Equivalent Soil Profiles: CPTu-based soil classification for LIQUEFACT

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ABSTRACT: CPTu testing is an extremely valuable tool for site characterization, with multiple applications in geotechnical design and practice, namely for soil profiling and characterization, foundation design, liquefaction susceptibility and ground improvement control. In this work, a new application of CPTu data is presented, consisting of the definition of Equivalent Soil Profiles (ESP) for soil profiling and classification, to be implemented in numerical models, particularly for soil-foundation-structure interaction studies in shallow-founded buildings in liquefiable soils. While this classification is based on the estimate of cyclic resistance of the soil, it is hazard-independent, consisting on the definition of an equivalent 3-layered soil profile. The classification is based on only three features, highly influential to the performance of buildings: the depth of the non-liquefiable crust, the liquefaction resistance of the potentially liquefiable soil layer and its thickness. The selection of these parameters is justified by its influence on the ground surface acceleration and on the bearing capacity of shallow foundations. One of the most relevant advantages of this classification is the consideration of the performance of buildings in the event of liquefaction. A case study in the greater Lisbon area has been studied, where the procedures and classification of this innovative methodology are discussed. Finally, the comparison of LSN results of the original and the equivalent soil profiles is presented.

Keywords: CPTu testing; soil profiling; soil classification; liquefaction; LSN

1. Introduction

Earthquake-induced liquefaction is responsible for considerable structural damage. However, conventional liquefaction assessment focuses only on triggering, without the consideration of building performance. The LIQUEFACT project (www.liquefact.eu) has required the development of a new soil profiling and classification method, capable of defining and classifying soil response in the event of liquefaction for the study and analysis of soil-foundation-structure interaction. This need has led to the proposal of a new CPTu-based methodology of soil classification, independent of the seismic hazard. In the context of performance-based design and loss assessment frameworks, the selection of a hazard-independent, but risk-sensitive, classification of a soil profile in terms of liquefaction resistance is advantageous to accommodate different seismic hazard levels, particularly for its application to any region or seismicity.

For liquefaction mapping, a hazard-independent liquefaction resistance classification can be combined with seismic hazard maps, which are regularly updated. In addition, liquefaction triggering assessment methods are based on different assumptions and thus can provide considerably different results.

The analyses of the performance of soil deposits during the 2010-2011 Christchurch earthquake sequence identified the importance of pore water flow and seismic isolation as key differences between the CPT-based simplified triggering procedure [1, 2] and non-linear effective stress analyses [3]. However, the definition of soil type and resistance parameters were found to be consistent across these different assessment procedures.

For the purpose of this project, the definition of a simplified equivalent soil profile should take into account the main parameters that influence the performance of the shallow-founded buildings, in the event of liquefaction. In this work, a stratified multi-layered soil profile is converted into an simplified soil profile, with equivalent liquefaction response, based on the three governing parameters, as illustrated in Figure 1.

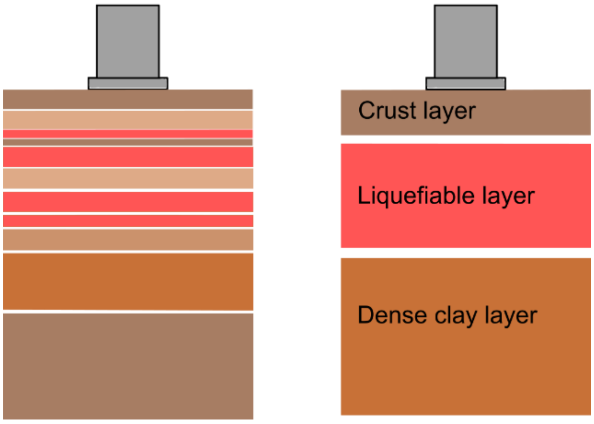


Figure 1. Soil profile: borehole data versus equivalent soil profile

The use of qualitative liquefaction indices has been proposed by various researchers, as a means to classify a soil profile with a single number, namely using the Liquefaction Potential Index (LPI) or the Liquefaction

Severity Number (LSN) [4-8]. While the indices are practical and useful for mapping and zonation, these fail to take into account the influence of foundation geometry or the time of liquefaction in terms of settlements and tilt of the buildings.

