Recent developments in procedures for estimation of liquefaction potential of soils

Développements récents des méthodes d'estimation du potentiel de liquéfaction des sols

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ABSTRACT: Liquefaction of soils is associated with a loss of shear strength due to an increase of pore pressure. It causes important damages during earthquakes and is insofar a high risk factor for buildings and infrastructures. A proper estimation of liquefaction is required for a safe and economic design regarding earthquake resistance. In the last few decades various semi-empirical formulae based on collected data from historical earthquakes had been suggested. This paper point out recent developments in this area in relation with European Standards Eurocode 8 (2010) as well as methods described in Summary Report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils (Youd et al. 2001) during last decade.

RÉSUMÉ : La liquéfaction des sols est associée à une perte de résistance au cisaillement due à une augmentation de la pression interstitielle et peut être la cause de nombreux dommages lors de tremblements de terre. Il s'agit par conséquent d'un risque important pour les bâtiments et infrastructures. Une estimation correcte du risque de liquéfaction est nécessaire afin d'obtenir un dimensionnement à la fois sécurisé et économique. Différentes formules semi-empiriques basées sur des données collectées lors de précédents tremblements de terre ont été suggérées ces dernières années. Cet article met en avant les développements récents dans ce domaine, en relation avec la norme européenne Eurocode 8 (2010) et avec les méthodes décrites dans le rapport des workshops sur l'évaluation de la résistance des sols à la liquéfaction du NCEER en 1996 et du NCEER/NSF en 1998 (Youd et al. 2001).

KEYWORDS: liquefaction, seismic design, Eurocode 8, Cyclic Stress Ratio, Cyclic Resistance Ratio

1 INTRODUCTION

Liquefaction of soils is associated with a loss of shear strength of soil due to an increase of pore pressure. Liquefaction may lead to important deformations and is insofar a high risk factor for buildings and infrastructures. Different types of loading may trigger liquefaction such as earthquakes, pile driving, train traffic or blasting. The present study takes care of seismic design and considers only earthquakes.

For a safe and economic design regarding earthquake resistance, a proper estimation of liquefaction is required. In the last few decades various semi-empirical formulae based on collected data from historical earthquakes had been suggested for a performance-based seismic design in liquefied zone for seismically active areas.

It is quite obvious to see that the techniques used for estimating liquefaction keep changing as the collecting data increase with time. Consequently, divergences may be observed between standards currently used for design of structures and research reports. Recent developments in this area in relation with European Standards, particularly the EN 1998 "Design of structures for earthquakes resistance" (Eurocode 8), as well as methods described in Summary Report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils (Youd et al. 2001) and their actualizations during last decade are presented here and discussed.

Procedures used for estimating potential of liquefaction during earthquakes depend on slope angle with a distinction between level ground sites and steeply sloping grounds (Robertson and Cabal 2010). The present study deals exclusively with procedures estimating the liquefaction resistance of the soil during earthquakes for level ground sites therefore with slope angles less than 5 degrees. It refers in the European standards to section §4.1.4 of EN 1998 part 5 (Eurocode 8).

2 FIRST OBSERVATIONS

2.1 *Main steps for estimating liquefaction potential for seismic design*

According EN 1998 (Eurocode 8), Youd et al. (2001) and Robertson and Cabal (2010), screening criteria such as soil properties or groundwater table are firstly used to determine areas where liquefaction is more likely. In those areas, quantitative estimations based on semi-empirical relationships are then performed in three steps:

- evaluation of the maximal available cyclic loading on the site (Cyclic Stress Ratio CSR);
- evaluation of the resistance capacity of the soil under cyclic loads (Cyclic Resistance Ratio CRR);
- comparison of CSR and CRR with the evaluation of the Factor of Safety FS.

The steps were taken from the Simplified Procedure of Seed and Idriss (1971).

