and Koseki (2010) developed a graphic method able to predict the failure behaviour of Toyoura sand specimens as observed in the laboratory. Later, in order to establish a framework to directly compare field and laboratory liquefaction behaviours of sand, Chiaro and Koseki (2012) presented a simplified procedure for predicting earthquake-induced sloped ground failure, namely liquefaction and shear failure.

In this paper, the proposed simplified procedure is described in detail and its performance is assessed for the case of the 2012 Emilia Earthquake (M_w=5.9 and a_{max}=0.26g) by considering a soil profile consisting of uniform clean sand and varying systematically the key factors that govern soil shear behaviour such as soils density and slope ground inclinations.

2 PROPOSED SIMPLIFIED PROCEDURE FOR SEISMIC SLOPE FAILURE ANALYSIS

The proposed simplified procedure for seismic sloped ground failure analysis consists of a framework where cyclic stress ratio (CSR), static stress ratio (SSR) and undrained shear strength (USS) are formulated considering simple shear conditions, which simulate field stress during earthquakes more realistically. Hereafter, procedure details are described.

The earthquake–induced CSR at a depth z below the ground (Figure 1) is formulated by adjusting the well-known Seed and Idriss (1971) simplified procedure for evaluating the CSR to the case of simple shear conditions. Therefore, by converting the typical irregular earthquake record to an equivalent series of uniform stress cycles (Seed and Idriss, 1975), considering the flexibility of the soil column throughout a stress reduction coefficient (Iwasaki et al., 1978) and introducing a magnitude scaling factor (MSF; Idriss and Boulanger, 2004), the following expression can be derived (Chiaro, 2010). Note that, values of the unit weight of soils below and above the ground water table have been assumed to derive CSR.

$$\mathrm{CSR}_{7.5} = \frac{\tau_{\mathrm{cyclic}}}{p_0'} = \frac{0.65\,(a_{7.5}/a_{\mathrm{g}})\,r_{\mathrm{d}}}{[(1+2\,K_0)/3]\,[1-0.5\,(z_{\mathrm{w}}/z)]} \tag{1}$$

$$a_{7.5} = a_{\max}/\,\mathrm{MSF} \tag{2}$$

$$\mathrm{MSF} = [6.9\ \exp(-\mathrm{M_w}/4) - 0.058] \le 1.8 \tag{3}$$

$$r_{\mathrm{d}} = (1 - 0.015\,z) \tag{4}$$

where a_{max} (g) is the peak ground (horizontal) acceleration; a_g is the gravity acceleration (=1 g); $a_{7.5}$ (g) is the effective peak ground acceleration; M_w is the moment magnitude of the earthquake; K_0 is the coefficient of earth pressure at rest; and z (metres) is the depth below the ground surface. It should be noted that the stress reduction coefficient (r_d) is a unit-less factor. MSF is a factor for adjusting the earthquake-induced CSR to a reference M_w = 7.5, provided that such an earthquake induces 15 equivalent stress cycles of uniform amplitude.

Assuming infinite slope state and simple shear conditions, the SSR induced by gravity on a soil element of sloped ground, at a depth z underneath the ground surface and a depth z_w beneath the water table, can be calculated as follows (Chiaro, 2010):

$$\mathrm{SSR} = \frac{\tau_{\mathrm{static}}}{p_0'} = \frac{\tan\beta}{[(1+2\,K_0)/3]\,[1-0.5\,(z_{\mathrm{w}}/z)]} = \frac{i/100}{[(1+2\,K_0)/3]\,[1-0.5\,(z_{\mathrm{w}}/z)]} \tag{5}$$

where i is the gradient of slope (%).

Finally, combining laboratory test results on Toyoura sand (clean sand) and simulation results using a newly developed model for liquefiable sand (Chiaro et al., 2013b); an empirical formulation for USS is proposed:

$$\mathrm{USS} = 0.1015 + 0.0046\, D_r + 0.180\, \mathrm{SSR} \tag{6}$$

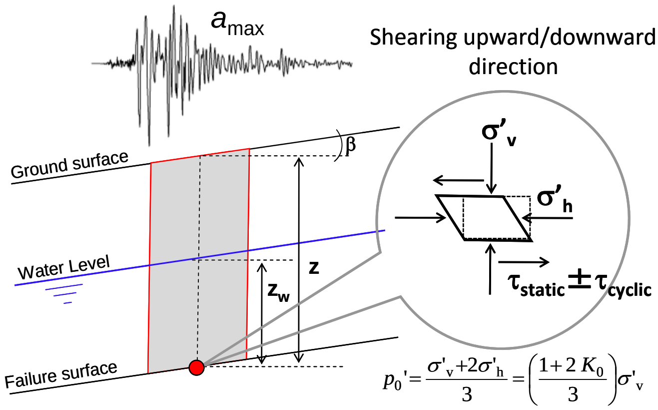

Figure 1: Stress conditions acting on a soil element beneath sloped ground during an earthquake