To illustrate the limitation of existing approaches, an example is provided in Figure 2 for a series of different soil profiles with distinct conceptual CRR at the liquefiable layers, but could result in the same LSN (e.g. 20), for a given PGA. While a value of LSN is indicative of a moderate superficial manifestation of liquefaction, the effects of liquefaction on an existing shallow-founded building would be distinct for each soil profile.

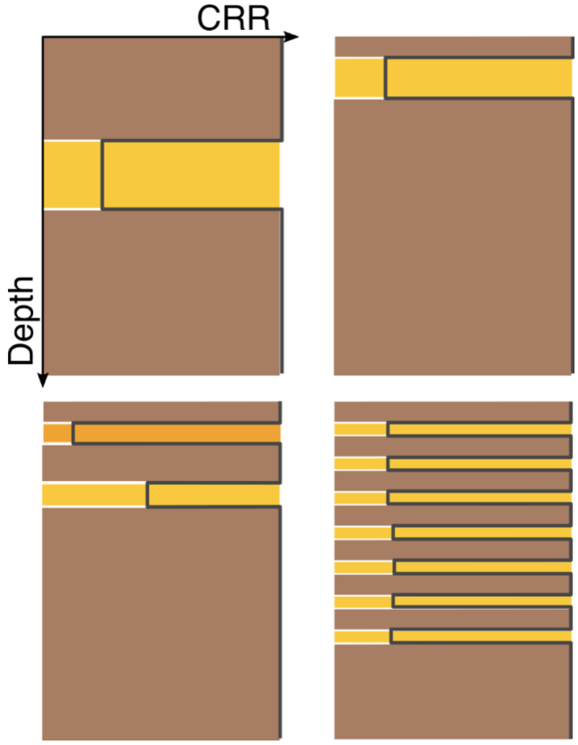


Figure 2. Different real soil profiles with distinct CRR profiles but identical LSN value (e.g. LSN=20, for a given PGA)

Besides the liquefaction resistance capacity via CRR, the thickness of the non-liquefiable crust, corresponding to the depth of the liquefiable layer in a three-layered profile, and the height of the liquefiable layer are the most important parameters for liquefaction response in shallow-founded buildings. As demonstrated in recent literature, these two parameters influence the manifestation of liquefaction at the surface [9-10], the intensity and characteristics of the ground surface shaking [11, 12], the foundation impedance [13] and building settlement [14-18]. Figure 3 schematically illustrates the influence of the depth and thickness of the liquefiable layer in the performance of two different buildings. Further discussion on the use of these parameters are reported elsewhere [19, 20].

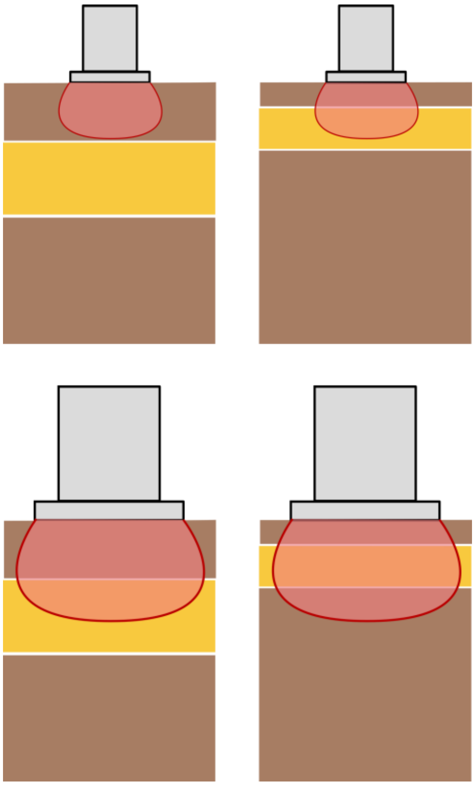


Figure 3. Different building widths and soil profiles

After liquefaction, the bearing capacity of a shallow foundation on a liquefied soil deposit can strongly decrease. The degraded bearing capacity is a key indicator of expected settlement and tilt of the building [16, 21, 22] and can be computed using Meyerhof & Hanna [23] proposal for a strong soil crust underlain by a weak soil layer. The degraded bearing capacity depends on the shear strength of the crust and the residual shear strength of the liquefied sand [16], as well as the thickness of the crust and liquefiable layer.

