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Enhanced liquefaction susceptibility evaluation of Lisbon sands by CPTu and SPT tests with laboratory GSD and plasticity

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ABSTRACT: Soil liquefaction is oftentimes the main cause of social and economic damages associated with seismic events. Nowadays, it is recognized that fines content and its plasticity play a major role in the soil behavior and therefore it is fundamental to ensure its correct interpretation and integration in the liquefaction triggering analyses. Within the framework of LIQ2PROEARTH project, an area in Lisbon, Portugal, was selected where several geotechnical in situ tests were performed, including SPT and CPTu. The present work analyses the results of two soil profiles, using fines content and plasticity indexes obtained in the laboratory, in the assessment of the factor of safety against liquefaction, the liquefaction potential index (LPI) and the liquefaction severity number (LSN). While recognizing that CPT-based liquefaction analyzes are more reliable, it was found that an additional laboratory characterization of fines content and plasticity, implemented in the interpretation of SPT data, provided converging results with the CPTu.

Keywords: fines content; SPT; CPTu; liquefaction

1. Introduction

Soil liquefaction is oftentimes the main cause of social and economic damages associated with seismic events. In recent years, many earthquake events have occurred where liquefaction was observed, namely in Japan [1], in Christchurch, New Zealand [2] or in Emilia-Romagna, Italy [3]. The earthquake events show how the soil behaves under cyclic motion and their study allows for deepen understanding of liquefaction susceptibility of different soils, helping in the correlation of field observations from real seismic events with formulations based on in situ tests.

The Standard Penetration Test (SPT) and Cone Penetration Test (CPTu) have been widely used to evaluate liquefaction characteristics of soils in the field, as these tests are the most commonly used worldwide for geotechnical site characterization. The development of SPT-based and CPTu-based liquefaction triggering procedures has been the object of study of many researchers and different methodologies have been proposed to estimate the cyclic resistance of a soil, based on the number of blow counts from SPT or the cone resistance from CPTu [4-6]. However, the liquefaction assessment procedures are based on different quantity and quality case histories and are constantly being improved with the implementation of new data. Each methodology requires a set of parameters obtained by empirical correlations that vary according to the selected method.

The physical properties strongly affect the behavior of a soil when subjected to cyclic motion, especially the fines content (FC), *i.e.*, the percentage of particles with a diameter smaller than 0.075mm, and the plasticity of these fines. The importance of fines content began to be noticeable when the CRR versus penetration resistance diagrams that distinguished liquefaction from non-liquefaction, originated from liquefaction case studies, were found to be strongly dependent on fines content [7, 8]. Since then, many studies have proven that the FC strongly affects the liquefaction susceptibility of soils, both in field tests [9, 10] and in laboratory tests [11, 12]. Nowadays, some liquefaction assessment methods include the fines content as a relevant parameter and the blow count from SPT and the cone resistance from CPTu are usually normalized to equivalent clean sand values, using FC as input data.

The aim of this research is to study the influence of laboratory test results, namely grain size analyses and Atterberg limits, in the liquefaction susceptibility of soils, using different liquefaction assessment approaches, namely the factor of safety against liquefaction, the liquefaction potential index (LPI) and the liquefaction severity number (LSN). To better understand the effect of these physical properties in different layers, the present work intends to analyze SPT and CPTu tests performed in an experimental site near Lisbon, Portugal, and discuss the influence of using estimates of fines content (from empirical correlations) or the integration of the laboratory-measured fines content in the liquefaction susceptibility of two soil profiles.

2. Case Study

Within the framework of a Portuguese research project, LIQ2PROEARTH, an experimental site was implemented in Lezíria Grande de Vila Franca de Xira, in the Lisbon region, Portugal. The main objectives of the project were to study the liquefaction susceptibility of the zone and to develop proposals of design guidelines for the application of soil characterization and liquefaction risk assessment protocols. In this sense, an extensive campaign was conducted, which included many field tests, namely standard penetration tests (SPT) and piezocone penetration tests (CPTu). The area was selected according to the geological, geomechanical and seismic characteristics of the zone, described in detail in [13, 14]. Figure 1 shows the location of the two sites selected for this work, where both SPT and CPTu were performed, close to each other.