Once the stress conditions and soil strength are known, the occurrence or not of ground failure can be assessed by means of a plot η_{max} (= [SSR+CSR]/USS) vs. η_{min} (= [SSR-CSR]/USS), where a liquefaction zone, a shear failure zone and a safe zone (i.e. no-liquefaction and no-failure) are defined (Figure 2).

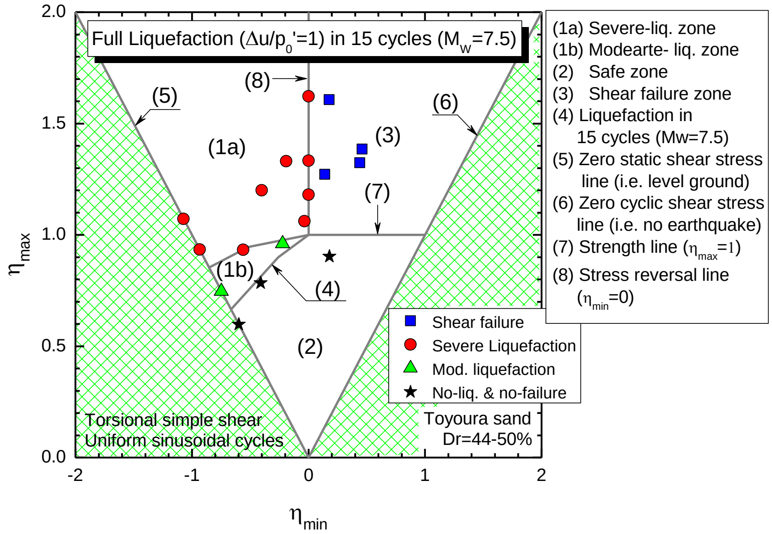

Figure 2: Soil liquefaction/failure modes based on the proposed simplified procedure (Experimental data from Chiaro et al., 2012 & 2013a; Chiaro and Koseki, 2010; De Silva, 2008; Kiyota, 2007; Arangelowski and Towhata, 2004)

3 ASSESSMENT OF LIQUEFACTION BEHAVIOUR FOR LEVEL AND SLOPED GROUND

In May-June 2012 a seismic sequence hit an extensive area of the Emilia-Romagna region in Northern Italy, producing an unusual and widespread soil liquefaction scenario (at least 485 cases over an area of about 1200 km^2 as reported by Alessio et al., 2013). In Figure 3, two pictures, taken by the authors (Koseki, 2012) a few days after the seismic event, show the extent of liquefaction at Sant'Agostino town. The ground surface inclination (*i*) was between 0% and 5% i.e. from level to very gentle sloped ground conditions. Although the existence of fine clean sand layers in the uppermost 5-10 m along with the presence of a high water table represented the most favourable conditions for the occurrence of soil liquefaction, it is still difficult to fully understand why such severe liquefaction was produced by an earthquake of a moderate magnitude of M_w = 5.9. To address this issue, hereafter, the assessment of liquefaction occurrence for the case of the 2012 Emilia Earthquake (M_w=5.9 and a_{max}=0.26 g) is made using the proposed simplified procedure. Thus, a soil column was examined and failure assessment was obtained for various soil elements, located at different depths beneath ground level. A total of 6 cases were generated by considering 2 slope inclination levels (i.e. i = 0% and 5%) and 3 relative density states (i.e. D_r=25%, 50% and 75%).