2. Equivalent Soil Profiles

2.1. Definition

The Equivalent Soil Profile (ESP) is a hazard-independent liquefaction classification system for performance and loss assessment of buildings on shallow foundations. The equivalent profile is a three-layered soil profile, with the same depth of the original profile, and is described by three parameters of the critical liquefiable layer: 1) depth, D_{liq}; 2) height, H_{liq}; 3) average cyclic resistance of the liquefiable layer for 15 cycles of uniform load, CRR_{n15}. A schematic of the ESP is provided in Figure 4. This classification system has been implemented as an algorithm and is particularly useful in stratified soils.

The main advantages of this classification system are: the use of field test results, preferably from CPTu; the evaluation of the performance of the soil profile independently of the seismic hazard using just three parameters; hence, it is capable of defining the profile without knowing the seismic hazard at the site; the use of logical, intuitive and physically representative parameters; and, the classification results are directly linked to the performance of shallow-founded buildings in the event of liquefaction.

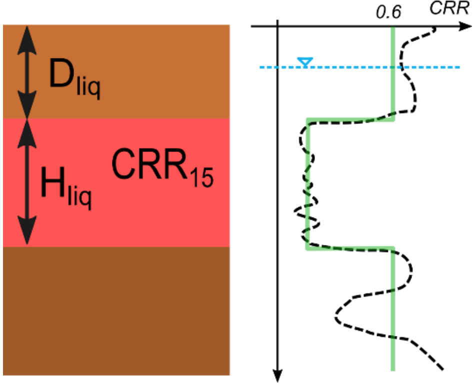


Figure 4. Definition of Equivalent Soil Profile (ESP)

2.2. CPTu-based procedure

The definition of the ESP is currently based on CPTu results, since this test conventiently provides reliable and continuous field data. Other field and laboratory tests can also be used, however the CPTu is considered the most appropriate for this purpose, since it is a nearly continuous test, provides measurements of strength and pore pressure (directly related to liquefaction resistance), and it is reliable and easy-to-interpret test, supported by extensive and regularly updated databases. The procedure algorithm automatically computes the CRR for a standard magnitude 7.5 earthquake event or equivalent 15 cycles of loading, using a simplified triggering procedure [e.g. 2]. Then a fitting protocol is applied to define a three-layered profile to the CRR values. The automatic procedure runs through every possible three-layered profile and computes the normalised difference $\tilde{\varepsilon}$ (Equation 1), between the CRR values of the computed and the equivalent profiles:

$$\tilde{\varepsilon} = \frac{\sum_{i=0}^{H}\left(CRR_{calc,i} - CRR_{fitted,i}\right)\cdot\Delta H}{CRR_{non-liq}\cdot H} \qquad [1]$$

where CRR_{calc} and CRR_{fitted} are the calculated and fitted CRR values, ΔH is the depth increment, H is the total height of the profile, and $CRR_{non-liq}$ is the non-liquefiable limit, currently set at 0.6, as

As shown in Equation 1, the calculation of the normalised diference corresponds to the fitting error between the original soil profile and ESP, in terms of CRR, and it is sensitive to the non-liquefiable limit of CRR and the maximum depth of the profile. The maximum value for CRR was defined at 0.6, since this value is commonly assumed in other approaches [2, 24]. A maximum depth of 20 metres was considered, since surficial consequences on shallow foundations of soil liquefaction below such depths are negligible [6].

