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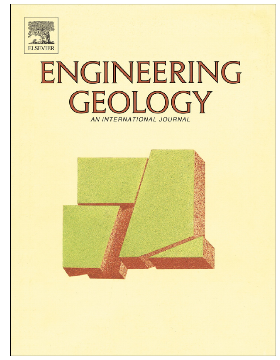

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Seismic microzonation based on large geotechnical database: application to Lisbon

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Abstract

Historically, Portugal has suffered the effects of several strong earthquakes. In particular, Lisbon and the south and southwestern Portuguese coast were affected by the largest known European earthquake on November 1st, 1755.

It is well known that the local ground conditions strongly affect the seismic ground motion, modifying the signal's amplitude, duration, and frequency content, which induces large variability in the motion induced to buildings and infrastructures.

Aware of this situation, the Lisbon Municipality promoted the development of a project to elaborate a new seismic microzonation map, based on a large geotechnical database and geological data.

The Eurocode 8 ground classification based on the V_{S30} parameter was adopted as reference. However, the geotechnical database has a very small number of geophysical logs and is mainly composed of borehole data and SPT blows number. An expedited methodology was applied to determine the N_{30} parameter, as a proxy of the V_{S30} parameter. Non-invasive field experiments (surface waves seismic profiles and HVSR performed with ambient vibrations) and data collected from independent geophysical reports were also used to check and validate the classification based on N_{30}. Because the distribution of the classified profiles was not uniformly distributed, the final microzonation map was obtained from the combination of the profile classification and the surface geology.

Keywords

Seismic Microzonation; Ground Classification; Geotechnical Database; SPT Data; Lisbon

1. Introduction

Lisbon was affected by moderate to strong earthquakes along its history, such as the earthquakes of January 26th, 1531, and November 1st, 1755. This last earthquake (M8.5) is considered by many authors as the largest earthquake that stroked Europe in historical times. Its source was located S-SW offshore Portugal, it produced a large tsunami that crossed the entire ocean to the Caribbean and it strongly affected a large area containing the whole country and large regions of Morocco and Spain. Moreover, its effects were also felted in Northern European countries.

In this event, the town of Lisbon was severely damaged. Many houses and monuments collapsed and a large part of the population (estimated around 10%) lost their lives (Pereira de Sousa, 1919-1932). Due to its historical seismicity and to its economic and social importance, Lisbon is nowadays considered to have moderate to high seismic risk (e.g. Matias et al., 2005).

It is well known that local ground conditions change the characteristics of surface seismic response as its amplitude, duration and frequency content. So, the seismic microzonation is a valuable tool for city planning and for identifying seismic mitigation measures (e.g. Panzera et al., 2018; Alonso-Henar et al., 2018; Hassan et al., 2017; Kolat et al., 2012; Hamzehloo et al., 2007; Bramerini et al., 2015).

Seismic microzonation maps were developed for different sites in different countries around the world, as the studies of Jiménez et al. (2000), Topal et al. (2003), Kienzle et al. (2006), Kiliç et al. (2006), Di Giulio et al. (2008), Papadimitriou et al. (2008), Walling and Mohanty (2009), Eker et al. (2012) and Kolat et al. (2012).

Kolat et al. (2012) developed a geotechnical microzonation model regarding the suitability of the residential areas in Yenisehir (Bursa), a rapidly developing settlement area in a seismically active region of Turkey. For this purpose, properties and dynamic behavior of the Quaternary alluvial soils in the study area were assessed. Soil classification, soil amplification, natural soil predominant period, resonance phenomena and liquefaction potential of the study area were evaluated using borehole data and microtremor measurements.

Eker et al. (2012) encompass dynamic soil characterization and site classification zonation mapping of the Plio-Quaternary and especially Quaternary alluvial sediments based on the current seismic codes to the north of Ankara (Turkey). Sediment characteristics were determined, and soil profiles were characterized by passive (Multichannel Analysis of Surface Wave Method, MASW) and active (Microtremor Array Method, MAM) surface wave methods at different locations. By combining these two techniques, they obtained the shear wave velocity profile of the site. The geological characteristics of these sedimentary units were compared with the geological and geotechnical boring and seismic site characterization studies to classify the soil deposits. This was performed to develop site categories which took site conditions into account according to the design codes of the International Building Code (IBC, 2006) and the Turkish Seismic Code (TSC, 1998). Then, the regional site classification map was assessed considering the values of average shear wave velocity parameter (V_{S30}) provided in the International Building Code (IBC, 2006) and the shear wave velocity data and thickness of the surface layer according to the Turkish Seismic Code (TSC, 1998).