2.2 *Factors affecting liquefaction and screening criteria*

Likelihood of occurrence and type of liquefaction depend according Day (2002) and Prakash and Puri (2012) on:

- soil properties: particle size gradation, relative density, particle shape;
- loading characteristics: intensity and duration of seismic shaking;
- site conditions: groundwater table, lateral earth pressure coefficient, preloading, aging and cementation …

Some of those factors may be used as screening criteria, insofar the quantity and reproductability of collected data during previous earthquakes are sufficient to conclude about the risk of liquefaction.

Important factors are water depth and saturation of the soil. Presence of water is one necessary condition for triggering of liquefaction. Moreover, liquefaction risks decrease with an increase of lateral earth pressure. Consequently, soils are more susceptible to liquefy as water table is near to the ground surface and, according the European standard, it is not necessary to investigate the potential of liquefaction for a depth greater than 15 m (Eurocode 8). However, the limit of the investigation depth and by the way of the validity area for the commonly used semi-empirical methods depends on the available data: for example, methods presented from Youd et al. (2001) rely principally on data collected in Holocene alluvial or fluvial sediment and for depths under 15 m and, for values beyond 15 m, it is indicated that simplified procedure is not verified with collected data.

Additional screening criteria to exclude the likelihood of liquefaction triggering, which are considered neither in Eurocode nor in the report of the NCEER and NCEER/NSF workshops are available. For example, Day (2002) gives a screening criterion based on loading characteristics: liquefaction is excluded if the both conditions $a_{max} < 0.10g$ and $M_L < 5$ are fulfilled, where a_{max} = peak ground acceleration, M_L = local magnitude and g = gravitational acceleration. A comparison of the peak horizontal acceleration and the local magnitude value is not enough to conclude, but gives additional information without high time and cost investment.

Criteria which are based on soil properties are discussed in the next part.

2.3 *Recent assumptions about fine grained soils*

In a first time, only sandy soils were considered as liquefiable. As cases of liquefaction were also observed in fine grained soils, additional criteria were developed. A description of the state-of-the-art in this area is given by Prakash and Puri (2010, 2012).

In Eurocode, a soil with fines is not susceptible to liquefy in both following cases:

- Clay Content > 20 % with Plasticity Index > 10
- Silt Content > 35 % and $N_1(60) > 20$ (see part 4.1)

In the review of Prakash and Puri, it appears that amount and type of clay minerals and plasticity index are more relevant than the amount of "clay-size" particles. However, divergences on the minimal value of Plasticity Index as criterion are observed between different research reports.

In order to develop proper criteria for fine grained soils with plasticity, it is suggested to consider the soils separately depending on their comportment (Idriss and Boulanger 2004 such as 2008, reported from Prakash 2012). With this classification, comportment of soils with "sand-like behavior" is better known than liquefaction susceptibility of soils with "clay-like behavior", for which it will take a long time before having a better comprehension of the phenomena.

3 EVALUATION OF THE CYCLIC STRESS RATIO (CSR)

3.1 *Methods referenced at of the NCEER and NCEER/NSF Workshops (Youd et al. 2001)*

According to the procedure of Seed and Idriss (1971) the Cyclic Stress Ratio is calculated on basis of the following relationship (Youd et al. 2001):

$$CSR = 0{,}65 \cdot \frac{\sigma_z}{\sigma'_z} \cdot \frac{a_{max}}{g} \cdot r_d \tag{1}$$

where a_{max} = peak horizontal acceleration generated by the earthquake; g = acceleration of gravity; σ_z and σ'_z = total and effective overburden stresses and r_d = stress reduction coefficient. The peak horizontal acceleration a_{max} is estimated with a local site analyses.

The CSR in the Eurocode is determined as following:

$$CSR = 0{,}65 \cdot \frac{\sigma_z}{\sigma'_z} \cdot \frac{a_{max}}{g} \cdot S \tag{2}$$

Neither charts nor relations are given for an estimation of S, defined as a 'soil parameter'. As equations 1 and 2 are similar, it will be considered in the following parts that r_d and S are equal.

