Validation and Verification of Semi-Empirical Methods for Evaluating Liquefaction Using Finite Element Method

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Abstract. Liquefaction is a hazardous and temporary phenomenon by which a soil saturated with water loses some or all of its resistance. The undrained conditions and a cyclic load increase the pores water pressure inside the soil and therefore a reduction of the effective stress.

Nowadays many semi-empirical methods are used to introduce a proposition to evaluate the liquefaction's potential using the in-situ test results. The objective of this paper is to study their ability to correctly predict the liquefaction potential by modelling our case using finite element methods.

The study is based on the data of Cone Penetration Tests experimental results of the Casablanca-Tangier High-Speed Line exactly between PK 116 + 450 and PK 116 + 950 and near of Moulay-Bousselham city. It belongs to the Drader-Soueir basin region which is located in the North-West of Morocco.

This region had a specific soil’s formation, the first 50 meters are characterised by the existence of sand layers alternating with layers of clay. These formations are very loose and saturated which suggests the possibility of soil liquefaction.

We present and discuss the results of applying the Olsen method [1], the Juang method [2] and the Robertson method [3], in the evaluation of liquefaction susceptibility.

Apart from the previous empirical analysis to evaluate the liquefaction potential, numerical modelling is performed in this study.

1 Introduction

The soils, during liquefaction, behave as a liquid and no longer support the shearing forces, which causes large deformations which subsequently affect the structures built on this soil.

For assessing the liquefaction potential, many semi-empirical methods are developed. This potential reflects the soil ability to resist the cyclic shear efforts and is mainly dependent on the relative density, the particle size, the soil texture, the saturation degree and the earthquake magnitude.

the case studied is based on the CPT tests data for a section of the Casablanca-Tangier High-Speed Line exactly between PK 116 + 450 and PK 116 + 950, and that is part of the basin Drader-Soueir which is located in the North-West of Morocco.

The aim of this paper is, on the one hand, to evaluate and estimate the liquefaction potential using three semi-empirical methods, namely the Olsen method [1], the Juang method [2] and the Robertson method [3] and, on the other hand, to check and validate these methods using the finite element method.

The numerical modelling of the liquefaction behaviour in this case is carried out in Quake/W software (from GeoStudio) [4], which simulates the soil’s behaviour under a cyclic loading by the generalized the finite element method. This modelling will help us to determine the semi-empirical method that predicts the best liquefaction susceptibility.

2 Semi-empirical methods used in the evaluation

The semi-empirical approaches evaluating the liquefaction potential are founded on the earthquakes observation, the liquefaction-induced effects, and the in-situ test results. The tests, which help to estimate the liquefaction potential, are mainly the Cone Penetration Test (CPT) and the Standard Penetration Test (SPT). These approaches can be divided into three categories:

- Approach by cyclic stress;
- Approach by cyclic deformation;
- Energy approach.

In this paper, the evaluation methods [1,2,3] proposed are based on the cyclic stress approach using the CPT test data.

2.1 Evaluating cyclic stress ratio

The CSR estimate for the three methods studied is based on the simplified method of Seed and Idriss (1971) [5] who proposed the following relationship:

$$CSR = \frac{\tau_{av}}{\sigma'_{v0}} = 0{,}65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{v0}}{\sigma'_{v0}}\right) r_d \qquad (1)$$

Where τ_{av} is the average cyclic shear stress; a_{max} is the maximum horizontal acceleration at the ground surface; g = 9,81 m²/s is the acceleration of gravity; σ_{v0} is the initial vertical total stress; σ'_{v0} is the initial vertical effective stress; r_d is the stress reduction factor.

The stress reduction coefficient r_d is expressed in terms of the depth by the following equations (Liao and Whitman 1986) [6]:

$$\begin{aligned} r_d &= 1 - 0{,}00765 & z \leq 9{,}15\,m \\ r_d &= 1 - 0{,}00765z & 9{,}15\,m < z \leq 23m \end{aligned} \qquad (2)$$

The Juang method [2] used the equation (1) to calculate the CSR with the introduction of MSF coefficient that adjusts the CSR value to an earthquake magnitude of 7.5. Equation (1) then becomes:

$$CSR = \frac{\tau_{av}}{\sigma'_{v0}} = 0{,}65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{v0}}{\sigma'_{v0}}\right)\frac{r_d}{MSF} \qquad (3)$$

Where MSF is expressed by the equation (4) according to I.M Idriss 1998 [7]:

$$MSF = {10^{2,24}}/{M_w^{2,56}} = \left(\frac{M_w}{7{,}5}\right)^{-2,56} \qquad (4)$$

M_w is the earthquake magnitude.