Papadimitriou et al. (2008) presented an automated methodology for performing a geographic information system (GIS)-aided seismic microzonation studies. It presupposes the existence of a geotechnical database containing data from boreholes and in situ geotechnical or geophysical tests for the study area that has been related to a GIS. Their study presents an exemplary GIS-aided seismic microzonation study for an urban municipality of the greater Athens (Greece) area, which reveals the efficiency of the automated methodology and explores its limitations. This research has similarities to the present study.

All these researches show the importance of performing seismic microzonation studies for the seismic risk mitigation. The Lisbon Municipality (CML) promoted the development of a new seismic microzonation map based on Eurocode 8 (EC8) (CEN, 2004) ground classification, to update the existing one mainly derived from the geological map accomplished during the eighties. This work is part of a larger project to evaluate the seismic vulnerability of housing stock and built heritage. The Lisbon ground classification is fundamental to identify the ground parameter to calculate the Building Seismic Resilience Index.

The EC8 ground classification has V_{S30} value (average S-wave velocity in the upper 30 m) as the primary parameter, calculated from the total time needed for a shear wave to travel the upper 30 m. However, only a few measurements of S-wave velocities in Lisbon are available. The immediate alternative available was to use a large geotechnical database (GDB) managed by the Lisbon Municipality, which contains more than 8000 boreholes most of them with results from standard penetration tests (N). An algorithm was developed to classify automatically each profile, using N_{30} value, defined as the average value of N in the upper 30 m, as a proxy of V_{S30}.

The seismic microzonation map was performed joining the classification obtained for each borehole with the geological map of Lisbon in scale 1:10 000 (Moitinho de Almeida, 1986). Non-invasive field experiments (surface waves seismic profiles and HVSR performed with ambient vibrations), as well as geophysical data collected from independent reports, were also used to check and validate the classification.

2. Geotechnical and geological data

2.1. Geotechnical Database (GDB)

The geotechnical database is the result of GeoSIG project that developed the geotechnical cartography of urban areas of Lisbon (Almeida et al., 2010). In this georeferenced database, all the geotechnical data available in Lisbon is compiled, and it is being continuously updated by data because all contractors are compelled to send this information to CML. The set of geotechnical data available in the GDB for this study includes 8792 boreholes, most of them with SPT results, from 1624 geotechnical reports (Figure 1). These boreholes were performed between 1935 and 2016 by different companies, which means that the information contained in the database is not homogeneous (e.g. equipment used, criteria to end the SPT, surface level, geological interpretation). The equipment used and surface-level information are not available in most reports and the geological information included in the database was always confronted with the geological information from neighbors' boreholes and compared with the geological map of Lisbon (Moitinho de Almeida, 1986).

Also, the spatial distribution of the data is not uniform: some areas have a high number of boreholes, while others are *shadow areas* because of the scarce geotechnical information (see Figure 1). Shadow areas are located mainly in the northern and western part of Lisbon and in the southeast riverside area. Geological diversity and urban evolution are mainly responsible for this distribution.

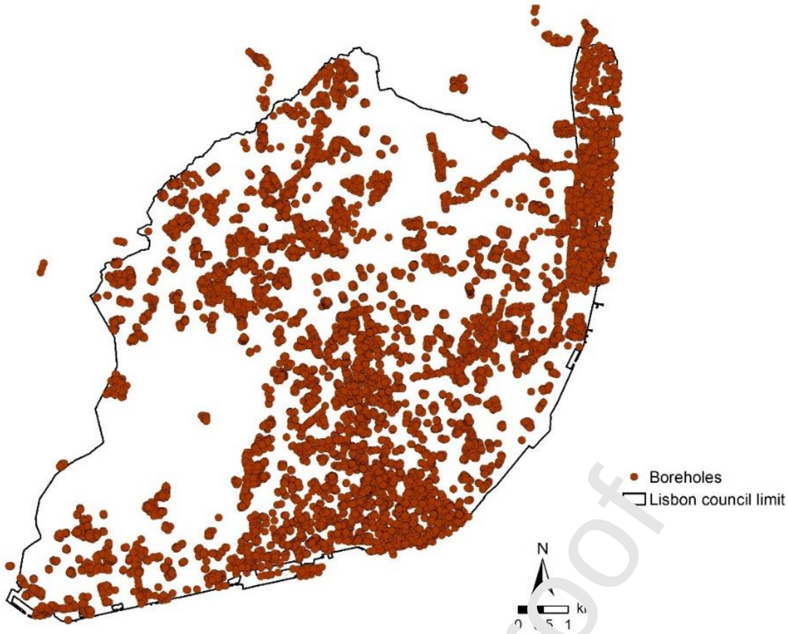


Figure 1. Spatial distribution of available geotechnical boreholes.

Each borehole has different information, such as borehole and report identification, the company that performed the work, geographical coordinates, and elevation. The main properties of the borehole are depth, lithostratigraphy (including surface formations), lithology, SPT results, and water level. The depth, lithostratigraphy, lithology, and SPT results of each borehole have been considered in the present study.