Figure 1. Location of the testing sites

The ground water level found in each location was 0.94m and 1.60m, for SI1 and SI7, respectively. The local peak ground acceleration (PGA or a_{max}) was defined based on the specifications from Eurocode 8 and the National Annex [15]. For a return period of 475 years and a building importance class of II for the seismic zone of Vila Franca de Xira, the PGA values are 0.20g for type 1 of seismic action and 0.31g for type 2. The corresponding moment magnitudes are 7.5 and 5.2 for seismic action type 1 and type 2, respectively.

Figure 2 shows the profiles in depth of the SPT number of blow counts and the cone penetration resistance for SI1 and SI7 without normalization to equivalent clean sand values. Both profiles show heterogeneous layers, more noticeable in the CPTu profiles as the measurements are nearly continuous in depth. However the two tests seem to converge, as the layers with higher q_{c1N} are also the layers with higher $(N_1)_{60}$. The heterogeneity of the profiles is evident, with some layers showing higher resistance, particularly from 2m to 3m and 5m to 7m in SI1 and from 7m to 13m in SI7.

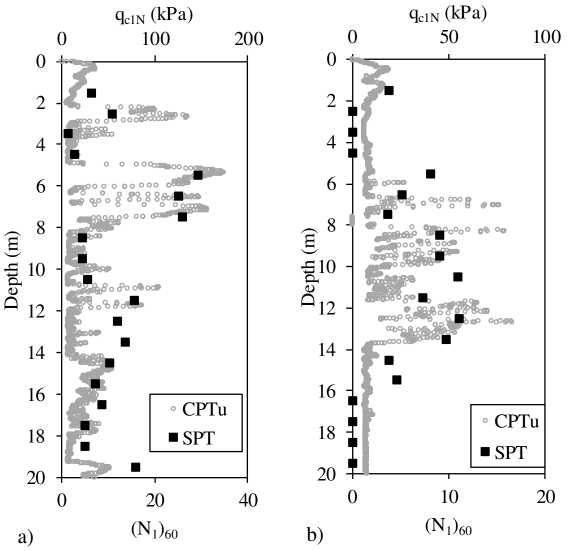

Figure 2. Resistance parameters for SPT and CPTu: a) SI1, b) SI7

3. Methodology

3.1. Liquefaction assessment

Over the years, different liquefaction susceptibility assessment procedures have been developed. The most commonly used is known as the Seed-Idriss simplified procedure (initially proposed by Seed and Idriss [16]), a stress-based framework that defines the factor of safety against liquefaction (FS_{liq}) as the ratio between the cyclic resistance ratio (CRR) and the cyclic stress ratio (CSR).

The CSR defines the design seismic action to which the soil is subjected, and is defined as Eq. (1), where σ_v and σ'_v are the vertical total and effective stresses respectively, a_{max} is the maximum horizontal acceleration, g is the acceleration of gravity and r_d is a shear stress reduction coefficient that depends on depth and seismic magnitude.

$$\mathrm{CSR} = 0.65\left(\frac{\sigma_v}{\sigma'_v}\right)\left(\frac{a_{max}}{g}\right) r_d \qquad (1)$$

The CRR evaluates the soil capacity to resist liquefaction and can be estimated based on in situ test results, namely standard penetration test (SPT) and cone penetration test (CPTu). The methodology used in this work was proposed by Boulanger and Idriss [6], here referred to as B&I14, based on the proposition from Idriss and Boulanger [17, 18], which includes a new magnitude scaling factor relationship and fines content estimation. Equations (2) and (3) present the deterministic CPTu and SPT-based correlations to obtain CRR for the reference magnitude of 7.5 and an effective vertical stress of 1atm.