The increments of depth and CRR are also influential on the final results and should be relatively small. The depth increment was set to 0.1m and the CRR increments were determined by setting the equivalent cone tip resistance for clean sand, designated as q_{c1Ncs} [1,2], ranging from 0 to 175 kPa in increments of 5kPa, from which a CRR range from 0.061 to 0.6 was derived.

Finally, the procedure outputs the soil profile which minimises the error, as schematised in Figure 5.

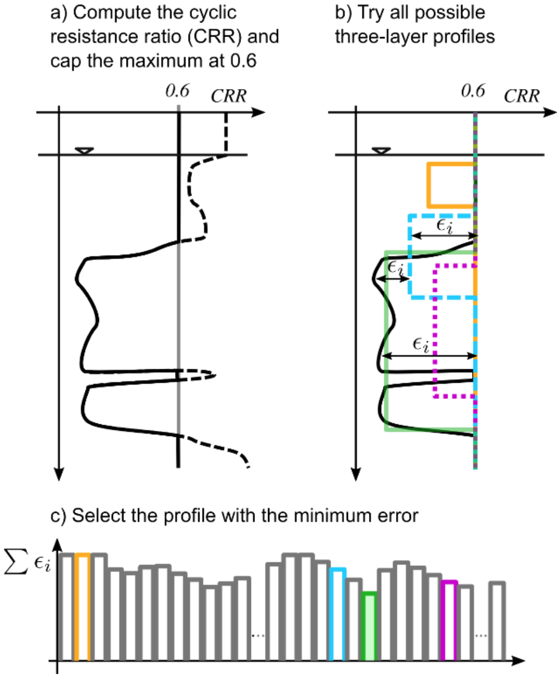


Figure 5. Procedure to implement the CRR-fitted method (after [20]).

After the computation of the ESP, the sum of absolute difference between the fitted profile and the CPT based CRR values divided by the total number points in the CPT up to 20 m in depth, called the normalised error, provides a measure of the fitting between the profiles. The code of this procedure is implemented in the software package ‘liquepy’ [25].

For the purpose of comparison, the LSN of both the original and the equivalent soil profiles are also calculated. This index represents the expected damage effects of shallow liquefaction on direct foundations, based on post-liquefaction volumetric deformations, associated with reconsolidation settlements, and it is defined as:

$$LSN = 1000\cdot\int\frac{\varepsilon_v}{z}dz \qquad [2]$$

where ε_v is the volumetric densification strain due to post-liquefaction consolidation of soil layer i, according to [26], and z is the depth of the soil layer in metres, below the ground surface. There is some controversy in the literature with regard to the maximum depth of calculation of LSN: some authors [3,7] suggest that only to the top 10 m of the soil profile should be considered, while others [8, 27] have been computing it to a depth of 20 m. Since 20 m is the maximum depth of the ESP, this depth has also been adopted for the calculation of LSN.

2.3. ESP Classification

The equivalent soil profile (ESP) is defined as a soil profile classification tool for the purpose of the seismic response of shallow-founded buildings in liquefied soils.

A set of ranges for each of the three governing parameters (CRR_{n15}, H_{liq} and D_{liq}) have been defined, as shown in Figure 6. From the combination of these ranges, a new site classification has been proposal, consisting of a total of 22 different soil profile classes, as indicated in Figure 7. Details on this classification can be found in Viana da Fonseca et al. [19].

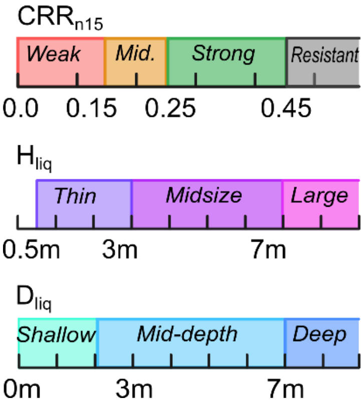
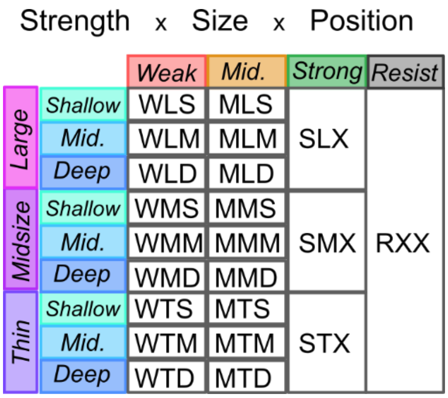