In this study, only 8117 boreholes were considered to develop the seismic microzonation map, because boreholes that did not have SPT results were not considered. From the 8117 boreholes, 439 (~5%) reach a depth of 30 meters and 3728 (~46%) exceed 15 meters depth, with the deepest borehole reaching 71.55 meters (Figure 2). The 8117 boreholes considered have 73192 SPT results. The most common number of SPT performed per borehole is between 5 to 10 SPT (Figure 2). On average 9 SPT are done per borehole, the standard deviation is 4.4 and the covariance is 49%. A maximum of 36 SPT results and at least 1 SPT result per borehole were performed. The median corresponds to 8 SPT results per borehole.

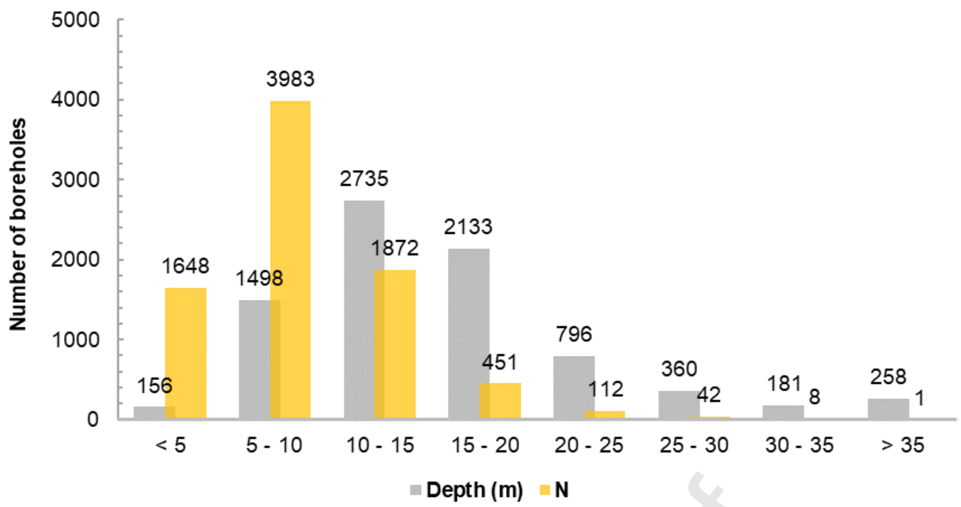


Figure 2. Statistical analysis of the depth of the boreholes and the number of SPT results per borehole.

The most common criteria to end the SPT test are the following:

i) at the third consecutive SPT tests with N value equal to 60, regardless of the penetration depth (most common);

ii) at the third SPT tests with N value equal to 60, even if non-consecutive;

iii) Prior definition of the minimum depth of the borehole, based on the expected depth reached by the excavation or foundation (uncommon).

The first two criteria partly explain why most boreholes are relatively shallow (<15 m).

2.2. Geological Map of Lisbon County

The geological map of the Lisbon County (Moitinho de Almeida, 1986), Figure 3, shows that in the southwest area Cretaceous formations (C) arise, while Paleogene and Miocene formations (M) appear in the northern and eastern areas of Lisbon. The Cretaceous formations (C) are composed by carbonate rocks (limestone and marls) – Bica Formation (C3) and Caneças Formation (C2) – and basaltic rocks – Lisbon Volcanic Complex (LVC). The Miocene formations (M), defined by Cotter (1956), are composed by sands, sandstone, clay, and limestone.