2.2. Evaluating cyclic resistance ratio

The CRR evaluation in this study is based on the CPT test data, which is among the most common in-situ tests in Morocco.

2.2.1. Olsen method

Olsen has simplified the CRR estimation by the equation (5), based on the study of several parameters influencing soil liquefaction (Olsen 1997) [1]:

$$CRR = 0{,}00128\left(\frac{q_c}{\sigma'_{v0}}\right)^{0,7} - 0{,}025 + 0{,}17R_f - 0{,}028R_f^2 + 0{,}0016R_f^3 \qquad (5)$$

With q_c is the resistance of the tip from the CPT test; R_f (friction ration) is a percentage expressed as:

$$R_f = \frac{f_s}{q_c} \times 100 \qquad (6)$$

f_s is sleeve friction resistance measured by CPT.

2.2.2 Juang method

For the Juang method, the CRR is expressed by (Juang and al., 2003) [2]:

$$CRR = C_\sigma exp\left[-2{,}9 + 1{,}264\left({q_{c1N,cs}}/{100}\right)^{1,25}\right] \qquad (1)$$

Where:

$$C_\sigma = -0{,}016\left({\sigma'_{v0}}/{100}\right)^3 + 0{,}178\left({\sigma'_{v0}}/{100}\right)^2 - 0{,}063\left({\sigma'_{v0}}/{100}\right) + 0{,}903 \qquad (2)$$

$$q_{c1N,cs} = K_I q_{c1N} \qquad (3)$$

$$K_I = 2{,}249(I_c)^4 - 16{,}943(I_c)^3 + 44{,}551(I_c)^2 - 51.497(I_c) + 22.802 \qquad (4)$$

$$I_c = \left[(3{,}47 - log_{10}q_{c1N})^2 + (log_{10}F + 1{,}22)^2\right]^{0,5} \qquad (5)$$

F is normalized friction ratio defined as:

$$F = {f_s}/{(q_c - \sigma_v)} \times 100 \qquad (6)$$

2.2.3. Robertson method

The Robertson's CRR estimation (Robertson and Wride 1998) [3] appears more difficult than the other two methods. The evaluation steps are summarized in the figure 1.

This method is limited by a standardized the resistance of the tip less than 160 and uses another criterion (liquidity limit and moisture content) to evaluate the liquefaction if Ic is greater than or equal to 2.6.

2.3. Evaluating factor of safety and liquefaction probability

The factor of safety is expressed by the same equation for all methods based on the cyclic stress approach [5]:

$$F_s = {CCR}/{CSR} \qquad (7)$$

From the factor of safety coefficient, we can determine the liquefaction probability [8]:

$$PL = \frac{1}{1 + \left({F_s}/{A}\right)^B} \qquad (8)$$

Where:

- A = 1 and B = 2,78 according to Olsen method [1];
- A = 0,96 and B = 4,50 according to Juang method [2];
- A = 1 and B = 3,30 according to Robertson and Wride method [3].