$$\mathrm{CRR}_{M=7.5,\sigma'v=1atm} = \exp\left(\frac{q_{c1Ncs}}{113} + \left(\frac{q_{c1Ncs}}{1000}\right)^2 - \left(\frac{q_{c1Ncs}}{140}\right)^3 + \left(\frac{q_{c1Ncs}}{137}\right)^4 - 2.80\right) \qquad (2)$$

$$\mathrm{CRR}_{M=7.5,\sigma'v=1atm} = \exp\left(\frac{(N_1)_{60cs}}{14.1} + \left(\frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.8\right) \quad (3)$$

For earthquake magnitudes other than the reference 7.5 and to account for the effective overburden stress, two correction factors are implemented, the MSF and the K_σ, respectively. The CSR or CRR are normalized according to Eq. (4). The formulations to calculate the MSF and K_σ are detailed in [6, 13].

$$\mathrm{CSR}_{M=7.5,\sigma'_v=1atm} = \frac{\mathrm{CSR}_{M,\sigma'_v}}{MSF \cdot K_\sigma} \quad or$$

$$\mathrm{CRR}_{M,\sigma'_v} = \mathrm{CRR}_{M=7.5,\sigma'_v=1atm} \cdot MSF \cdot K_\sigma \quad (4)$$

Besides, there are other approaches to determine the liquefaction susceptibility, namely the Liquefaction Potential Index (LPI) and the Liquefaction Severity Number (LSN). These parameters were developed to assess the potential liquefaction occurrence and the possible liquefaction-induced damages on soil and infrastructures.

The Liquefaction Potential Index (LPI) was first proposed by Iwasaki et al. [19] to characterize the liquefaction potential damage. Its calculation is based on the factor of safety against liquefaction, hence varies depending on the method used to calculate FS_{liq}. It considers the first 20 m depth below ground surface and can be obtained using Eq. (5), where $F=1-FS_{liq}$ for $FS_{liq} \leq 1$, $F=0$ for $FS_{liq} > 1$ and $w(z)=10-0.5z$ for $z \leq 20m$.

$$\mathrm{LPI} = \int_0^{20m} F \times w(z)\, dz \quad (5)$$

Iwasaki et al [20] defined intervals for LPI classification, classifying liquefaction potential as low when LPI is lower than 5, high when LPI is between 5 and 15 and very high if LPI is higher than 15.

The Liquefaction Severity Number (LSN) was developed by Tonkin and Taylor [21] and represents the effects of shallow liquefaction damage on residential land and foundations. This parameter is expressed by Eq. (6), where ε_v is the post-earthquake volumetric densification strain at depth z [22] and z is the depth of the layer of interest. This method considers all the layers with $FS_{liq}<2$.

$$\mathrm{LSN} = 1000 \int \frac{\varepsilon_v}{z} dz \quad (6)$$

Tonkin and Taylor [21] also defined LSN ranges for liquefaction effects, classifying the expression of liquefaction as little to none for values lower than 10, minor from 10 to 20, moderate from 20 to 30, moderate to severe from 30 to 40, major from 40-50 and severe damage for values higher than 50. This classification is used in this work to classify the two profiles.

3.2. Fines content considerations

Fines content and plasticity index play important roles on the liquefaction assessment, as it is recognized that soils with high percentage of fines and, more importantly, high plasticity are less susceptible to liquefaction [23]. Nowadays, the majority of methods used to normalize field test results include, in one way or another, the effect of fines content, making its correct determination of high importance.

There are different methodologies that include the consideration of FC and, as stated above, the methodology from B&I14 [6] includes the consideration of $(N_1)_{60cs}$ and q_{c1Ncs}, the values of SPT-blow count and cone resistance normalized to equivalent clean sands.

