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Comparison of Stress Based Semi-Empirical Methods in Evaluating Liquefaction Potential of Tangier Soils

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ABSTRACT

Semi-empirical approaches are widely used to characterize inclination of soils to liquefaction phenomenon through the concept of potential of liquefaction. This last is estimated by using procedures that are based on in situ tests. The standard and the cone penetration tests are commonly used. They enable estimating liquefaction potential by means of some established correlation formulas. These correlations depend however on the site where they were derived. The first task to achieve in order to adapt them to other sites such as sandy soils existing in the northern Moroccan city of Tangier is comparing them in terms of the estimated potential of liquefaction they provide. In this work, focus is done on four important stress based approaches: Seed, Blake, Roberston-Wride and Juang. Field tests consisting of core sampling and cone penetration testing were performed. They have facilitated the necessary data for evaluating the cyclic resistance ratio, needed in estimating the potential of liquefaction.

KEYWORDS: seism, liquefaction, soil, stress approach, cone penetration test, cyclic resistance ratio.

INTRODUCTION

Loose saturated sandy soils could undergo large strains during the occurrence of intensive earthquakes. As soil deformation is in general incompatible with requirements of stability, destructive effects and huge damage to buildings and infrastructures could happen. Liquefaction is associated to the apparition of pore water overpressures and loss of resistance occurs if the soil is insufficiently compacted. The applied shear stresses are transferred spontaneously from total stresses to pore water pressures [1]. This last could jump to sufficiently high values that could compensate the total confining pressure, yielding the soil to undergo large strains as its behavior becomes of fluidic type and the effective stresses tend to vanish.

In order to characterize vulnerability of soils to liquefaction phenomenon a lot of semi-empirical methods have been developed. They all try to provide estimation of liquefaction potential for a given soil under some earthquake risk. Most of these methods have been introduced by Seed and its fellows at Berkley during the seventies [2]. Semi-empirical methods are based upon comparing results gathered form sites where earthquakes have occurred and examining among them those for which liquefaction happened and those where this event has not been observed. In these approaches, potential of liquefaction is determined by correlating it to some appropriate propriety of the considered soil, that is measuring its capacity to resist liquefaction phenomenon.

Seed and Idriss [2] have identified the conditions for sandy soils to liquefy by measuring the standard penetration test (SPT) resistance and by evaluating, for a given seism, shear forces that were induced in the soil mass. The method was originally developed with SPT testing and was later adapted to use the cone penetration test (CPT). The original Seed and Idriss method consists in:

- Performing the SPT test in order to measure the penetration resistance and correlating this result with the cone penetration test [3,4].
- Estimating the initial stress state in the soil in terms of the shear stress caused by the seism. A classical formula is used for that. It gives the shear stress as function of the seismic acceleration, the gravity acceleration, the soil total vertical stress and a correction factor expressed in terms of soil depth.
- Defining a liquefaction limit state either empirically from historical case studies or by means of cyclic triaxial tests conducted on soil samples. Seed and Idriss [5] have given limit state curves that enable comparing the seismic demand represented by the ratio of shear stress over the soil vertical effective stress and the liquefaction resistance capacity defined as the modified SPT resistance.

Blake has proposed a simplified expression for evaluating the cyclic resistance ratio as function of the normalized clean sand SPT penetration resistance [6]. The main factors affecting the SPT testing results have been summarized by Robertson and Wride [7]. Because of the high vulnerability of SPT testing, several correlations have been proposed to estimate the cyclic resistance ratio for sandy soils using corrected CPT penetration resistance, [7].

Robertson [8] has proposed to compare the seismic demand to soil capacity when expressed in terms of the shear wave propagation velocity. He has proposed liquefaction limit states under two forms: a curve in the

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diagram having as axes the cyclic shear stress and the shear wave velocity, and secondly a curve in the diagram compounded from the modified SPT resistance and the soil vertical effective stress.

Among the other stress based approaches Juang method [9] is very interesting because it needs rather limited experimental resources.