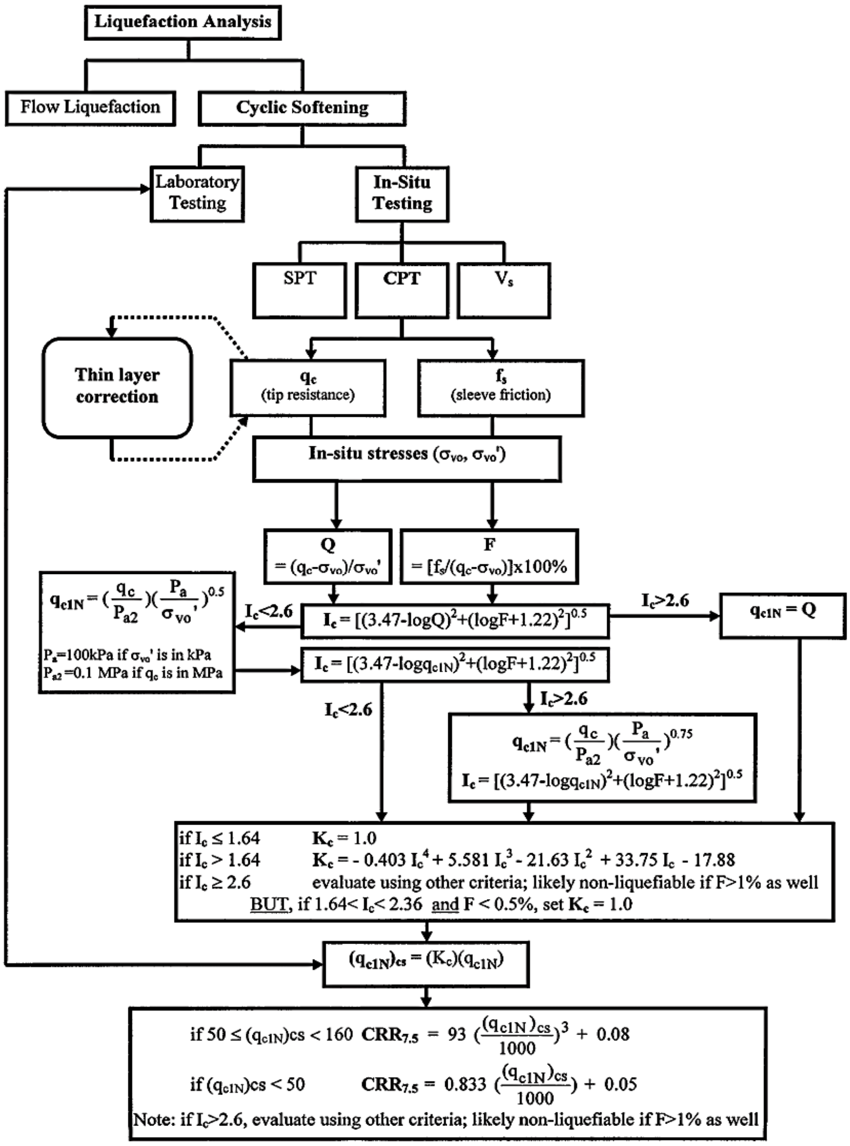

Fig. 1. Method for evaluating Cyclic Resistance Ratio (CRR) (Robertson and Wride 1998) [3]

3 Case study

Our case study positioned at the southern section of the High-Speed Line linking Tangier and Casablanca, it is between the PK 116 + 450 and the PK 116 + 950. Geographically, this section is located in the North-West of Morocco, precisely, 65 km South-East of Moulay Bousselham city.

3.1. Geological framework

Geologically, the section studied is part of the Drader-Soueir basin, which belongs to a unit that extends from the Gharb plain's South to the Oued Loukkos in the North and is limited by the clay and marly pre-Rif outcrops in the East. The unit is composed of the plio-quaternary soils that are quite varied but always more or less detrital (intercalation of sand, sandstone, sandstone limestone, sandy clay) resting on a very clear substratum formed by the Miocene blue marls [9].

The soils in the area are profoundly influenced by the textural nature of their bedrock made of quaternary sands. The granulometric analysis shows that the majority of the soils in this area contain at least 75% of the total sands, the most often 90%. The clay contents are located in the 4 to 6% except in depth where they sometimes reach 18 to 20%. The deep horizon frequently includes calcareous kidneys and needles.

Fig. 2. Satellite view of the section studied

3.2. The region's seismicity

In Oued Drader, the maximum intensity is measured at near VII, but due to the proximity of the area to the critical seismic intensity regions, including a historical seismic site, and for safety measures, considers an intensity of IX.

Many conversion laws between the intensity and the magnitude were developed by Cherkaoui 1991 [10] and Karnick 1968 [11], thus allowing a correlation between the two parameters. For an intensity equal to IX, the Drader-Soueir basin magnitude retained is M = 6.5.