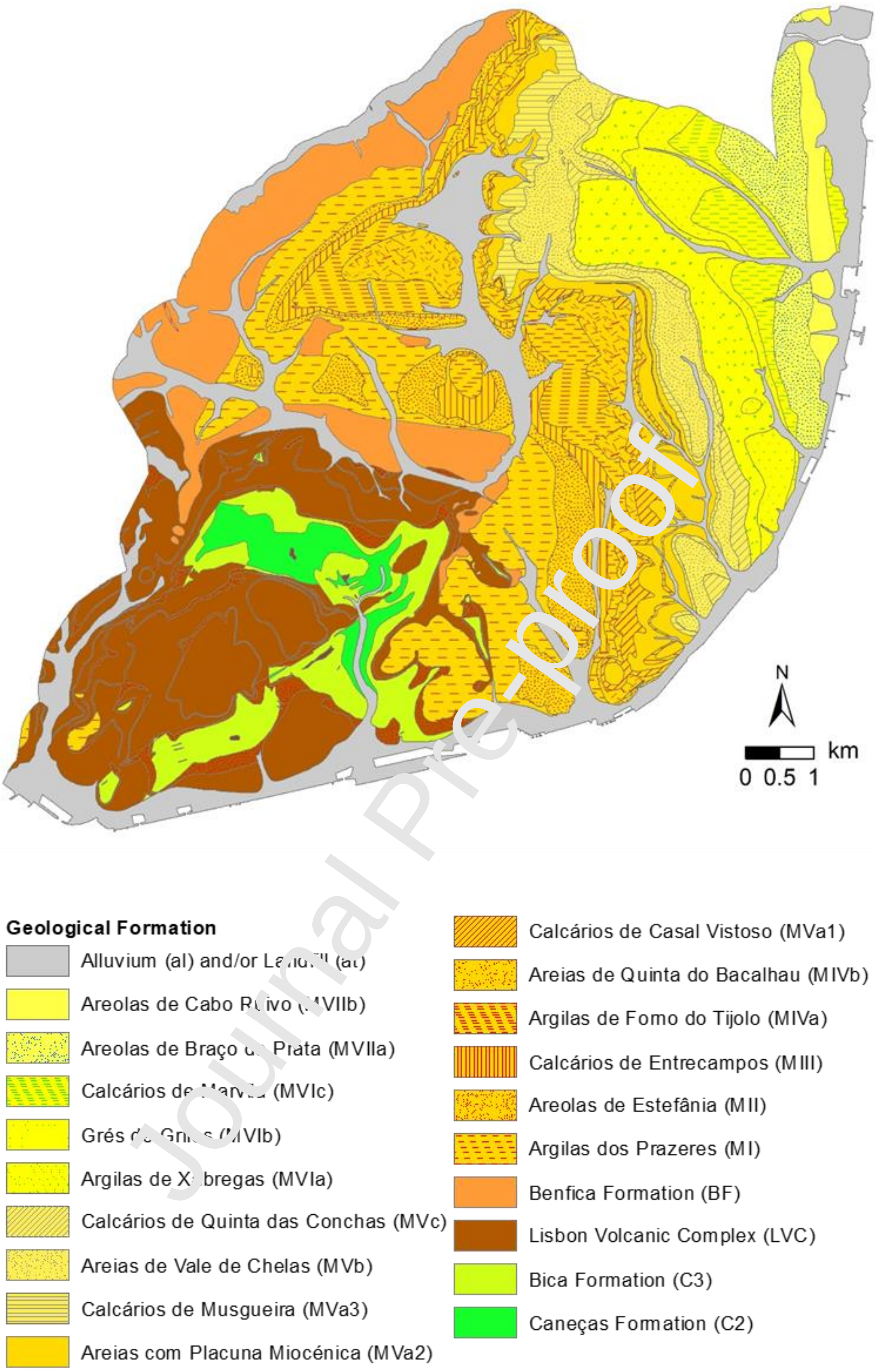


Figure 3. Geological map of the Lisbon County (adapted from Moitinho de Almeida, 1986).

The Paleogene Benfica Formation (BF), with a heterogeneous composition including conglomerates, sandstones, siltstones and argillites, limestone and marls, corresponds to the transition between the Miocene formations (M) and the Lisbon Volcanic Complex (LVC).

The map also presents the alluviums (al) and/or landfills (at), including the ancient Lisbon streams (inland alluvium) and the Tagus River's edge. At the map scale, it is not possible to differentiate the surface formations (alluvium (al) and landfill (at)), which are identified in the geotechnical surveys included in the GDB.

2.3. Surface formations distribution

In general, the geological substratum in urban areas is modulated by human action, including landfills of different types and origins, to adapt the topography to the land uses (Vasconcelos and Marques, 2010). These occurrences that are not included in the actual geological map, significantly modify the geotechnical profile of surface layers and some areas (Vasconcelos, 2011).

Lisbon is strongly urbanized and in constant development, so it is expected to present a different distribution of the surface formations from the one displayed on the geological map. The surface formations include landfills (at) of anthropogenic origin and alluvium (al) with heterogeneous composition depending on the eroded lithologies and containing often organic material (Almeida, 1991). These alluviums occupy a significant area including the formations directly associated with the Tagus riverbed and all the riversides and water lines that flow to the river. From the 8792 geotechnical boreholes analyzed, 7938 (~90%) identified the existence of surface formations composed by alluviums (al) and/or landfills (at). Figure 4 shows the distribution of the surface formations in Lisbon County.