The normalization using fines content is performed by introducing equivalent clean sand adjustments, Δq_{c1N} and $\Delta(N_1)_{60}$, as in Eq. (7) and (8) for CPTu and SPT, respectively.

$$\mathrm{q}_{c1Ncs} = \mathrm{q}_{c1N} + \Delta \mathrm{q}_{c1N} \quad (7)$$

$$(\mathrm{N}_1)_{60cs} = (\mathrm{N}_1)_{60} + \Delta(\mathrm{N}_1)_{60} \quad (8)$$

These adjustments were empirically derived from liquefaction case history data [6] and are calculated using Eq. (9) and (10), where FC is the percent fines content. In the CPTu case, an iterative process is used to obtain Δq_{c1N} based on q_{c1N}.

$$\Delta \mathrm{q}_{c1N} = \left(11.9 + \frac{q_{c1N}}{14.6}\right) \exp\left(1.63 - \frac{9.7}{FC+2} - \left(\frac{15.7}{FC+2}\right)^2\right) \quad (9)$$

$$\Delta(\mathrm{N}_1)_{60} = \exp\left(1.63 - \frac{9.7}{FC+0.01} - \left(\frac{15.7}{FC+0.01}\right)^2\right) \quad (10)$$

These adjustments vary considerably up to values of FC around 35% and start stabilizing after that, as for FC values higher than 35% the soil matrix is mainly dominated by the fines.

For the SPT results, two methods were compared to determine the fines content of each layer in the considered soil profiles. In the first, the FC was determined based on the lithological description of the SPT log, provided by the field test operators. Table 1 presents the values of fines content according to the type of soil. These were empirically determined, using a conservative approximation inferred from a chart by Boulanger and Idriss [6] of the evolution of $\Delta(N_1)_{60}$ with the percentage of fines.

Table 1. FC values depending on soil type

Type of soil	Fines content (%)
Clay	100
Silt	90
Fine silty sand	30
Fine to medium sand	10
Sand	5

In the CPTu normalization, the B&I14 method includes a formulation to compute the fines content, based on the soil behavior index (I_C), defined in Eq. (11), where C_{FC} is a fitting parameter considered zero in this case as no site-specific data was available to estimate its correct value.

$$\mathrm{FC} = 80(I_C + C_{FC}) - 137 \tag{11}$$

In addition to these two methodologies, a more accurate estimation of the fines content and plasticity index was obtained, analyzing the soils collected with the SPT sampler, at each depth. The collected soils were tested in the laboratory, and the grain size curve and plasticity index of each layer were determined.

Figures 3 and 4 show the estimated and laboratory-measured fines content using the SPT and CPTu correlations for SI1 and SI7, respectively. The plasticity indexes obtained in the laboratory are also represented in Figure 3a and 4a, as the values next to the FC point at each depth. The estimated CPTu values show a very intricate profile, with constant changes from soils with 100% to no fines content. This is not reflected in the SPT profile, and consequently it is not represented in the laboratory measurements, as they provide constant values for each SPT sample. Therefore, in the CPTu analyses with $\mathrm{FC}_{\mathrm{lab}}$, 1m thick layers with constant FC value were considered. This can mean that, for densely layered profiles, the values obtained in the laboratory may not be fully representative of the 1m layer. However, these results help in the definition of the most critical layers in terms of liquefaction susceptibility, especially in the SPT case.