Given that the Oued Drader region is part of the Seismic Zone No. 3 according to the RPS 2000 revised in 2011, it is therefore considered a maximum acceleration of 0.14 g [12].

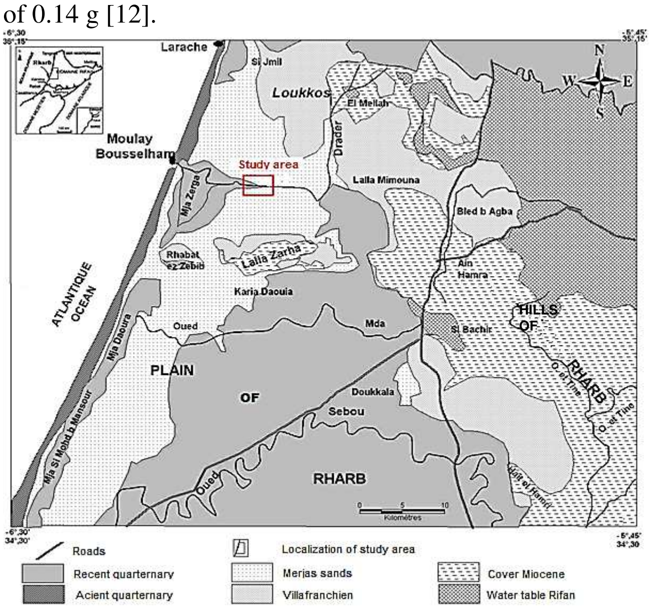

Fig. 3. The Pre-Rif Simplified Geological Map [9]

4 Results and discussions

4.1. Evaluating liquefaction potential

In this study, we evaluate the liquefaction susceptibility using the data from 6 surveys of the test CPT along the section between the PK116 + 450 and the PK 116 + 950 of the High-Speed Line.

This evaluation is made by, on the one hand, the estimation of the safety factor and the liquefaction probability by the 3 semi-empirical methods which are the Olsen method [1], the Juang method [2] and the Robertson method [3] and based on the cyclic stress approach, the results of each one are presented in the figures 4, 5 and 6. On the other hand, by modelling the two surveys executed in the PK 116 + 580 (figure 7) and the PK 116 +720 (figure 8), which aims to analyse and study the soil response when it is subjected to a cyclic loading, and to examine the possibility of a certain generation of an excessive overpressures, which could result liquefaction.

According to the analysis of the different graphs in the figures 4, 5 and 6, it is found the common layers which are the most affected in the depths between 6 and 14 m, with a high liquefaction probability at the silty and the sandy soils such as the silty sand to sandy silt where the factor of security much less than 1 for the three methods [1, 2, 3] in the PK 116 + 950 survey and the silts sensitive also in the PK 116 + 650 survey.

The PK 116 + 780 survey presents a low probability due to the important alternation of clay layers which are less susceptible to liquefaction.