3.2 *Assessment of stress reduction ratio r_d according Youd et al. (2001)*

Cited in the report of the NCEER and NSF/NCEER workshops (Youd et al. 2001), the relationship proposed by Liao and Whitmann (1986) is a linear approximation of the average values from the Simplified Procedure by Seed and Idriss (1971), see Figure 1, and can be used in routine practice and noncritical projects:

$$r_d = 1{,}0 - 0{,}00765 \cdot z \quad \text{for} \quad z \le 9{,}15 \text{ m} \tag{3}$$
$$r_d = 1{,}174 - 0{,}0267 \cdot z \quad \text{for} \quad 9{,}15\text{m} < z \le 23 \text{ m}$$

where z is the depth below ground surface in meters. For an easier handling of the software, Blake (1996) proposed the following relation (Youd et al. 2001):

$$r_d = \frac{1{,}000 - 0{,}4113 \cdot z^{0{,}5} + 0{,}04052 \cdot z + 0{,}001753 \cdot z^{1{,}5}}{1{,}000 - 0{,}4177 \cdot z^{0{,}5} + 0{,}05729 \cdot z - 0{,}006205 \cdot z^{1{,}5} + 0{,}00121 \cdot z^2} \tag{4}$$

The obtained values of the stress reduction factor with those equations are average values and it is notable that the range of possible values increases with the depth, as illustrated in the Figure 1.

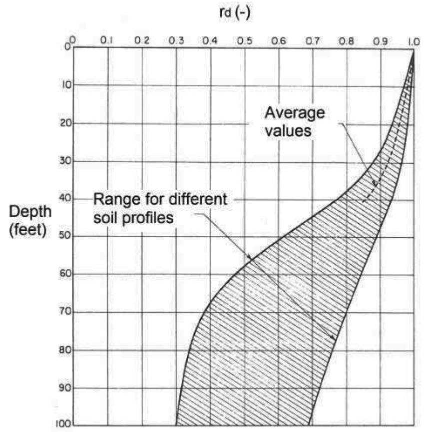

Figure 1. r_d values vs. depth curves developed by Seed and Idriss (1971)

3.3 *Recently added methods (Cetin et al. 2004, Idriss and Boulanger 2010)*

During the last decade additional relations have been developed in order to reduce the incertitude previously mentioned.

The procedure of Idriss (1999) considers the moment magnitude M_w in addition to the depth below ground surface z (Idriss and Boulanger 2008, Idriss and Boulanger 2010):

$$r_d = exp(\alpha(z) + \beta(z) \cdot M_w)$$
$$\text{with } \alpha(z) = -1{,}012 - 1{,}126 \cdot \sin\left(\frac{z}{11{,}73} + 5{,}133\right) \tag{5}$$
$$\text{and } \beta(z) = 0{,}106 - 0{,}118 \cdot \sin\left(\frac{z}{11{,}28} + 5{,}142\right)$$

According to Seed (2010), the criteria of the Simplified Procedure and later of Idriss and Boulanger (2008) are not enough conservative because of over-predicted r_d-values. Seed compares the relationships of Idriss and Boulanger (2008) with those of Cetin et al. (2004). In that last procedure, a new relationship is developed with a probabilistic approach, which considers not only the depth and the magnitude scale but also the peak horizontal acceleration and the relative shear wave velocity[1] $V^*_{s,12m}$.

Idriss and Boulanger (2010) come back to the deviations related by Seed in their actualized report "SPT-Based Liquefaction Triggering Procedures" (Idriss and Boulanger 2010)[2]. They refer also to another recent method, developed by Kishida et al. (2009), in which the same parameters as in the relationship of Cetin et al. (2004) are being used. An example for the use of those three methods with different magnitudes and a shear wave velocity V_s = 120 m/s is given in Figure 2.