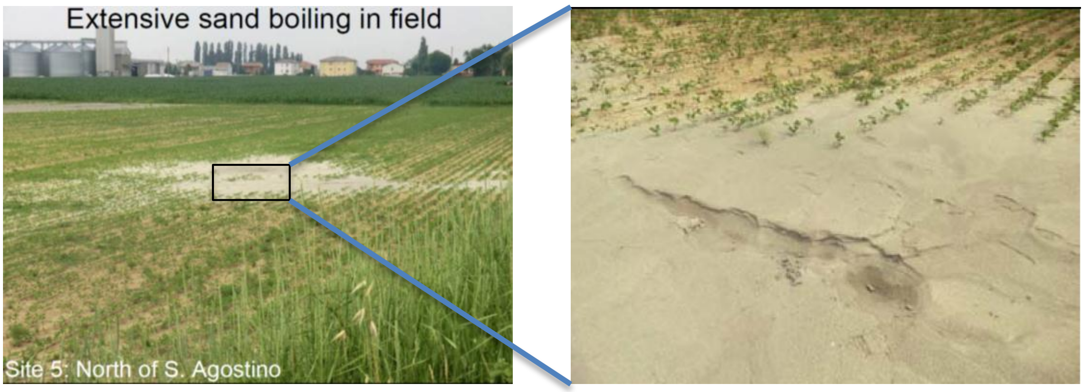

Figure 3. Liquefaction induced by the 2012 Emilia earthquake, Italy (Koseki 2012)

3.2 Evaluation of field cyclic stress ratio and static stress ratio characteristics

Figure 5(a) shows the variation of $CSR_{7.5}$ with depth and density. It can be seen that $CSR_{7.5}$ increases up to a depth of about 5-6 m and then slightly decreases independently from density state. Yet for loose soil, the maximum CSR is approximately 0.28, while for the denser soil the maximum CSR is 0.32. Thus, the looser the soil is, the lower the $CSR_{7.5}$ is. This is because loose soil is much more deformable than denser soil.

Figure 5(b) displays the variation of SSR with depth, density state and ground inclination. SSR increases with both soil density and depth, being nil for level ground conditions.

It should be noted that both the CSR and SSR values change with D_r through the coefficient of earth pressure at rest (Jaky, 1944; K_0 = 1- sin ϕ'; where ϕ' is the friction angle). In this study it was assumed that ϕ' = 28+0.14 D_r (Schmertmann, 1978).

3.3 Evaluation of field undrained shear resistance

Figure 5(c) shows the variation of USS with depth, soil density and ground surface inclination. It can be seen that USS increases markedly with increase in density. For dense sand (Dr=75%) USS=0.45 is approximately double than the case of loose sand (Dr=25%) USS=0.21. In addition, the presence of static shear provides additional resistance to the soil. The latter behaviour although may appear peculiar it has been experimentally confirmed by conducting torsional shear tests with initial static shear stress on Toyoura sand specimens (Chiaro et al., 2012).

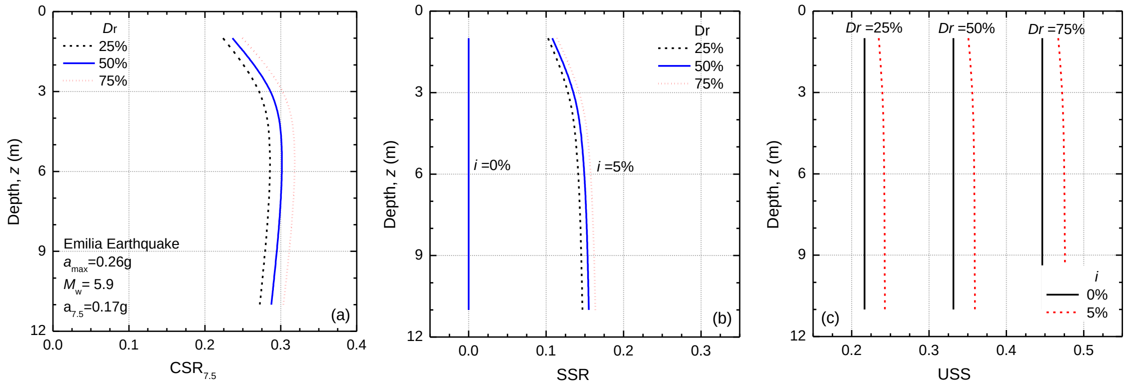

Figure 5. Variation of (a) CSR, (b) SSR and (c) USS with depth, density and ground inclination

3.4 Evaluation of field maximum and minimum stress components

In Figures 6 and 7, maximum (η_{max}) and minimum (η_{min}) shear stress variation with depth, density and ground inclination is shown. It can be seen that for level ground conditions, η_{max} and η_{min} values are symmetrical respect to the zero stress line, being the SSR=0 (i.e. η_{max} = CSR/USS and η_{max} = - CSR/USS). For sloped ground conditions, η_{min} moved toward the zero stress line, while η_{max} increases, resulting in a non-symmetrical stress conditions that may induce much more severe liquefaction. In addition, it was observed that both η_{max} and η_{min} are much lower for dense sand compared to loose sand.