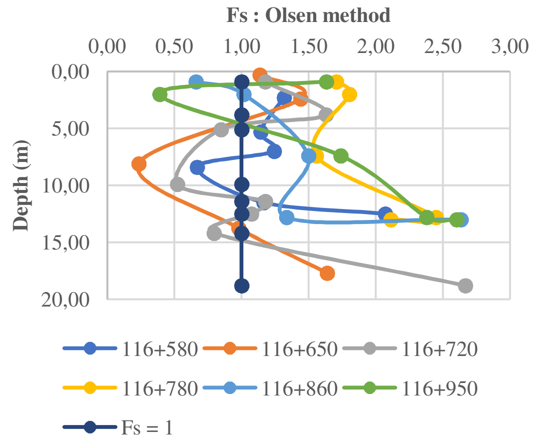

Fig. 2. The Fs Values by the Olsen method

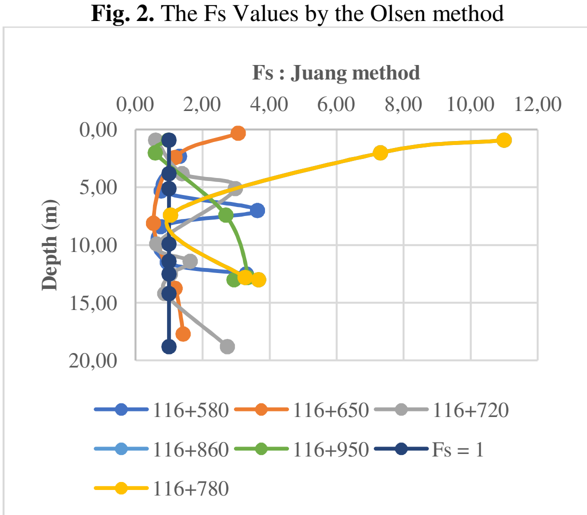

Fig. 3. The Fs Values by the Juang method

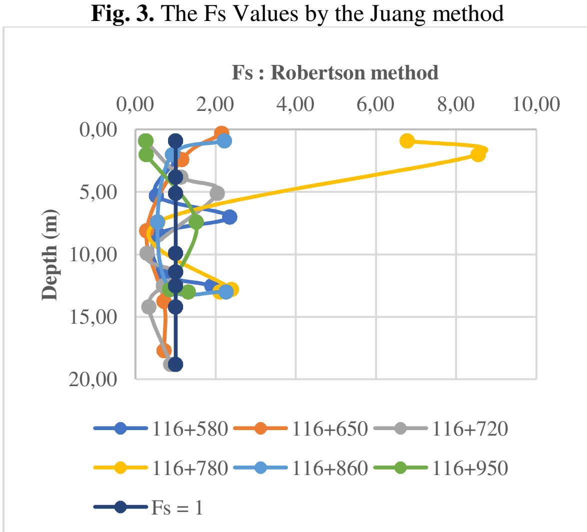

Fig. 4. The Fs values by the Robertson method

Returning to the numerical modelling results of the two surveys the PK116 + 580 and the PK116 + 720 presented in the figures 9 and 10, we find that the Pore Water Pressure significantly increases, for the first survey, in the sand layer and also in the silty sand to sand and the silty sand to sandy silt layers, and for the second survey, in the three successive layers' silty sand to sandy silt- silty sand to sandy silt - silty sand to sand. This increase, according to the Terzaghi postulate [13], compensates the total stress so it causes the loss of the shear strength and therefore increases the liquefaction risk.

These layers are generally located between 6 and 14 m, which confirms the results preliminary analysis of the semi-empirical methods except that for the fine clayey or sensitive silt layer the pore water pressure is average.

We can conclude that the region of the Drader-Souier basin can be considered as very susceptible to liquefaction, due, on the one hand, to the formations nature in the area, which are characterized by the existence of sand and silt layers alternate with more clayey layers, which are saturated with water because of the basin hydrogeological nature, on the other hand, with the seismic risk present in this region.

4.2. Validation and Verification of Semi-Empirical Methods

As we have already said, the Layers susceptible to liquefaction, from the results of the numerical modelling are the sand layer, the silty sand to sand and the silty sand to sandy silt layers in the PK116 + 580 and the three successive layers' silty sand to sandy silt- silty sand to sandy silt - silty sand to sand in the PK116 + 720, the rest of the layers has an average susceptibility except for the layers more or less clayey that have a low risk.

Comparing these results with the Table 1 results, we find that:

- These results are close to that of the Olsen method [1] even, it does not have an aspect physical well-defined and knowing that it is easy to exploit.
- The Robertson method [3] is also close to modelling results except that it is more restrictive for fine soils.
- The Juang method [2] has an aspect physical robust but in our case study these results are far from that of the modelling except for the layers where the soils are fine and loose soil.