Other approaches that are not stress based were also proposed such as Dobry method [10] which constitutes a strain approach and Park method [11] which is an energetic approach. A lot of other semi-empirical methods are reported in the literature [12].

Liquefaction of soils could also be stated by means of rational approaches based on analytic methods where mechanical models of the soil behavior are used [13-20]. An extensive comparative study of all the proposed variants of these physically based formulations is presented in Smith [21].

Since correlations formulas used in estimating liquefaction potential, depend to some extent on the site where they were derived, their systematic use for other sites is questionable. In this work, we analyse the possibility to use these correlations in order to estimate liquefaction potential, for the particular case of sandy soils that are encountered in the northern region of Morocco near from the city of Tangier.

The objective is to investigate the degree of accordance the semi-empirical methods can achieve when tested to predict potential of liquefaction for Tangier soils. A case study is examined in this comparison. It consists of the site where the complex Tangier City Centre was built.

MATERIALS AND METHODS

The mean factors controlling liquefaction of cohesion less saturated soils are the duration and the intensity of the earthquake motion, as well as soil density and the confining effective pressure. In order to characterise soil response under the action of cyclic seismic acceleration, a lot of methodologies were developed [2,10,11,12]. Methods that are based on cyclic stresses and strains were developed from laboratory tests. Due to the fact that the cyclic response of a soil is controlled by factors such as the nature of soil, existing pre-strains, the loading history and some others altering effects that could not be reproduced exactly during laboratory tests, empirical relationships that are based on in situ measurements seem to be more effective. These are obtained from the well known standard tests such as the CPT which characterises the quasi static resistance to penetration of a soil and the SPT test which gives the dynamic soil resistance to penetration action. Some precautions should be considered while using these tests as the rod can be subjected to bucking problem for depths exceeding $30\,\mathrm{m}$, the domain of validity of these tests is then limited to depths that do not exceed this limit. In addition, these tests do not apply properly for soils containing grains having diameters greater than $2\,\mathrm{cm}$.

In order to represent in a simple manner soil motion resulting from an earthquake, by using only a single parameter, an effective procedure was developed by Seed and Harder [6]. The liquefaction potential is evaluated in this context by comparing a normalized index which is related to the cyclic soil resistance capacity C_{RR} to the ratio of the cyclic stress demand C_{SR} being applied to the soil.

At a given site, the C_{SR} is essentially a function of peak ground surface acceleration a_{max} and earthquake magnitude M. The C_{RR} is determined from a limit state curve that is obtained by calibration of the available case histories consisting of C_{SR} and in situ test data such as normalized SPT blow count $N_{1,60}$ or CPT resistance q_{c1N}. The limit state curve can then be given as an empirical equation where the C_{RR} is a function of $N_{1,60}$ or q_{c1N}. This enables evaluating the safety factor F_S as

$$F_S = \frac{C_{RR}}{C_{SR}} \tag{1}$$

The demand ratio C_{SR} is defined as

$$C_{SR} = \frac{\tau_{av}}{\sigma'_{vo}} = 0.65\frac{a_{max}}{g}\frac{\sigma_{vo}}{\sigma'_{vo}}r_d \tag{2}$$

where τ_{av} is the average shear stress resulting form the earthquake at the given depth, a_{max} is the maximum acceleration at the soil surface, g the acceleration of gravity, σ_{vo} the total vertical stress at the considered depth, σ'_{vo} the effective vertical stress at the considered depth and r_d a reduction stress factor that accounts for soil column deformability. Figure 1 gives factor r_d as function of depth z according to NCEER [22].