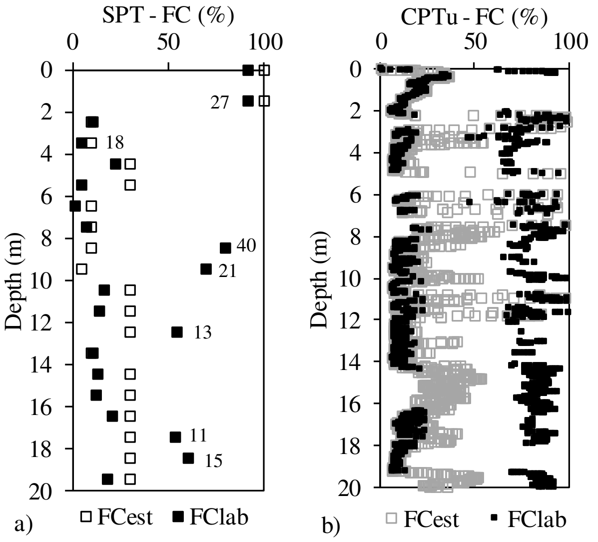

Figure 3. Profiles in depth of the FC from SI1: a) from SPT, b) from CPTu

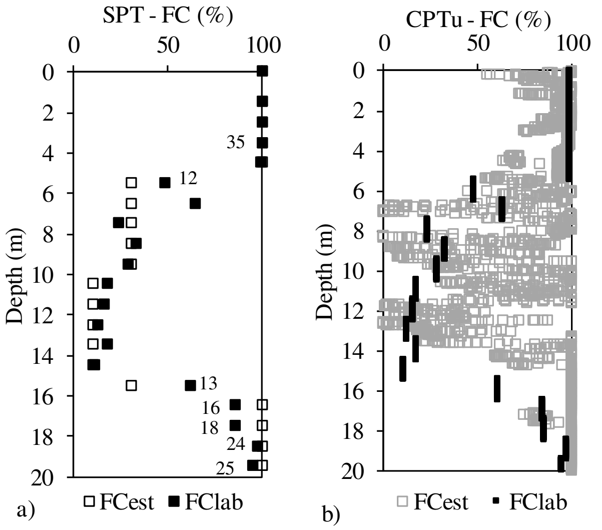

Figure 4. Profiles in depth of the FC from SI7: a) from SPT, b) from CPTu

4. Results and Discussion

4.1. Factor of safety against liquefaction

As explained before, an analysis to the influence of the consideration of different methods for FC calculation was performed, for two investigation sites using SPT and CPTu results. The SPT-based liquefaction assessment was performed using a spreadsheet, where the B&I14 methodology was implemented. On the other hand, the CPTu results were analyzed on Cliq® software (version 2.2.0.37, [24]), which includes the implementation of the B&I14 procedure and allows for the definition of the fines content of each layer.

Figures 5 and 6 present the results of $\mathrm{FS}_{\mathrm{liq}}$ analysis, for SI1 and SI7, respectively. In terms of factor of safety against liquefaction, the consideration of the estimated values or the laboratory measured values, in both SPT and CPTu (Figure 5a, 5b, 6a, 6b), does not seem relevant, as apparently the same layers are susceptible to liquefaction. In this case, $\mathrm{FS}_{\mathrm{liq}}$ under 1 was considered critical, *i.e.*, the layers that have $\mathrm{Fs}_{\mathrm{liq}}<1$ are considered susceptible to liquefaction. Moreover, different seismic action type consideration does not seem to influence the results, neither in the SPT nor in the CPTu. Therefore, Figures 5c and 6c only show the results for seismic action type 1. Analyzing the SI1 case, Figure 5c shows the results, only considering the layers with FC<35%, taken as the most critical. This soil profile is very heterogeneous, with sand/silt/clay interlayers, which hampers the clear definition of the critical layers. However, some layers were highlighted as being susceptible to liquefaction. The SPT test alone is not enough to clearly define the critical layers, as it considers a macro approach and does not detect the small interlayers. Evidence of that is the 6m to 8m layer, where the SPT defines a non-critical layer, as the collected soils do not represent the entire layer. Also analyzing the SPT results of Figure 5c, the $\mathrm{FC}_{\mathrm{lab}}$ consideration refines the results, and presents results closer to the CPTu results than the $\mathrm{FC}_{\mathrm{est}}$, which have some values out of the defined critical layers (open squares).

