Development of liquefiable zone mapping using semi-empirical methods

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ABSTRACT

One of the most significant processes in soil dynamics is liquefaction. It is a loss of strength coupled by a quick increase in pore pressure, causing soil particles to break apart for a brief period. There have been several approaches published for calculating the residual or liquefied shear strength of cohesionless soils. This article gives cone penetration test relationships for assessing vulnerability to loss of strength and liquefied shear strength in a variety of soils. Then, based on the results of our studies, we were able to map the liquefiable zones of the Mnasra region, located in the Gharb basin and extending over an area of 4000 km2, which is characterized by two main facies: (i) a predominantly gravelly and/or conglomeratic facies, separated by silt-clay levels (east of the nappe), (ii) a predominantly sandy, sandstone and calcareous facies, separated by silt-clay levels (coastal zone and southern sector on the Maâmora side). IPL calculations predict a spatial-temporal variation in liquefaction at depths ranging from a low probability of liquefaction to a certainty.

Keywords: Liquefaction mapping; Pulverulent soils; Semi-empirical method.

1. Introduction

During liquefaction, the soil behaves like a liquid and can no longer withstand settlement forces, causing significant deformations that eventually harm the buildings built on the soil. Numerous semi-empirical techniques are developed for evaluating the liquefaction potential. This potential, which is primarily influenced by the relative density, particle size, soil texture, saturation level, and earthquake magnitude, represents the soil's capacity to withstand cyclic shear efforts (Seed & Idriss, 1971; Robertson & Wride, 1998; Juang and al., 2003; Boulanger & Idriss, 2008).

The case study is based on CPT test data from the Mnasra area, part of the Sebou basin, as part of the construction of a high-speed railroad line crossing the Oued Sebou alluvial plain (Fig. 1).

The aim of this research is, on the one hand, to assess liquefaction susceptibility based on geological and hydrogeological data and, on the other hand, to estimate liquefaction potential based on geotechnical data by calculating the liquefaction probability index (IPL) using semi-empirical methods, particularly the method of Robertson & Wride (1998). Simultaneously, and based on the IPL results and calculations, it was possible to map liquefiable zones along the bed of the Oued Sebou and the Mnasra-Oulad Salama region, while indicating spatial-temporal variations in liquefaction probability as a function of the depth and level of the Mnasra nappe.

2. Data

2.1. Geological and morphological framework

The Mio-Plio-Quaternary Gharb basin, which contains the Sebou basin, is centred around fundamentally Soltanian marine sand and sandstone strata (similar to Weichselian). Most of the surface formations in the Gharb basin consist of these deposits, which are characterized by continental deposits of Gharbian clayey or silty alluvium (corresponding to the recent Holocene) along the banks of the Oued Sebou (Cirac, 1985; Flinch, 1993).

The southern domain corresponds to the offshore part of the Rharb basin and is characterized by a shelf of variable width, ranging from 35 to 20 km. It is thinned at the southern edge where it is connected at the shelf break to a major canyon called ‘‘the Rharb submarine valley’’. The smoothness (low rugosity) of the shelf and swollen geometry of isobaths of the inner part 1 illustrate the volume of recent sedimentation driven by the input from the Sebou River, characterized by the highest volumetric flow and the largest sediment load of all Moroccan rivers (Jaaidi, 1993).

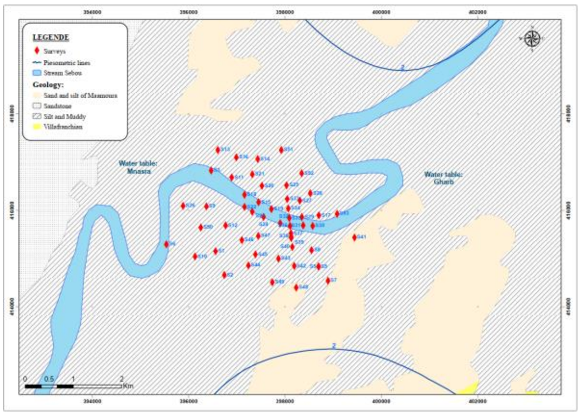

Figure 1. Geological map of the study area with piesometrical levels, Ghab Basin, Morocco.