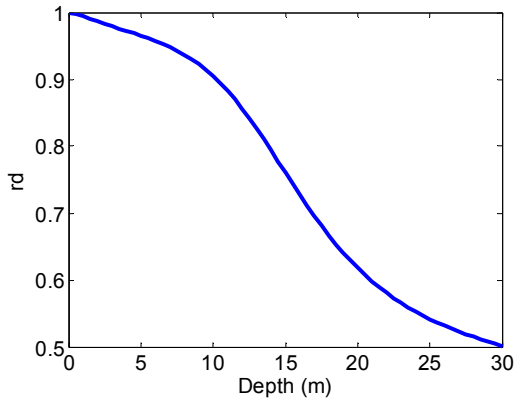

Figure 1: Stress reduction factor r_d as function of depth z (NCEER [22])

The earthquake magnitude influences the seism duration and may increase significantly the number of stress cycles. The amplitude effect of an earthquake is not included in (2). In order to take this effect into account, a scaling factor denoted MSF (Magnitude Scaling Factor) has been introduced, figure 2. The reference amplitude for a stress based approach was fixed at degree 7.5 according to Richter scale. Various formulas were presented in the literature to give the MSF coefficient. When this factor is calculated as function of the seism magnitude M which is retained in the analysis of liquefaction risk, the normalisation of the C_{SR} ratio is performed according to the following equation

$$C_{SR\,7.5} = \frac{C_{SR}}{MSF} = \frac{\tau_{av}}{\sigma'_{vo}\ MSF} = \frac{\tau_{7.5}}{\sigma'_{vo}} \tag{3}$$

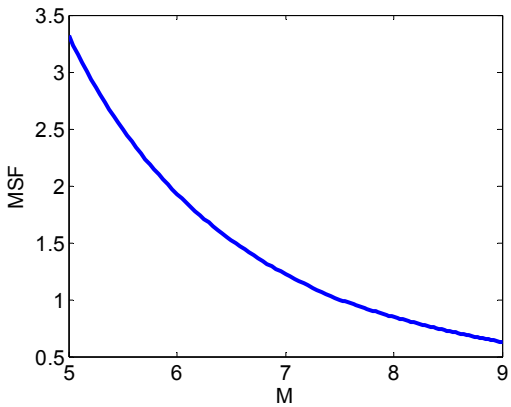

Figure 2: The scaling factor MSF as function of earthquake magnitude (NCEER [22])

Evaluation of the cyclic resistance ratio C_{SR} depends on the performed test. Various methods were proposed to estimate the capacity coefficient C_{RR}. They are given in the following by assuming that σ'_{v0}, σ_{v0} and q_c are expressed in atm unit ($1\,atm = 10^5\,Pa$).

a) Seed method

According to Boulanger and Idriss [23], the SPT penetration resistance $N_{1,60}$ is normalized by performing iterations using the following equation

$$N_{1,60} = \min\left\{37; N_{60} \times \min\left(1.7; \left(\sigma'_{v0}\right)^{-0.784+0.0768\sqrt{N_{1,60}}}\right)\right\} \tag{4}$$

where for the first iteration $N_{1,60} = N_{60}$. Then $N_{1,60}$ is adjusted to an equivalent clean sand as

$$N_{1,60cs} = N_{1,60} + \exp\left(1.63 + \frac{9.7}{FC} - \frac{246.5}{FC^2}\right) \tag{5}$$

where FC is the fine content in %.

When only level ground conditions with negligible slopes are considered, the cyclic resistance ratio is obtained by the following equation

$$C_{RR7.5} = K_\sigma \exp\left(7.092\times10^{-2}\left(N_{1,60cs}\right) + 6.299\times10^{-5}\left(N_{1,60cs}\right)^2 - 7.608\times10^{-5}\left(N_{1,60cs}\right)^3 + 2.402\times10^{-5}\left(N_{1,60cs}\right)^4 - 2.8\right) \tag{6}$$

where K_σ is the overburden correction factor obtained as function of the effective vertical stress under the following form

$$K_\sigma = \min\left\{1; 1 - \frac{\log\left(\sigma'_{v0}\right)}{18.9 - 2.55\sqrt{N_{1,60}}}\right\} \tag{7}$$

b) Blake method

For clean sand soil, Blake, see reference [6], has approximated the simplified base liquefaction limit state, defined by equation (6), using the following interpolation formula