These conclusions are even more relevant when analyzing the SI7 profile, as it presents layers that are more homogeneous. The SPT analyses (Figure 6a) suggests that all the 20m profile is susceptible to liquefaction, almost considering the entire profile as one layer. However, when analyzing the CPTu results (Figure 6b), the separation between layers is evident. When the layers with more than 35% FC are hidden (Figure 6c), a single critical layer is detected and the representation is clearer. Once again, the SPT results with FC_{est} show some values out of the critical layer, meaning that the consideration of FC_{lab} improves the results and brings them closer to the CPTu.

4.2. LPI and LSN

As discussed in section 3.1, the use of other approaches can be helpful to fully understand the influence of different considerations and to provide information about the damages induced by soil liquefaction. For this purpose, the values of LPI and LSN were computed for the SPT and CPTu results of the two soil profiles, using both types of seismic action and both the estimation of fines content (FC_{est}) and the measured laboratory values (FC_{lab}).

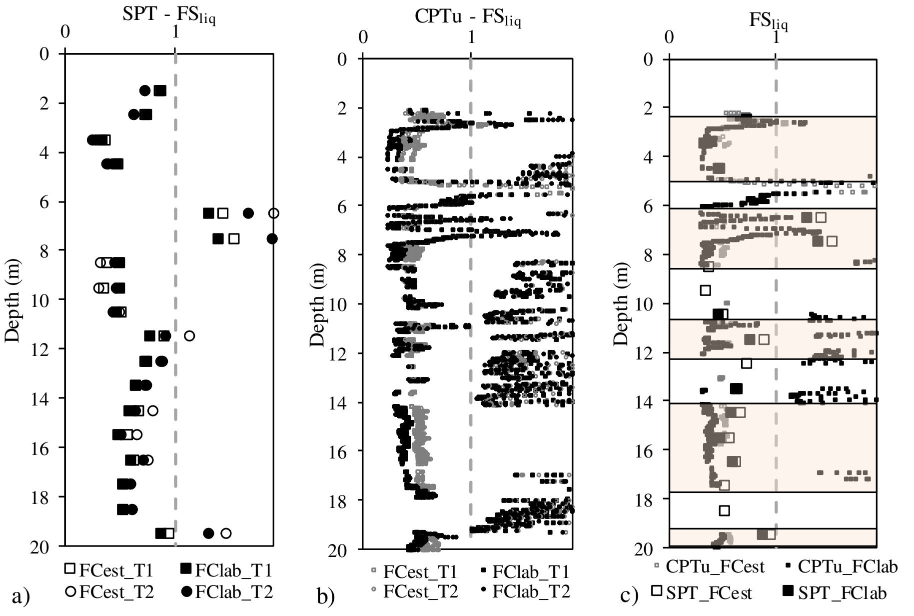

Figure 5. Factor of safety against liquefaction analysis for SI1: a) SPT; b) CPTu; c) definition of critical layers