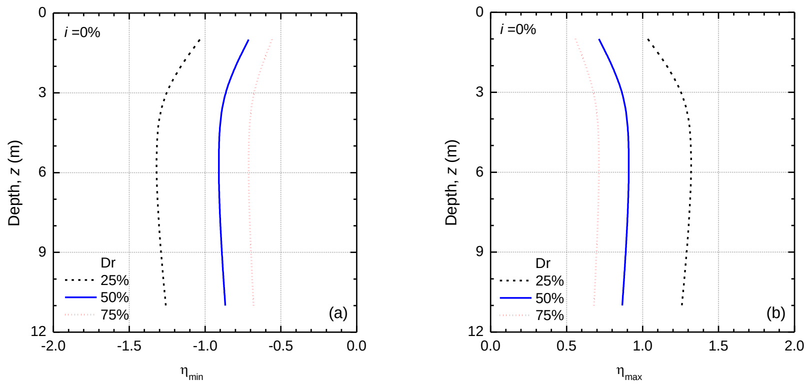

Figure 6. Variation of (a) maximum and (b) minimum shear stresses with depth and density for level ground conditions (*i* =0%)

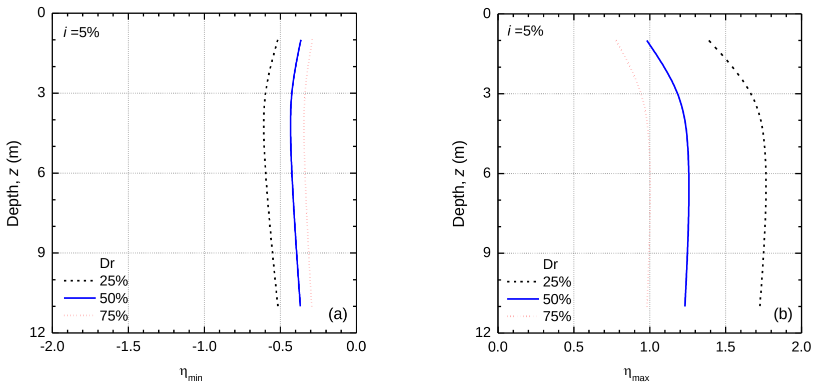

Figure 7. Variation of (a) maximum and (b) minimum shear stresses with depth and density for sloped ground conditions (*i* =5%)

3.4 Prediction of liquefaction behaviour for level and sloped ground

Figure 8(a) and (b) show the predictions of liquefaction behaviour obtained by using the Chiaro-Koseki simplified procedure for the case of level and gentle sloped ground conditions, considering three different level of density. One can see that for the 2012 Emilia Earthquake (a_{max}= 0.26g and M_w=5.9), soil is likely to experience severe liquefaction, except for the case of dense sand in level ground conditions. Also, it clearly appears that gentle sloped conditions significantly decrease the resistance of soil against liquefaction.

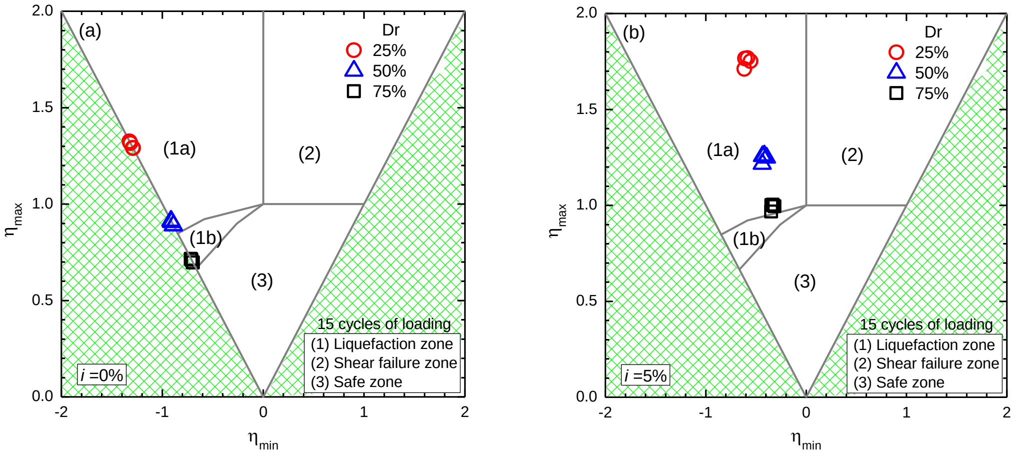

Figure 8. Liquefaction prediction based on the proposed simplified procedure for: (a) level ground and (b) gentle sloped ground conditions