$$C_{RR7.5} = \frac{0.048 - 4.721\times10^{-3}\left(N_{1,60}\right) + 6.136\times10^{-4}\left(N_{1,60}\right)^2 - 1.673\times10^{-5}\left(N_{1,60}\right)^3}{1 - 0.1248\left(N_{1,60}\right) + 9.578\times10^{-3}\left(N_{1,60}\right)^2 - 3.285\times10^{-4}\left(N_{1,60}\right)^3 + 3.714\times10^{-6}\left(N_{1,60}\right)^4} \tag{8}$$

where no correction is considered for overburden pressures.

c) Robertson and Wride method

The main factors affecting the SPT as summarized by Robertson and Wride [7] include among others the energy delivered by the SPT sampler as well as the rod diameter and length. These factors affect repeatability of SPT tests. Because of this, several correlations have been proposed to estimate the cyclic resistance ratio for sandy soils from corrected CPT penetration resistance. The truly normalized cone penetration resistance is given by

$$q_{c1N} = \frac{q_c}{P_a} \times \min\left\{\left(\frac{P_a}{\sigma'_{v0}}\right)^n; 2\right\} \tag{9}$$

where q_c is the measured cone tip penetration resistance, n is a coefficient that depend on the material class and P_a is a constant reference pressure ($Pa = 1\,atm$). The exponent n is evaluated iteratively as function of the material index, Mitchell and Tseng [12], and which is defined by

$$I_c = \sqrt{\left(3.47 - \log\left(q_{c1N}\right)\right)^2 + \left(1.22 + \log\left(\frac{f_s}{q_c - \sigma_{v0}}\right)\right)^2} \tag{10}$$

where f_s is the measured lateral friction. In the first iteration the value $n = 1$ is assumed. Depending on the obtained index I_c at convergence of these iterations, the exponent takes the following values

$$\begin{aligned} n &= 0.5 \quad \text{if} \quad I_c \le 2.6 \\ n &= 0.7 \quad \text{if} \quad I_c > 2.6 \end{aligned} \tag{11}$$

According to Robertson and Wride [7], clean sandy soils having less than 5% of fine content have the following cyclic resistance ratio

$$\begin{aligned} C_{RR7.5} &= 0.05 + 8.33\times10^{-4} q_{c1N,cs} \quad \text{if} \quad q_{c1N} < 50 \\ C_{RR7.5} &= 0.08 + 9.3\times10^{-8}\left(q_{c1N,cs}\right)^3 \quad \text{if} \quad 50 \le q_{c1N} < 160 \end{aligned} \tag{12}$$

with

$$q_{c1N,cs} = K_c q_{c1N} \tag{13}$$

and

$$\begin{aligned} &K_c = 1 \quad \text{if} \quad I_c \le 1.64 \\ &K_c = -0.403I_c^4 + 5.581I_c^3 - 21.63I_c^2 + 33.75I_c - 17.88 \quad \text{if} \quad I_c \ge 1.64 \end{aligned} \tag{14}$$

d) Juang method

In case of Juang method, see reference [6], C_{RR} has been identified by using a neural network approach where the inputs were q_{c1N}, I_c evaluated by taking $n = 0.5$, σ'_v and $C_{SR7.5}$. The result is given by the following formula

$$C_{RR7.5} = C_\sigma \exp\left(-2.957 + 1.264\left(\frac{q_{c1N,CS}}{100}\right)^{1.25}\right) \tag{15}$$

with

$$C_\sigma = -0.016\left(\frac{\sigma'_v}{100}\right)^3 + 0.178\left(\frac{\sigma'_v}{100}\right)^2 - 0.063\left(\frac{\sigma'_v}{100}\right) + 0.903 \tag{16}$$

and

$$q_{c1N,CS} = q_{c1N}\left(2.429I_C^4 - 16.943I_c^3 + 44.55I_c^2 - 51.497I_c + 22.802\right) \tag{17}$$

where q_{c1N} and I_c are evaluated by taking the exponent $n = 0.5$.