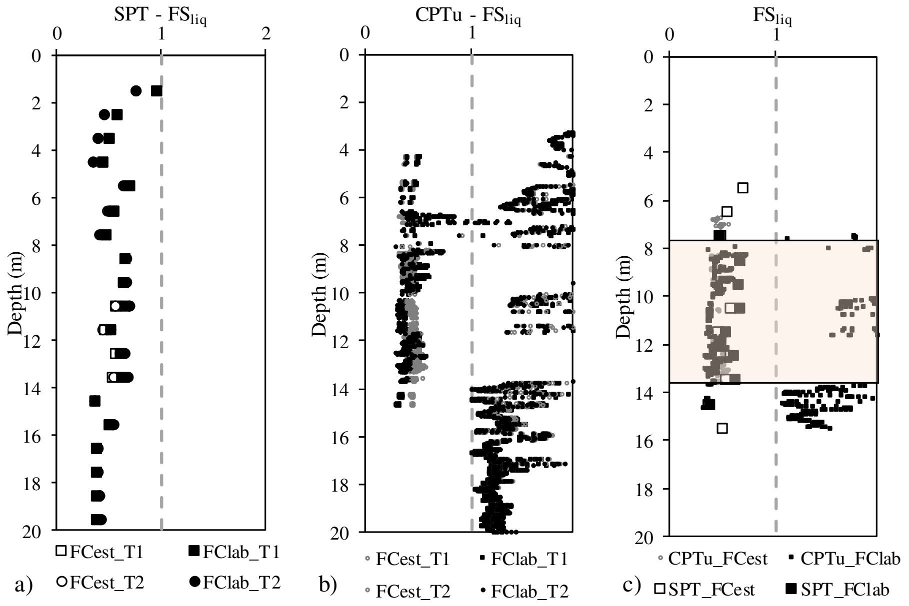

Figure 6. Factor of safety against liquefaction analysis for SI7: a) SPT; b) CPTu; c) definition of critical layers

Analysing the results in Figures 7 and 8, it is noticeable that, in general, the seismic type action does not affect significantly the values of LPI and LSN. Moreover, in the CPTu case, the use of the estimated FC or the laboratory FC does not give very different results. This means that the formulation used for the estimation of FC [6] is appropriate to estimate the FC, since the results are very similar to the ones found when using FC from laboratory.

However, in the SPT results, this is not verified. There is no significant changes in the LPI and LSN values for different seismic action type, but there is a considerable difference between the results using FC_{est} and FC_{lab}. In the case of LPI, the SPT_lab value is closer to the CPTu, reinforcing the importance of the use of the laboratory FC especially in the SPT analysis. Major differences are also found in the LSN values as the FC_{est} gives much higher values. Nonetheless, all the LPI values are high, suggesting that these two profiles have high to very high risk of liquefaction. The LSN analysis is more dubious, being the SI1 profile more critical with the SPT suggesting severe damage and the CPTu suggesting moderate to severe expression of liquefaction. On the other hand, in the SI7 profile the SPT suggests minor to moderate expression of liquefaction while the CPTu is less conservative, suggesting minor liquefaction expression in the case of an earthquake with the predefined characteristics.