2.2. Lithology and stratigraphy

Located in the center of the Gharb, the upper aquifer is composed of silty clay deposits that date back to the Quaternary. It has little hydrogeological significance and is of middling quality. Facies dominated by gravelly and/or conglomeratic levels, separated by silty-clayey levels (east of the nappe), and facies dominated by sandy levels, sandstones, and calcarenites, separated by silty-clayey levels (coastal zone and southern sector on the Maâmora side) are the two subgroups of the plio-quaternary-age soils through which the deep nappe flows. In particular, the permeable layers are scattered with semi-permeable clay lenses of different thickness. Because of this arrangement, the Gharb deep aquifer is multi-layered (Aberkan, 1989; Kili and al., 2007).

The Oued Sebou, which serves as the main watercourse for the plain, is thought to have deposited the Mnasra nappe, a single free aquifer that is stored in the Mio-Pliocene and Quaternary fills of the Gharb plain, some of which is of fluvial origin (Cirac, 1985; Flinch, 1993; Flinch & Vail, 1998; Chalouan & Michard, 2004). A clay to clay-marl impermeable screen of Upper Miocene and Middle Pliocene age underlies the water table (Cirac, 1985; Wernli, 1987).

2.3. The region's seismicity

Morocco is situated in an area that separates the African and Eurasian plates, in the far northwest of the continent. Regionally speaking, Morocco is impacted by the Azores-Gibraltar seismicity line, a significant complex transform fault that connects the Mid-Atlantic Ridge to the Gibraltar region and has previously caused several extremely strong earthquakes (Iben Brahim et al., 2004).

The seismic activity observed in Morocco and its neighbouring regions between 1990 and 2001 is displayed in Figure 1. A zone of intense seismic activity stretches from the Atlantic Ocean to the Strait of Gibraltar in northern Morocco. The interactions between the African and Eurasian continents at their boundary where the African and Eurasian plates collide are reflected in this line of seismicity (Iben Brahim et al., 2004).

The maximum intensity in the Mnasra area is almost VII, but for safety concerns, it is IX due to the vicinity of locations of important seismic intensity, including the seismic site. A maximum horizontal acceleration of 0.14 g is taken into consideration, and considering the unfavourable case, a magnitude of 7.1 is retained in the CRR calculations, with reference to the most recent earthquake that shook the Marrakech region of Morocco, given that the study area is classified as seismic zone No. 3 according to the Moroccan Seismic Regulations 2011.

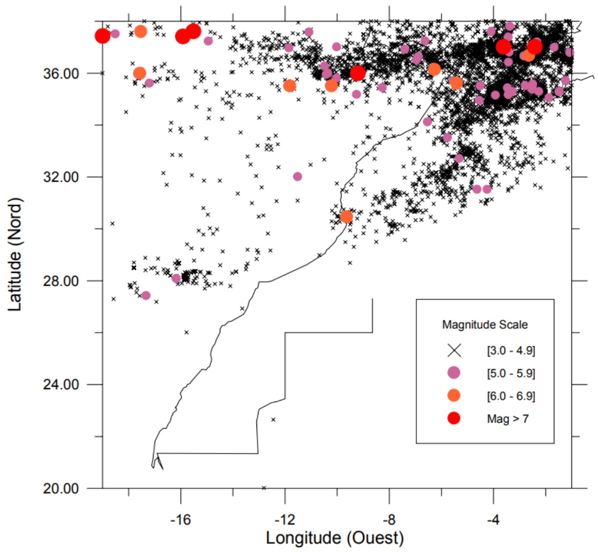

Figure 2. Seismicity map of Morocco for the period of 1900 to 2001 (Iben Brahim and al., 2004).

3. Methodology

To evaluate a soil's resistance to liquefaction, two variables must be computed or estimated: (1) the seismic demand on a soil layer, stated in terms of CSR; and (2) the soil's liquefaction resistance, expressed in terms of CRR. The latter variable is also known as the ratio of cyclic stress needed to cause liquefaction or the cyclic stress ratio Seed and Idriss (1971).