In Juang method the cyclic demand C_{SR} is evaluated by using in equation (1): $MSF = (7.5/M)^{2.56}$, $r_d = 1 - 0.00765z$ if $z \le 9.15$ m and $r_d = 1.174 - 0.0267z$ if $9.15 \le z \le 23$ m.

RESULTS

A campaign of tests was conducted in the site of Tangier City Centre. 16 core sampling tests and 18 CPT tests were performed, [24]. Figure 1 shows the implantation plan of CPT and core sampling tests. Among the CPT results, test number 14 was the most severe with regards to liquefaction phenomenon. Figure 2 illustrates the extracted material from well number S'8 which is located near from the CPT test number 14. Figure 3 gives the CPT testing results associated to this test. It shows $N_{1,60cs}$(kPa) resistance profile and q_c (kPa) tip penetration resistance profile. Figure 4 gives the safety factor as evaluated by the four methods: Seed, Blake, Robertson-Wride and Juang.

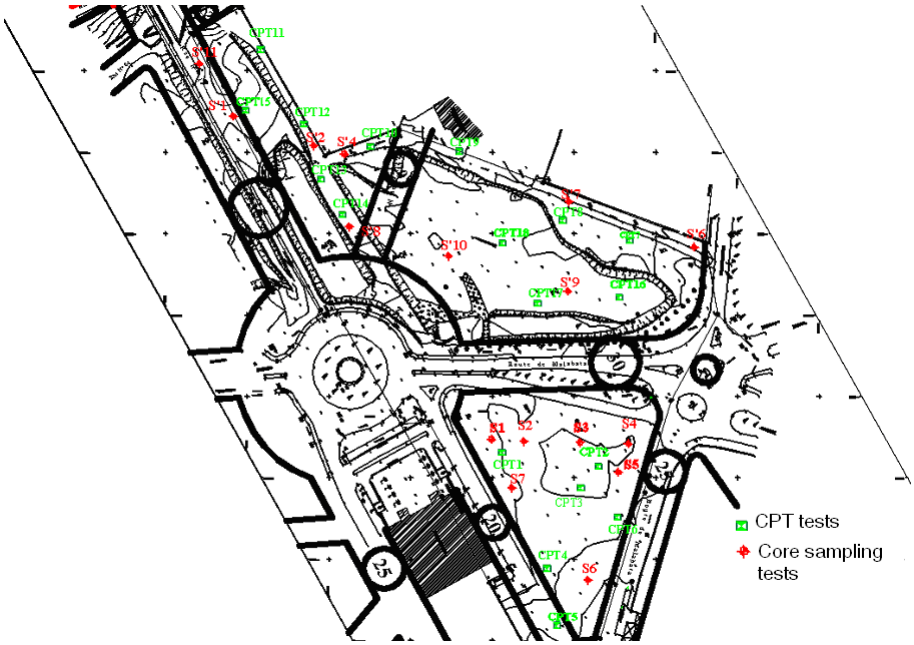

Figure 1: Implantation plan for CPT and core sampling tests

Core sampling between 0 and 5.1 m

Core sampling between 5.1 m and 10.4 m

Core sampling between 10.4 m and 15.5 m

Core sampling between 15.50 and 24 m

Figure 2: Soil material extracted during core sampling as function of depth, well number S'8