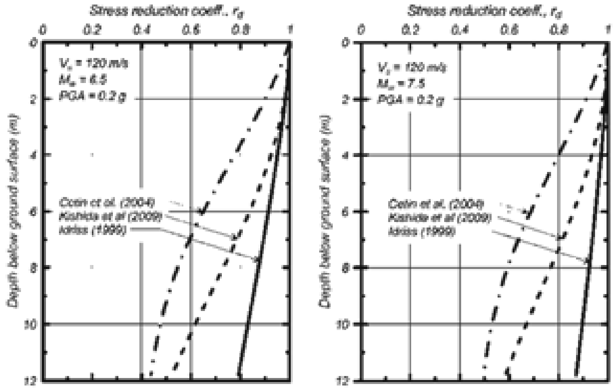

Figure 2. Comparison of r_d-values for M = 6.5 and for M_w = 7.5 with a shear wave velocity Vs = 120 m/s (Idriss & Boulanger 2010)

Relationships presented here are more accurate but also more complicated, due to an increasing number of collected data with the time and the introduction of new input parameters. However, divergences as shown in Figure 2 between recent methods, particularly those of Idriss and Boulanger (2008, 2010) and of Seed (2010), point out that further investigations are required in this area.

4 EVALUATION OF THE CYCLIC RESISTANCE RATIO (CRR)

In Eurocode 8, an estimation of potential of liquefaction requires field tests, either Standard Penetration Tests (SPT) or Cone Penetration Tests (CPT). Results of CPT and SPT are currently used to estimate the Cyclic Resistance Ratio, as it is mentioned in the European standard and in actual reports (Youd et al 2001, Robertson and Cabal 2010). Annex B of Eurocode 8 includes a detailed description of the procedure based on the SPT and some indications about the procedure based on CPT. A method based on results from tests measuring shear wave velocity (Spectral Analysis of Surface Waves SASW or Multichannel Analysis of Surface Waves MASW) is also mentioned, it is however indicated that this method is still subject of research developments.

4.1 *Methods based on Standard Penetration Test (SPT)*

The standard penetration resistance N_m measured during a SPT is used as input parameter and firstly transformed in a normalized value $N_1(60)$ for an overburden pressure of approximately 100 kPa and a hammer efficiency of 60 %. According Youd et al. (2001):

$$N_1(60) = N_m \cdot C_N \cdot C_E \cdot C_B \cdot C_R \cdot C_S \qquad (6)$$

with correction factors for a normalization to a common reference effective overburden stress (C_N), for hammer energy ratio (C_E), for borehole diameter (C_B), for rod lengths (C_R) and for samplers with or without liners (C_S).

In Eurocode, some correction factors are not considered (C_B, C_R, C_S). Concerning the corrections C_E and C_N: C_N should not exceed 2.0 according Eurocode; Youd et al. (2001) recommend nevertheless a maximal value of 1.7. Furthermore, Idriss and Boulanger (2008) modify in the EERI Monograph MNO-12 the correction factors C_N and C_S.

Correlations between $N_1(60)$ and CRR in Eurocode are similar to those from Youd et al.(2001), as it is shown on Figures 3 and 4. In the report of Youd et al. (2001), values can be read from diagram or also evaluated with relationships corresponding to the represented curves.

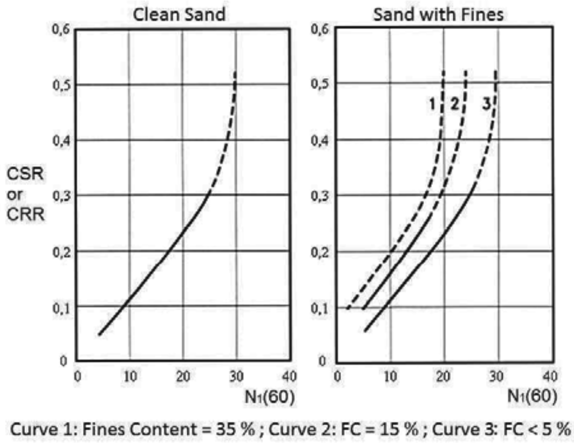

Figure 3. Correlation between corrected blow count $N_1(60)$ from SPT and Cyclic Stress Ratio leading to liquefaction for a Surface Wave Magnitude M_S = 7.5 (equal to the moment magnitude M_W for this range) (Eurocode 8)