Figure 6. Ranges and classes of the three governing parameters of ESP


Strength x Size x Position

		Weak	Mid.	Strong	Resist
Large	Shallow	WLS	MLS	SLX	RXX
	Mid.	WLM	MLM		
	Deep	WLD	MLD		
Midsize	Shallow	WMS	MMS	SMX	
	Mid.	WMM	MMM		
	Deep	WMD	MMD		
Thin	Shallow	WTS	MTS	STX	
	Mid.	WTM	MTM		
	Deep	WTD	MTD		

Figure 7. Equivalent soil profile classes

This ESP procedure and site classification were preliminarily applied to a case study site in Christchurch, from a selected set of 100 CPTu and a comparison was made regarding the computed LSN value for the original CPT and ESP profiles [19, 20].

3. Case study results

A large pilot site for liquefaction susceptibility assessment and microzonation has been set up in the Greater Lisbon area, as part of the Portuguese participation in the LIQUEFACT project. Extensive geological and geotechnical characterization campaigns were carried out, involving a wide variety of field testing, complemented by high-quality sampling for subsequent laboratory testing. Details on these works are provided elsewhere, inclusively in other papers in this conference [28-32]. For the purpose of this paper, only CPTu results will be applied. A set of 39 CPTu, spatially distributed within the pilot site area, were selected for the application of the newly developed ESP procedure, as a means to obtain a set of soil profile classes and its distribution for site classification and zonation [28].

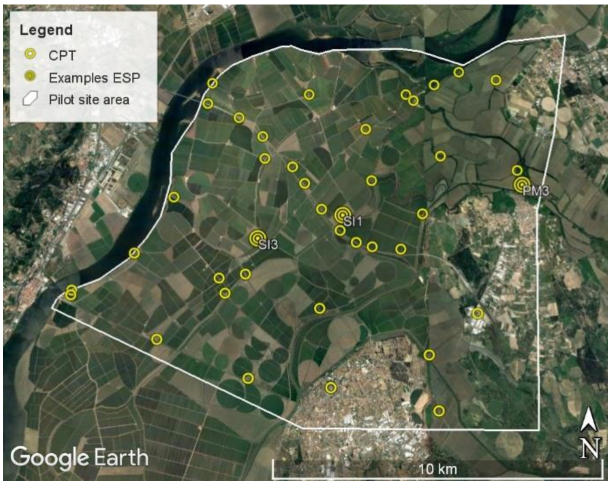
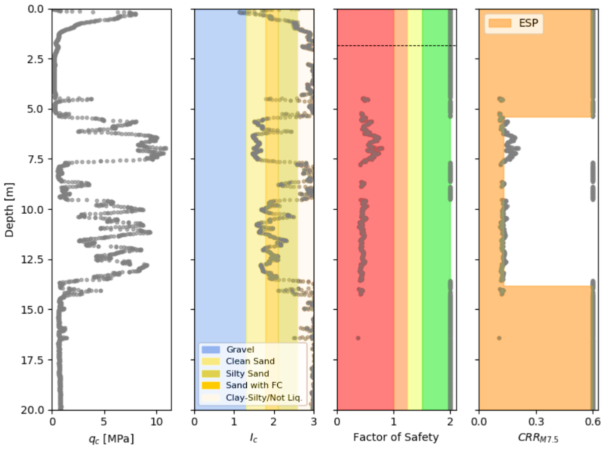