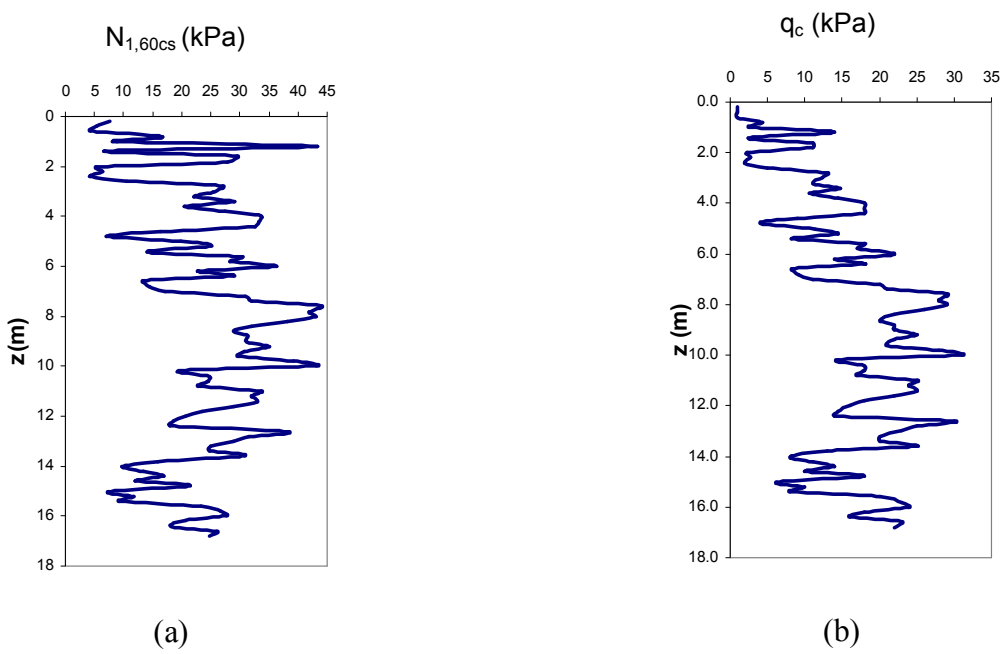

Figure 3: CPT results of test number 14;
(a) Clean sand equivalent normalized penetration resistance profile
(b) Tip resistance profile

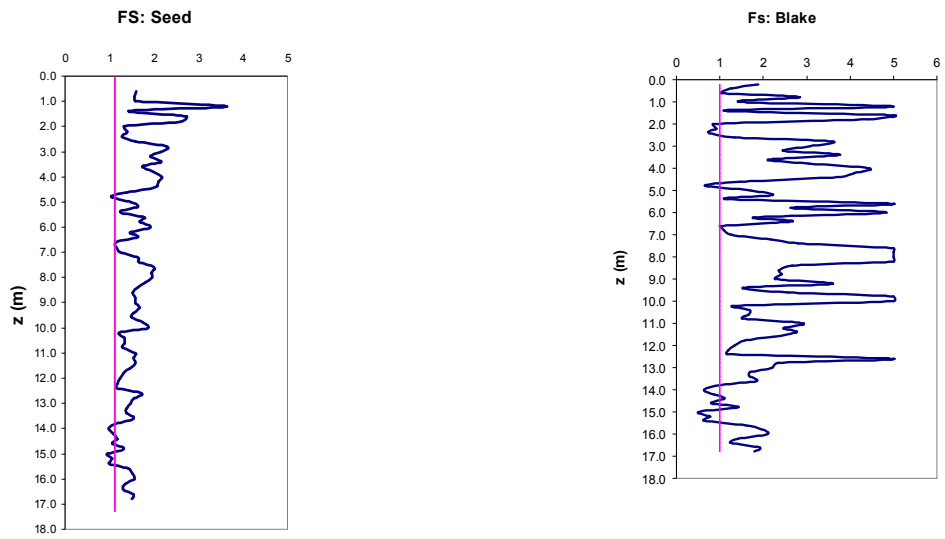

Figure 4: Variation of the safety coefficient as function of depth for the four semi-empirical methods