4 DISCUSSION

In the case of the 2012 Emilia Earthquake, the existence of fine clean sand layers in the uppermost 5-10 m along with the presence of a shallow water table represented the most favourable conditions for the occurrence of soil liquefaction. However, it is not fully understood yet why such severe liquefaction was produced by an earthquake of a moderate magnitude of M_w = 5.9. An attempt is made hereafter to find a plausible explanation.

In order to evaluate the liquefaction hazard at a site, both the a_{max} and the effective number of cycles are needed. The magnitude scaling factor (MSF) can then be used to correct the analysis for earthquake magnitudes other than 7.5 (Youd and Idriss, 2001; Idriss and Boulanger, 2008; etc.), provided that such an earthquake induces 15 equivalent stress cycles of uniform amplitude. In this study, the concept of effective peak ground acceleration ($a_{7.5} = a_{max}$/MSF) was introduced. It may represent a critical input parameter for calculating $CSR_{7.5}$, and thus assessing and comparing the extent of liquefaction induced by earthquakes with different magnitudes and accelerations, as described hereafter.

For the 2012 Emilia Earthquake (M_w = 5.9 and a_{max} = 0.26g), MSF=1.52 and $a_{7.5}$ = 0.17g (i.e. a_{max} is reduced by a factor of 0.66). On the other hand, for the 1964 Niigata Earthquake, Japan (M_w = 7.5 and a_{max} = 0.16g), which also produced extensive liquefaction and ground failure (refer to Chiaro and Koseki (2012) for liquefaction assessment). Despite the difference in magnitude and acceleration levels, it appears that the Emilia and Niigata earthquakes have similar ground motion characteristics when evaluated in terms of effective peak ground acceleration, $a_{7.5}$ (Figure 9). Thus, it may be expected that also their effects in terms of liquefaction level and ground failure are similar.

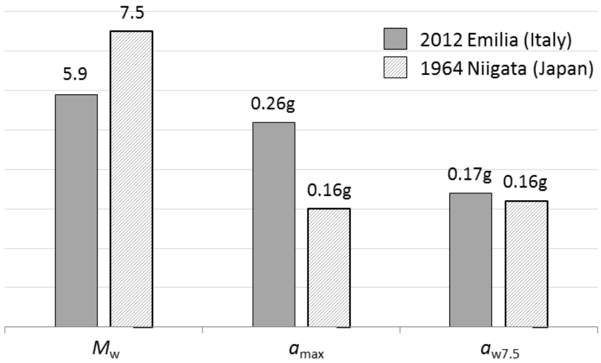

Figure 9. Ground motion features for 2012 Emilia and 1964 Niigata earthquakes

5 CONCLUSIONS

Prediction of ground failure involving earthquake-induced liquefaction of sloped sandy deposits is essential for understanding comprehensively the triggers and consequences of liquefaction. In this paper, an attempt is made to identify key factors that govern failure of sandy sloped ground during earthquakes and a simplified procedure, to assess whenever liquefaction or shear failure occurs within a saturated sandy sloped deposit, is presented. It is shown that the proposed simplified procedure is capable of predicting the severe liquefaction behaviour observed for level-gently sloped ground in Northern Italy following the 2012 Emilia earthquake.

This study also may suggest that the effective peak ground acceleration ($a_{7.5}$ = a_{max}/MSF), introduced in this paper, may be a good parameter to judge the severity of an earthquake in terms of ground motion characteristics, compared to the peak ground acceleration and moment magnitude used singularly.

Despite the number of approximations that can be made in this kind of study (with regards to determination of soil densities, cyclic and static stress ratios, and undrained strength in the field), the proposed method provides a useful framework for assessing liquefaction and shear failure of sloped ground in many practical proposes. Whenever greater accuracy is justified, the method can be readily supplemented by test data on particular soils or by ground response analysis to provide evaluations that are more definitive.

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