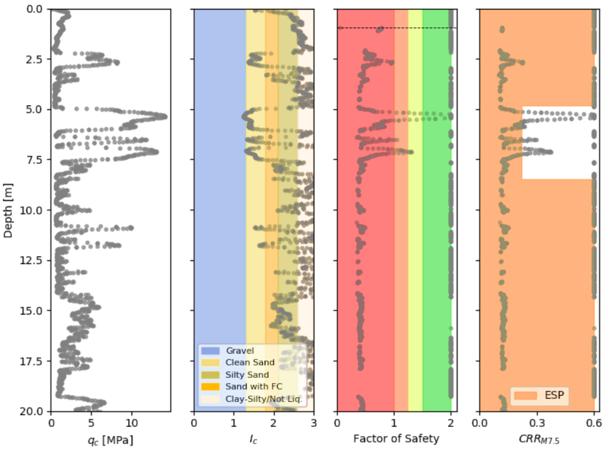
Figure 8. Pilot site area and location of the selected points

For the purpose of illustrating the application of the ESP procedure, the results obtained for points SI1, SI3 and PM3, located as shown in Figure 8, are provided in Figure 9. These figures include the cone penetration resistance (q_c) and soil behaviour type (I_c) profiles from the original CPTu, the original and equivalent cyclic resistance ratio (CRR) and the original factor of safety against liquefaction, for reference.

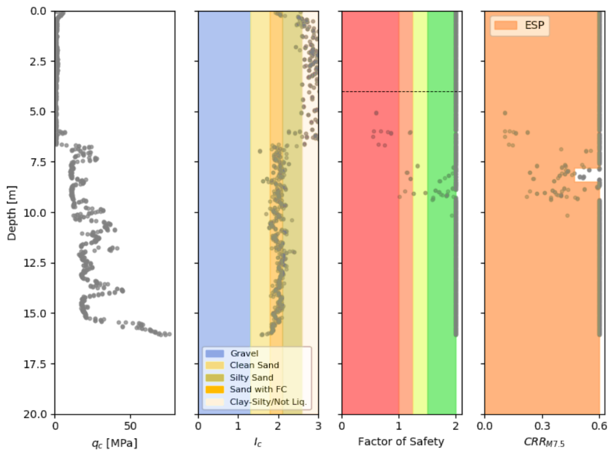
These points were specifically selected to illustrate the wide variety of soil profiles within the pilot site area, ranging from very weak (e.g. WLD or WLM) to resistant (RXX) profiles.



a) ESP: WLM



b) ESP: MMM



c) ESP: RXX

Figure 9. Equivalent soil profiles for three different points: a) SI3 (WLM, Weak Large Mid-depth profile); b) SI1 (MMM, Mid-strength Midsize Mid-depth profile); c) PM3 (RXX, Resistant profile)

The soil profiles in the 39 points were classified following the methodology described above and the distribution of ESP in the pilot site was obtained, as shown in the chart in Figure 10. The following ESP distribution was obtained: more than 65% of the points correspond to weak soil profiles, about 24% are mid-strength profiles, only 3% are strong and the remaining 8% correspond to resistant soil profiles. As shown in the chart, the liquefiable layers are predominantly located at medium depths (between 2 to 7 m). This information had significant influence in the microzonation of the pilot site area [28].

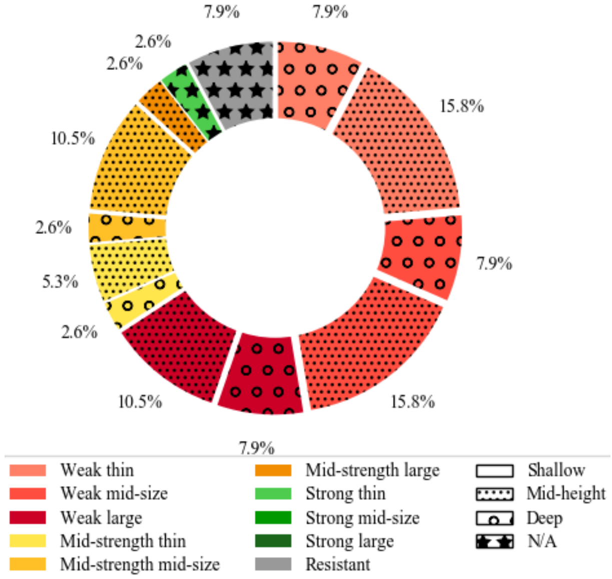


Figure 10. Equivalent soil profile distribution in the pilot site

Indeed, this plot clearly illustrates the liquefaction susceptibility of the pilot site, which can be applied to the assessment of the severity of liquefaction-induced damages in the buildings in the area. The use of LSN is particularly convenient to assess the expected damage in each point and can also be applied for comparing the prediction from the original and the equivalent soil profile response. This comparison of LSN_CPT and LSN_ESP is provided in Figure 11, using the color code of typical performance of LSN shown in Table 1.