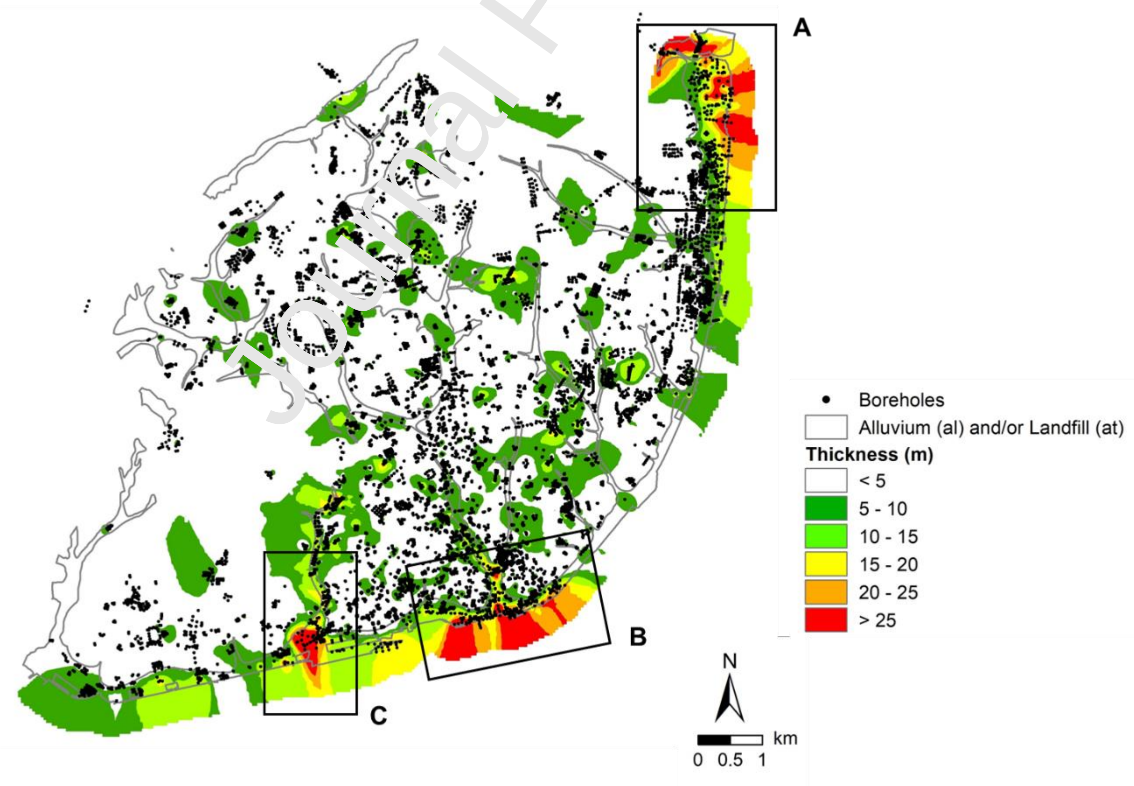


Figure 4. Distribution of surface formations (alluvium and landfill) in Lisbon, applying a data interpolation for thicknesses > 5 meters. A – Parque das Nações; B – Baixa; C – Alcântara.

The largest thickness of the surface formations is found in the riverside zones, particularly in the Parque das Nações (A), Baixa (B) and Alcântara (C) (Figure 4). A data interpolation of the deeper thicknesses (over 5 meters) of these formations shows areas that are not mapped in the geological map, namely anthropogenic landfills (at) which are independent of alluviums (al) (Figure 4). This is due to the natural urban evolution of the town and the thicker formations present in the inner part of the town resulted, in most cases, from the exploitation of old quarries. However, the reports present in the GDB were performed between 1935 and 2016, which indicates that the identified surface formations may no longer exist and other formations that are not identified in this analysis may exist. An example is a study carried out by Dias (2013) of the surface formations thickness variation obtained through the aerial photography and LiDAR data analysis, between 1944 and 2006, in part of the Lisbon County. This author verified that the construction of landfills (at) and excavations performed during that period could introduce variations up to ~ 30 meters in the surface formations thickness. For this reason, it is necessary to interpret these results with caution.

3. Ground classification

3.1. Eurocode 8 ground classification

Nowadays, the main parameter adopted for site classification is V_{S30}, first proposed by Borcherdt and Glassmoyer (1992). V_{S30} has been incorporated in Ground Motion Prediction Equations (e.g. Chiou and Youngs, 2008; Boore and Atkinson, 2008) and in seismic codes, as Eurocode 8 (CEN, 2004).

In recent seismic microzonation studies, V_{S30} is the main parameter, because it has the advantage of being obtained in a cost-effective manner through seismic testing (e.g. Bramerini et al., 2015; Nunziata, 2007).

When V_{S30} is not measured directly, as in the present study, standard penetration test blows count N or undrained shear strength, S_u, are used and are identified in Eurocode 8 ground classification as secondary parameters.