Evaluation of the cyclic stress ratio (CSR)

The following formula was developed by Seed and Idriss (1971) to determine the cyclic stress ratio:

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

- σ'_{v0} is the effective vertical stress in (kPa).
- a_{max} is the maximum amplitude of horizontal acceleration in (m/s²).
- g is the the acceleration of gravity = 9,81 m²/s.
- σ_{v0} is the total vertical stress due to the weight of the overlying soils (kPa).
- r_d is the stress reduction coefficient that reflects the flexibility of the soil column in (m).

The following formulae Liao and Whitman (1986) can be used to estimate typical values of r_d for ordinary practice and noncritical projects:

$$r_d = 1 - 0{,}00765\ Si\ Z \leq 9{,}15m \qquad (2a)$$

$$r_d = 1 - 0{,}00765\ Si\quad 9{,}15m \leq Z \leq 23m \qquad (2b)$$

where z is the depth in meters below the ground's surface. Additional formulae for determining r_d at deeper depths have been proposed by some researchers Robertson and Wride (1998), however the evaluation of liquefaction at these deeper depths is below the depths where normal applications should be made and where the simplified method is proven.

The mean and range of values suggested by Seed & Idriss (1971) are presented in Fig. 3, together with the mean values of r_d calculated from (2).

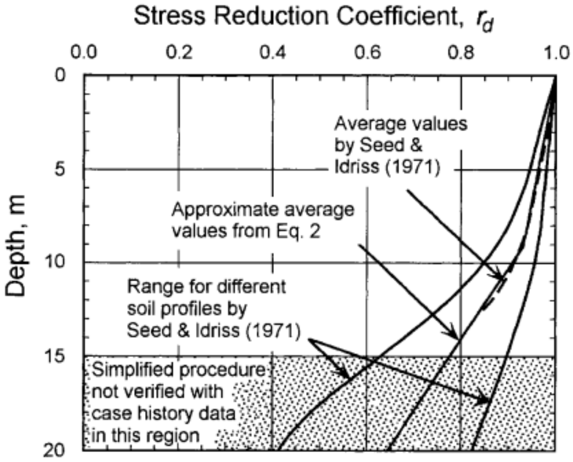

Figure 3. rd versus Depth Curves Developed by Seed and Idriss (1971) with Added Mean-Value Lines Plotted from Eq. (2).

Cyclic Resistance Ratio (CRR) from cone penetration test

Robertson and Wride's Cyclic Resistance Coefficient (CRR) evaluation method is defined as follows (Robertson & Wride, 1997; Robertson & Wride, 1998):

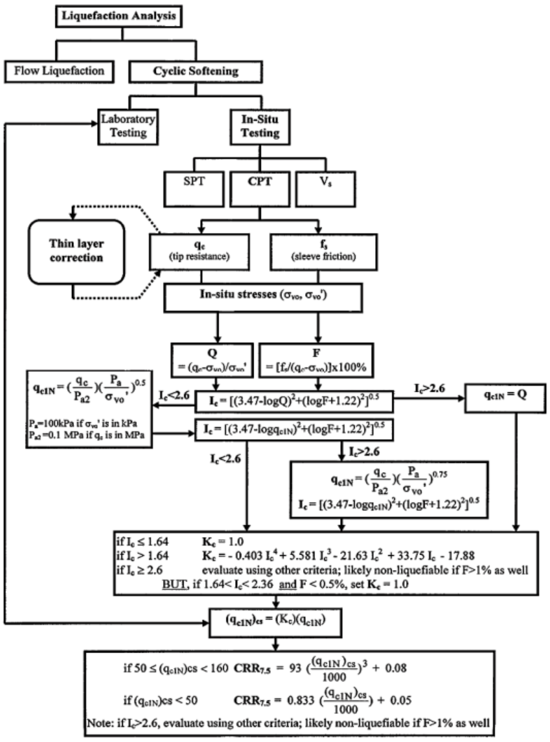

Figure 4. Robertson & Wride's (1998) method for calculating the cyclic stress ratio (CRR).