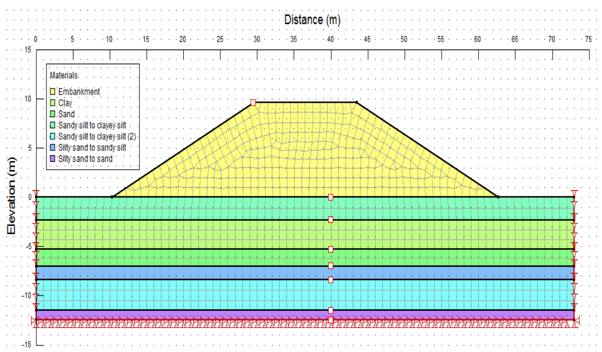

Fig.5. The component layers of the PK 116 + 580 survey

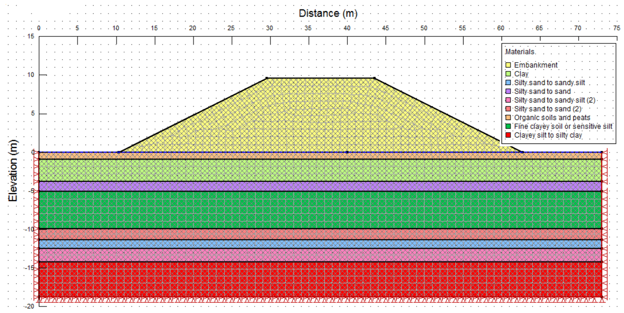

Figure 6 : The component layers of the PK 116 + 720 survey

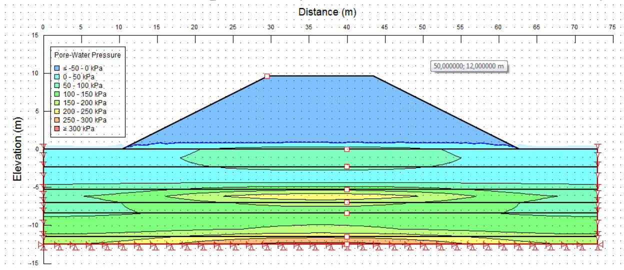

Fig. 7. The PWP distribution in the PK 116 + 580 survey

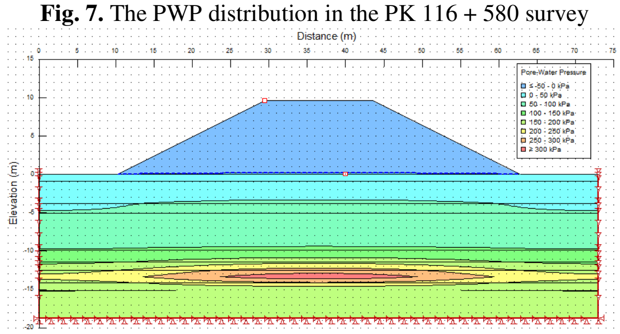

Fig. 8. : The PWP distribution in the PK 116 + 720 survey

Table 1. The liquefaction probability results of the three methods in the PK116 + 580 and PK116 + 720 surveys

	PK	Classification	Olsen	Juang	Robertson
Zone 1	116+580	Sandy silt to clayey silt	0.32	0.20	0.46
		Clay	0.41	0.73	0.90
		Sand	0.35	0.00	0.06
		Silty sand to sandy silt	0.75	0.75	0.87
		Sandy silt to clayey silt	0.40	0.51	0.80
		Silty sand to sand	0.12	0.00	0.11
Zone 2	116+720	Organic soils and peats	0.39	0.89	0.99
		Clay	0.20	0.16	0.40
		Silty sand to sand	0.61	0.01	0.09
		Fine clayey soil or sensitive silt	0.86	0.86	0.98
		Silty sand to sand	0.39	0.08	0.50
		Silty sand to sandy silt	0.45	0.41	0.77
		Silty sand to sandy silt	0.65	0.60	0.97
		Clayey silt to silty clay	0.06	0.01	0.60

Conclusion

Based on the data from six surveys of the CPT test between the PK 116 + 450 and the PK 116 + 950 from the High-Speed Line, the liquefaction potential calculations were carried out using three methods based on the cyclic stress approach which are the Olsen method [1], the Juang method [2] and the Robertson method [3].

The results of these calculations and the numerical modelling with the finite element method allowed us to conclude that the Drader region presents a high risk of liquefaction due the geological, hydrogeological and seismic context of the region.

We also compared the different methods results used in this study and those of the numerical modelling concluded that the Olsen method [2] seems to be the closest and the simplest to operate among those proposed.

We also conclude that the Robertson [3] method is restrictive for the fine soils even if they are not loose and the Juang method [2] results are furthest from the modelling results even if it has an aspect physical robust.

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