According to EC8 site classification scheme, the sites are classified into five main categories. The selection of each class is done based on the V_{S30} value, or alternatively based on the standard penetration test blow count N, plasticity index PI and undrained shear strength S_u determined up to 30 m deep. For classes A and E, the depth of the seismic bedrock with V_S larger than 800 ms^{-1} is also necessary. Ground type A corresponds to a shallow (< 5 m) rock or other rock-like geomaterial (V_{S30} > 800 ms^{-1}), B corresponds to deposits of very/stiff soil with several tens of meters in thickness (360 ms^{-1} < V_{S30} < 800 ms^{-1}; N > 50; S_u > 250 kPa), C are deep deposits of medium dense/firm soils (180 ms^{-1} < V_{S30} < 360 ms^{-1}; 15 < N < 50; 70 < S_u < 250 kPa), D are loose/softs soils (V_{S30} < 180 ms^{-1}; N < 15; S_u < 70 kPa), and E are surface alluvium (V_{S30} value of type C or D) with thickness between 5 to 20 m underlain by stiffer geomaterial (V_S > 800 ms^{-1}).

Additionally, two special ground types were included - S1 and S2 - which are related to liquefaction and cyclic mobility phenomena. Due to their specific nature as well as the scale map design, these two special types are not included in this study.

Most boreholes considered in the study reach less than 30 m deep, so it was necessary to extrapolate the N values to a depth of 30 meters. For this, it was adopted the deepest N value as representative of the ground between the borehole's bottom and 30 meters (see section 3.2).

A large number of N-V_S empirical correlations can be found in the literature. Lopes et al. (2014) reported more than 90 of the type $V_S = a \times N^b$, where N is between uncorrected values.

It is well known that N value depends on equipment energy, hole diameter, depth, water level among others.

The (N1)60 value is corrected for equipment energy and effect of depth, including the confining stress.

In this paper, it was decided to not make any correction to N because:

i) In many SPT tests, the type of equipment was not identified in the report, which made impossible the homogenization of the equipment energy. Also, the equipment energy was never measured in the SPT tests included in the database and the Portuguese practice was never characterized and it is well known that the equipment energy varies from country to country. Due to the above reasons, it was decided to not adopt average correction factors for equipment energy.
ii) The confining stress affects both N and V_S, so to estimate V_S it makes physical sense to use N, as it is commonly adopted in the N-V_S empirical correlations.

It is well known that SPT test can be considered fairly adequate to assess the strength of granular material, while for cohesive soils only a qualitative assessment is obtained. However, in this paper N value was used because it was the geotechnical parameter available with a larger cover of Lisbon county.

3.2. Classification algorithm

The GDB has a large number of borehole data and SPT results, but less than 10 reports include V_S profiles.

In general, the classification was based on N values. However, in rock and/or stiff soils, SPT was not available or when available were disregarded because SPT is not appropriate for those geomaterials, the classification was based on geological criteria, described in the following section.

The classification of a large number of geotechnical information available was automated after a set of tests and validation covering all ground conditions.

For boreholes where N was not available or reliable, the classification was based on lithology. For that purpose, the geological formations were grouped and classified according to the following ground types:

i. Ground type A: formations composed by basaltic or carbonate rocks (Lisbon Volcanic Complex (LVC), Bica Formation (C3), and Caneças Formation (C2));
ii. Ground types B and C: formations composed by soft calcarenite rocks, clayey deposits and sandy soils (Benfica Formation (BF) and the Miocene formations (M)).

Figure 5 plots a representative cross-section of a valley with the definition of ground zones (GZ) depending on the average value of N. H_1, $H_{2,}$ and H_3 refer to thickness of GZ1, where N ≤ 15, GZ2 where 15 < N ≤ 50 and GZ3, where N > 50, respectively. H_{sis} is the depth at which a layer with V_S > 800 ms^{-1} was identified.

A site where average N ≤ 15 is classified as ground type D (profile 1 in Figure 5). Sites, where average N is in the range from 15 to 50, are classified as ground type C (profiles 2 and 3 in Figure 5). Sites where N is considered as representative and average N > 50 are classified as ground type B (profiles 4, 5 and 6 in Figure 5). Based on surface lithology, if estimated V_S is larger than 800 ms^{-1} or if the weaker material at surface is at most 5 m thick, then the soil is classified as ground type A (profiles 7 and 8 in Figure 5).

Ground type E is not represented in Figure 5. If H_{sis} is between 5 and 20 m and the upper soil is characterized by the average N (indicating that SPT is considered appropriate to characterize that layer), then the ground type is classified as E.