Safety factor (SF) and liquefaction probability index (IPL) assessment

The safety factor is expressed by (Youd and al., 2001; Idriss and al., 2004):

$$F_s = {CRR}/{CSR} \quad (3)$$

The chance of liquefaction can be calculated using the safety factor (Juang and al. 2003).

$$\boldsymbol{IPL} = \frac{\mathbf{1}}{\mathbf{1}+\left({Fs}/{A}\right)^{B}} \quad (4)$$

Where, A = 1 and B = 3.30 according to the Robertson and Wride (1998).

From the probability index defined by equation (14), the class of occurrence of liquefaction (Table 1) (Juang and al., 2003; Idriss & Boulanger, 2008):

Table 1. Occurrence of liquefaction by probability index by Juang and al. (2003).

IPL	**Classe**	**Description (probability of liquefaction)**
$IPL \ge$ 0,85	5	Liquefaction almost certain
0,65 ≤ IPL < 0,85	4	Liquefaction very likely
0,35 ≤ IPL < 0,65	3	Liquefaction and no-liquefaction are possible
0,15 ≤ IPL < 0,35	2	Liquefaction unlikely
IPL < 0,15	1	Liquefaction almost impossible

4. Results and Discussions

The geotechnical study of the Oued Sebou alluvial soil revealed the presence of a sandy horizon, extending over a thickness of 6 to 15 m. In addition, in situ tests showed poor mechanical characteristics of the sandy-clay-loamy material, which classifies it as loose sand. Given the lithology of the soils and their granulometry, we can also distinguish two nappes: the Mnasra nappe and the Gharb nappe (see Fig.1), which fall within the range of liquefiable soils.

Formations consisting of sands, silts, silts, sandy mud, and soft clays, mainly silty-clay and silty-sandy, present a very high risk of liquefaction, according to the calculated IPL, which varies between 0.66 and 0.98 (Table 2). As the depth increases, and beyond 15 m, the liquefaction probability index decreases to zero, due to the absence of a water table and the grading of the sediments, which become sandstone, and above all to the compact structure of the soil.

As depth increases, there is a greater chance of liquefaction (Table 2, Figs. 5, 6 and 7). Note that because of the high degree of saturation in this zone, liquefaction is unlikely to occur at depths below 7 meters, with the exception of boreholes situated along the bed of the Oued Sebou alluvial plain. Because of the sandy formation, which occasionally satisfies the liquefaction condition in the presence of the water table and is silty, clayey, and silty, the probability of liquefaction increases with depth until it becomes certain. There are seven to fourteen slices of sediment that are guaranteed to liquefy; these are found mostly in the boreholes around the mouth of the Oued Sebou and its boundaries.

At a depth of 21 m (Table 2 and Fig. 7), liquefaction is most likely finalized along the Oued Sebou borders a nd becomes sporadic at the Oued Sebou. This indicates t hat the soil lithology is compact and that the water table is absent at this depth.

Slabs of sediment exhibiting certain and extremely probable liquefaction can be found, roughly speaking, in the deposits of the Oued Sebou's alluvial plain and its northern border in the Mnasra region. These sediments are found at progressively deeper depths from the Mnasra area (0 m deep) towards the middle of the Oued Sebou alluvial plain (8 m and 15 m deep). They are mostly composed of sands and silts, frequently clayey-silty or silty. This reflects the Oued alluvial plain's northern extension.

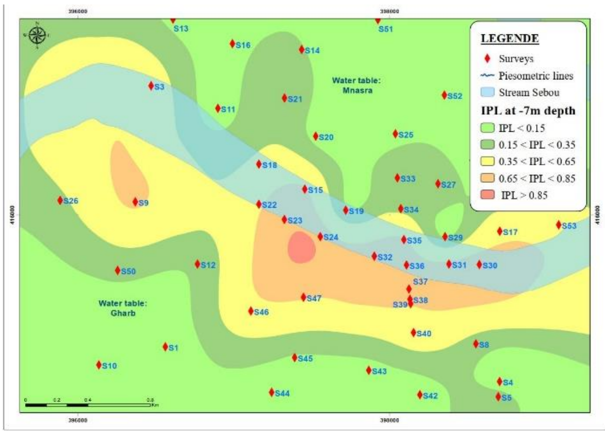

Figure 5. IPL variation at -7m depth.