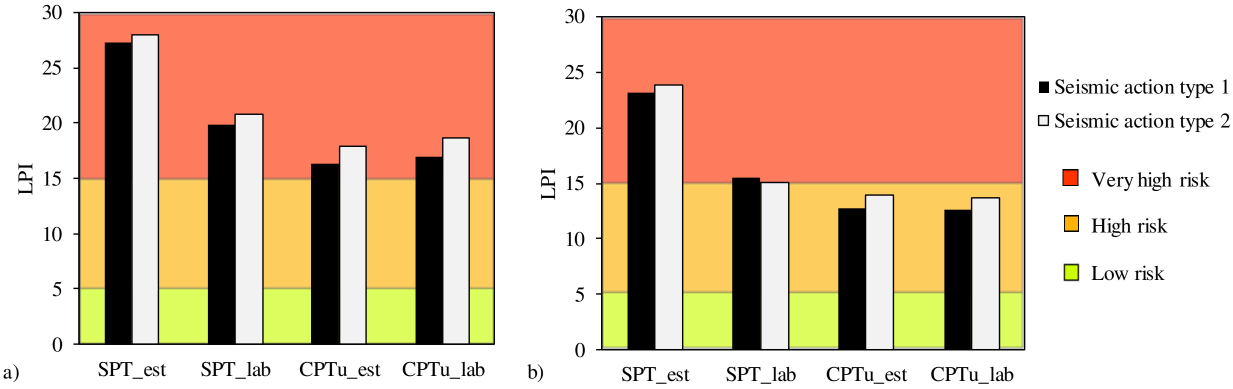

Figure 7. LPI results: a) SI1; b) SI7

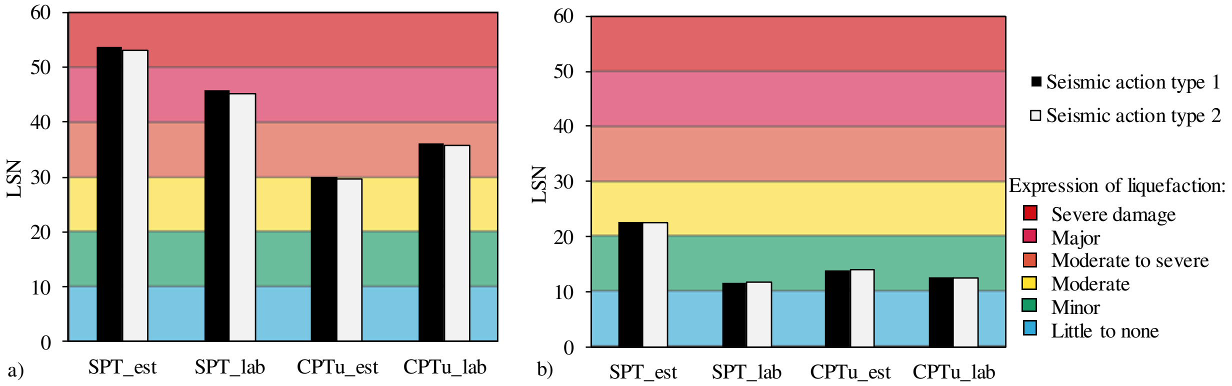

Figure 8. LSN results: a) SI1; b) SI7

5. Conclusions

In order to assess the influence of the fines content and plasticity in the liquefaction susceptibility of two soil profiles located near Lisbon, a study was conducted, analyzing the SPT and CPTu tests considering estimates and the "real" laboratory-measured fines content.

In terms of the factor of safety against liquefaction, the consideration of the estimated values or the laboratory-measured values, in both SPT and CPTu, does not seem relevant, as apparently the same layers are susceptible to liquefaction. In the CPTu, it is shown that the approximation to compute fines content gives similar results to the use of the real fines content determined with collected soils. However, when the layers with more than 35% FC and considerable plasticity are excluded, the profiles look clearer and it is easier to detect the critical layers. This is especially relevant in the SI7 profile, as the layer definition in SI1 is more complex due to the heterogeneity of the profile with sand/silt/clay interlayers. It is also evident that the SPT test alone is not enough to clearly define the critical layers, as it considers a macro approach and does not detect the small interlayers, therefore SPT should not be considered a reliable test for this purpose.

In addition, the influence of the consideration of the estimated versus the laboratory-measured fines content is more evident in the LPI and LSN than in the factor of safety. Considerable differences between the SPT and CPTu results were found, with the SPT results being more conservative - too much - giving higher values of both parameters. The consideration of FC_{lab} in the SPT analysis converges the results with the CPTu, reinforcing the importance of the use of the laboratory FC especially in the SPT analysis. In the CPTu case, the use of estimated or laboratory FC gives similar results, as the correlations for fines content assessment with CPTu results are already very refined. In fact, the CPTu results do not benefit from this inclusion, as the liquefaction is better analyzed based on the soil behavior index and not only on fines content. It is also important to note that the seismic action type variation, in this case, does not provide different results.

To conclude, it is clear that the use of laboratory-measured fines content, FC_{lab}, and associated plasticity is beneficial in the analysis of SPT results, as it provides additional information, more accurately characterizing soil behavior. The inclusion of these parameters approximates the SPT to the CPTu results. The necessity of complementing the SPT blow count results with a thorough FC evaluation in the laboratory is clear, as SPT results were found to be rather unreliable if based uniquely on the lithological description of the SPT log. Moreover, the necessary enhancing of these results by complementing this procedure with laboratory tests is costly and inefficient for practical purposes. More profiles will be analyzed in the future to confirm these tendencies, but this work emphasizes the highest performance and reliability of using CPTu results and their unified approach.

These conclusions highlight the need for further development of a liquefaction susceptibility assessment method, considering laboratory-measured fines content associated with plasticity index, as a means to quantify soil behavior.

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