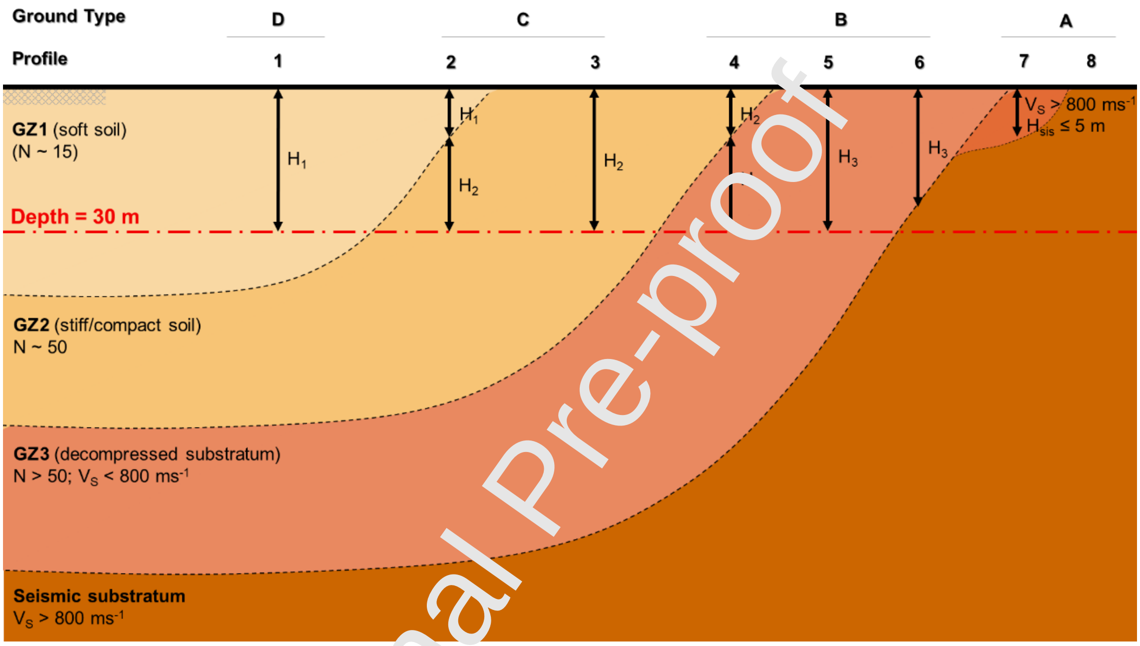


Figure 5. Reference cross-section: definition of variables used in the classification algorithm.

An algorithm to classify the ground profile was developed and applied to all boreholes where N value was available.

The classification algorithm is structured according to the flowchart plotted in Figure 6. The main steps can be identified as follow:

1. Calculation of the extrapolated N value (N_e) for a penetration of 30 cm, based on the N values and on its penetration length in the 2nd stage; the maximum value of N_e was taken equal to 180 to avoid extremely high values without accuracy and/or physical meaning that could bias the N_e average value for a given borehole/profile; identification of the seismic bedrock and its depth (H_{sis}) through the lithology identified in each borehole, based on expert opinion;

2. Identification of geotechnical zone 1 (GZ1) characterized by depth H_1, measured from the surface at which the mean N_e value (N_{med1}) is approximately equal to 15;

3. Identification of geotechnical zone 2 (GZ2) characterized by the thickness (H_2), which is taken as the difference between the depth of the last SPT where the mean value of N_e (N_{med2}) is less than or equal to 50 and the depth H_1;

4. Identification of geotechnical zone 3 (GZ3) characterized by the thickness (H_3), which corresponds to the difference between the depth of 30 meters and the depth of H_2, for which calculated the mean value of N_e (N_{med3}) of this geotechnical zone;

5. Based on these parameters, N_{30} value is computed for each borehole using equation 1 (step 12 in Figure 6):

$$N_{30} = \frac{H_1 + H_2 + H_3}{\frac{H_1}{N_{med1}} + \frac{H_2}{N_{med2}} + \frac{H_3}{N_{med3}}} \tag{1}$$

Throughout the different calculation steps, additional requirements were implemented to:

i) Identify the existence near-surface block or pavement (step 1 in Figure 6), that is considered not representative of the ground profile, being its value disregards (N_e(i=1) represents the shallower SPT done in the borehole);

ii) Check the existence of GZ1 (step 4 in Figure 6): if the upper 2 values of N_e are higher than 15, that the existence of GZ1 is considered not likely;

iii) Identify singular blocks embedded in soil layer (see step 3 in GZ1 and step 2 in GZ2 of Figure 6), that may generate a sharp increase of the N value, but are not representative of the layer;

iv) Most boreholes reach less than 30 m deep, so it was necessary to extrapolate the N values to a depth of 30 meters; it was adopted the deepest N value as representative of the ground between the borehole's bottom and 30 m (see step 11 in Figure 6).

The algorithm classifies the borehole in the five ground types defined in EC8 or, if none of those ground types is attributed, the site is classified as Unknown (see step 13 in Figure 6).