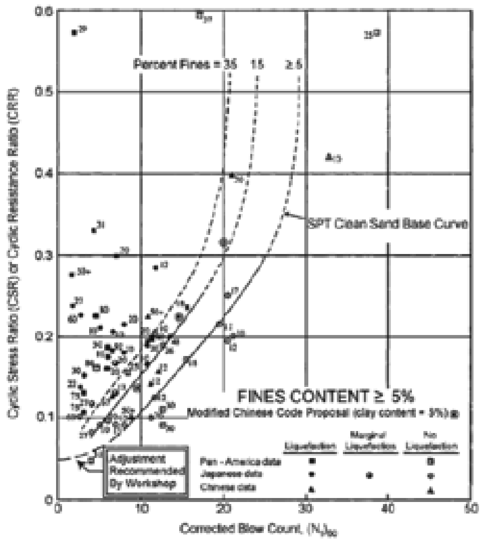

Figure 4. SPT Base Curves for a Moment Magnitude M_w = 7.5 (Youd et al. 2001)

The procedure described here is established for clean sands and sands with fines content. For fine grained soils, see part 2.3. An important change in the last decade is also the apparition of probabilistic methods, developed in parallel by Idriss and Boulanger (2010) and by Seed et al. (2003). Those methods are nevertheless still in development.

[1] The relative shear wave velocity is measured 12 m below ground surface and divided by the needed time for a shear wave to reach the surface.

[2] See pages 65 to 68 of this report.

4.2 *Methods based on Cone Penetration Test (CPT)*

A method based on CPT is detailed in the report of the NCEER and NCEER/NSF Workshops (Youd et al. 2001). This method was critically reflected by Howie and Vaid (2000) and has been actualized during the last decade; the last report was published by Robertson and Cabal (2010).

CPT has in comparison to SPT advantages such as good repeatability of the results which are represented as continued profiles or a better identification of layered soils (Youd et al 2001, Robertson and Cabal 2010). However, the procedures which were firstly developed for estimating potential of liquefaction are based on SPT, which explains why those tests are often used and that the data bases are more extended. This difference tends to be reduced, as procedures based on CPT were during the last decade subject of larger investigations (Robertson and Cabal 2010).

4.3 *Further corrections by the SPT and CPT methods*

Influencing factors about the calculated value $CRR_{7,5}$ are the inclination of the ground surface, the depth, particularly the overburden pressure and the earthquake magnitude. The correction factor K_{σ} for a low sloping ground was reviewed and discussed by Seed (2010), based on the monograph of Idriss and Boulanger (2008). Those correction factors are not considered in Eurocode 8.

Correction factors for the earthquake magnitude (Magnitude Scaling Factor MSF) depend in the most cases of the Moment Magnitude M_w. In the Eurocode, the correction factor depends on the Surface Wave Magnitude M_s. Pertinence of Magnitude type is discussed by Youd et al. (2001).

5 CONCLUSIONS

Procedures for estimation of liquefaction potential are still in development, which results in an increasing number of divergences between research reports and standards commonly used. A more accurate study of the last reports on this theme is therefore required to obtain a valid actualization of the estimation of liquefaction potential in the Eurocode. Following are some points which could be additionally considered or further investigated in order to improve the actual European standard:

- Scope of available screening criteria for a preliminary judgment about liquefaction susceptibility
- Influence of Fines Content and consideration of Fine Grained Soils
- Explanations about the soil parameter S
- Probabilistic SPT-Procedures
- More details about CPT and eventually about tests measuring shear wave velocity (Spectral Analysis of Surface Waves SASW or Multichannel Analysis of Surface Waves MASW)
- Divergences between correction factors by assessing the Cyclic Resistance Ratio.

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