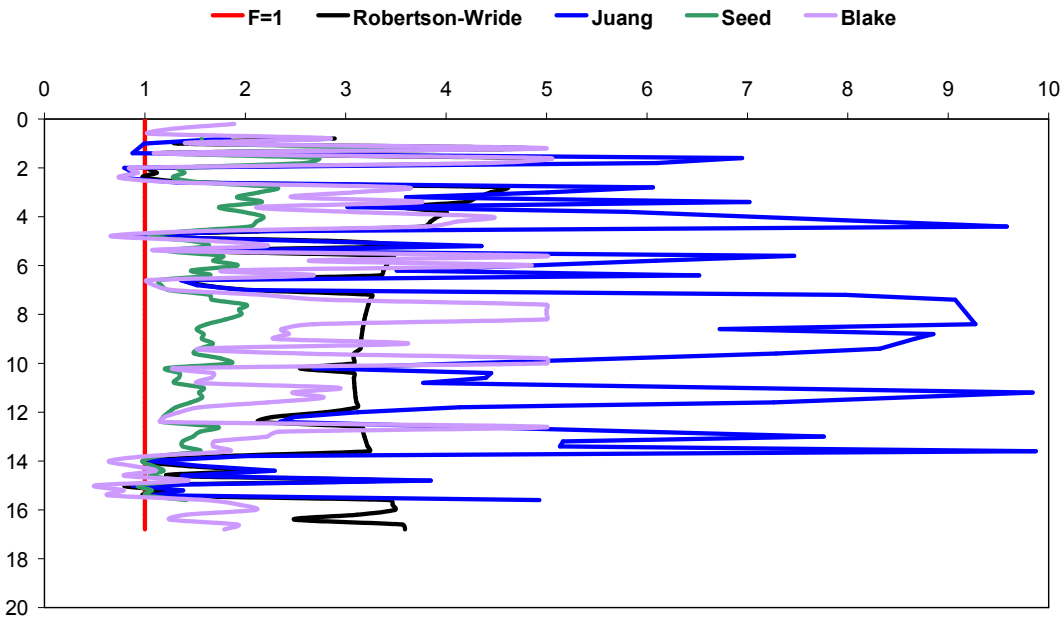

Figure 5: Comparison of safety coefficient results

As the water table level is located about 3m of depth, one should not consider liquefaction for shallow depths less that 3m. It is seen from figure 5 that all the methods predict a safety factor that is less than one for a depth near from 5m and for depths located between 14 m and 16 m. Blake method appears to be more conservative than the others. It is followed by Juang method, then by Robertson-Wride and Seed methods. Seed method is the most optimistic among the four considered methods.

DISCUSSION

It should be noted that the quality of the site characterisation work is very important for accurate evaluation of liquefaction potential. With regard to Seed and Blake methods using SPT testing, it is extremely important that the tests respect the standards as indicated in NCEER [22]. Nevertheless SPT tests can produce incorrect values of $N_{1,60}$ in situations where discontinuities exist in the soil layers such as hard sand overlaying soft clay, Boulanger and Idriss [23]. On the contrary, CPT testing is more constant. It is then more reliable using correlations for identifying $N_{1,60}$ by means of CPT results before using Seed and Blake SPT based approaches, Moss [25]. These correlations depend however on the considered site and can not be used without precaution in sites where they have not been established.

In the case study considered here, as Seed and Blake results were obtained indirectly by using correlations between CPT and SPT testing results, they are not well suited to be applied and should be discarded. As Juang method is simpler to use than Robertson –Wride method, in particular because it does not require iterations, it is well adapted to be used in evaluating liquefaction potential for Tangier soils. Furthermore, Juang method was established by using neural network approach and seems to be less dependent to the sites used for its identification in comparison with Robertson-Wride method.

Conclusion

Various semi-empirical methods enabling determination of liquefaction potential were considered in this work. Their results were compared in a case study where an important site characterisation work was performed, including CPT and core sampling tests. The obtained results have shown that the four considered semi-empirical approaches predict liquefaction under almost the same conditions. Due to the fact that Seed and Blake methods are SPT based and more sites dependent that the CPT based methods Robertson-Wride and Juang, they are a priori inappropriate to be used. As Juang method is more robust and faster than Robertson-Wride, it is well suited to be used for evaluating accurately liquefaction potential of Tangier sandy soils.

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