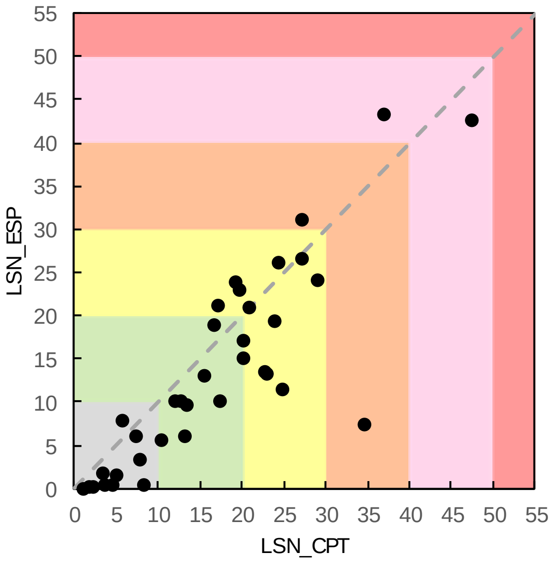


Figure 11. Comparison of LSN from CPTu and ESP

Table 1. Liquefaction severity based on LSN ranges [26]

LSN		Typical performance
0 – 10	⬜	Little to no liquefaction
10 – 20	🟩	Minor expression of liquefaction
20 – 30	🟨	Moderate expression of liquefaction
30 – 40	🟧	Moderate to severe liquefaction
40 – 50	🟥	Major expression of liquefaction
> 50	🟥	Severe damage, extensive evidence of liquefaction

The comparative results in Figure 11 evidence considerable agreement between the original and the equivalent LSN, with a tendency for a lower LSN_ESP than the corresponding LSN_CPT. This is justified by the fact that the ESP computes the critical layer and the calculated LSN only considers such layer, ignoring interbedded layers of sand and clay. This has the advantage of providing a potentially more reliable assessment of liquefaction severity, since interbedded layers show better performance (lower excess pore pressures and lower settlements) due to the low permeability of clays. Further discussion and evidences on this topic are provided elsewhere [33].

4. Conclusions

This paper introduced a new CPTu-based approach for obtaining a simplified equivalent three-layered soil profile. The designated Equivalent Soil Profile (ESP) has been defined as a soil profile classification tool for the purpose of estimating the performance of shallow-founded buildings on liquefiable soils in the event of liquefaction. This methodology is hazard-independent, as it uses three simple, intuitive and physically representative parameters: the depth (D_{liq}) and the thickness of the liquefiable layer (H_{liq}) and its cyclic resistance ratio (CRR_{n15}). Typical ranges of values for each of these variables have been defined, from which a proposal of 22 different soil profile classes has been derived.

The application of the ESP methodology to the analysis of 39 CPTu tests in the Portuguese pilot site of the LIQUEFACT project is presented in this paper. From this exercise, it was concluded that the majority of the soil profiles are weak and located at mid-depth, around 2 to 7m, which was decisive for the purpose of microzonation [27]. The comparison between the generated equivalent soil profiles and the respective LSN classification was established to demonstrate the applicability of this new simplified approach to a more reliable assessment of severity of liquefaction-induced damages. The use of this ESP classification for the estimate of the settlement and bearing capacity analysis of shallow foundations in liquefied soils has the advantage of being capable of reproducing the response of the soil profile across the full hazard range using just three parameters, since these are directly related to the performance of shallow-founded buildings.

Acknowledgements

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