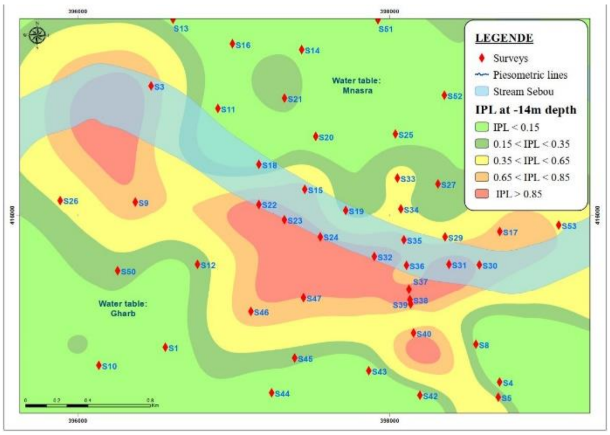

Figure 6. IPL variation at -14m depth.

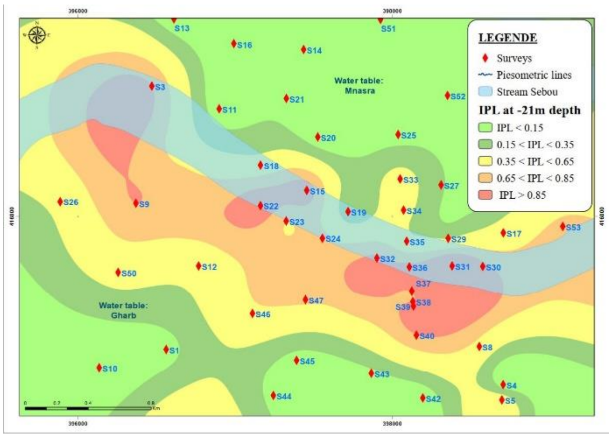

Figure 7. IPL variation at -21m depth.

Table 2. Result of IPL calculation using the Robertson & Wride method for drill holes S24 and S19.

S	Lithology of the terrain	Depht(m)	IPL Value
S24	Silty to Silty-Clayey	0 To 7m	0,66
	Sand-Silty-Clayey	7 to 14m	0,98
	Soft Clays Sandstone	14 to 21m	0,77
S19	Muddy and clays	0 To 7m	0,49
	Silty and sand to sand-clayey	7 to 14m	0,71
	Sandstone	14 to 21m	0,36

In conclusion, the results of the computations demonstrated that the liquefaction phenomena are significantly influenced by the seismic stress and the saturation level of the soil.

Furthermore, an initial investigation was conducted using the over-consolidation (ROC) ratio that is, the ratio of the total effective stress divided by the confining stress. The soil's potential for liquefaction is assessed using this ratio. This method relies on soil texture and mechanical tests.

According to the IPL calculation results, under-consolidated soils (ROC<1) have a higher likelihood of liquefying than over-consolidated soils (ROC>1).

Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications, extensions, and future developments.

5. Conclusions

Geotechnical engineers have not paid enough attention to the phenomenon of liquefaction in soil treatment and geotechnical studies, despite the fact that it is one of the most dangerous phenomena affecting water-saturated soils, due to the fact that Morocco has not experienced earthquakes with high magnetudes.

However, with the recent earthquake in the province of Al Haouz in Morocco, with a magnetude greater than 7.1 on the Richter scale, the idea has been totally changed towards the creation of a map of liquefiable zones with a magnetude of 7.5, particularly for projects that should be built on the edge of the sea, an alluvial plain or a watercourse.

This manuscript is the first to map potentially liquefiable areas in Morocco. IPL calculations have shown that sandy, silty and muddy formations are potentially liquefiable when saturation is 100% and dynamic load exceeds 7, suggesting that groundwater level detection is very important during geotechnical studies.

Furthermore, thanks to the over-consolidation ratio, it is possible to estimate whether or not the soil is likely to liquefy before starting finite method calculations.

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