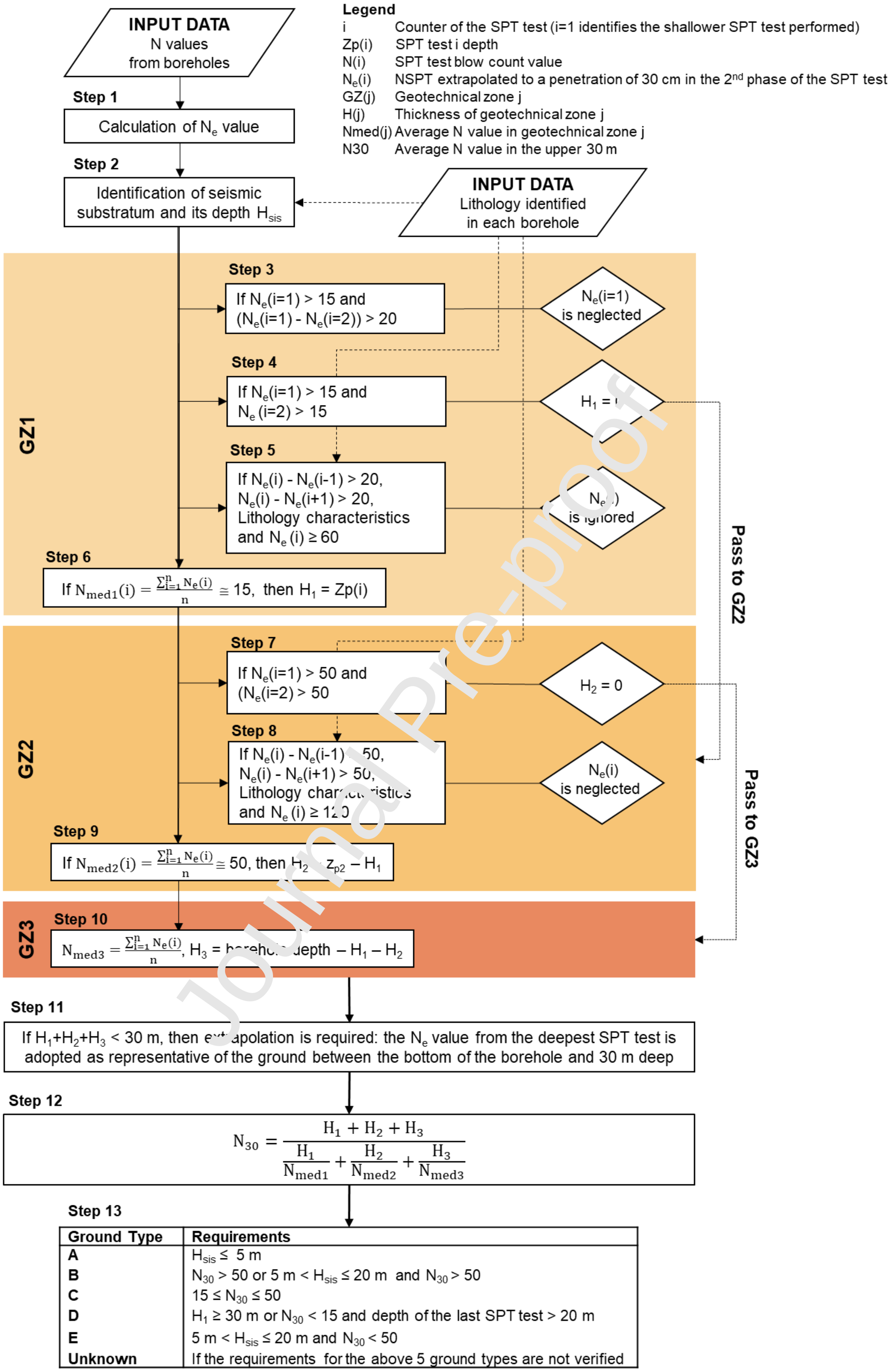


Figure 6. Flow chart of the proposed classification algorithm to ground seismic zonation.

4. Application of the classification algorithm to Lisbon's GDB

4.1. Analysis of 1st iteration of ground classification

The ground classification obtained by the application of the algorithm is presented in Figure 7.

In general, the distribution of the ground types is rather heterogeneous, especially in the distribution of grounds type B and C (Figures 7A and 7B). It is not possible to distinguish zones with ground type B or ground type C. Additionally, there are areas with irregular distribution of the boreholes or due to nonexistence or limited information, which prevents a reliable classification of the ground type.

As an example, Figure 7C shows a zoom of the Parque das Nações area, to put in evidence the difficulty in creating fairly homogenous zones. It is visible the high lateral variability of the ground type, related to the lateral variability of the surface geology.

Figure 7. Ground classification obtained from the application of the algorithm. A - Boreholes classified as ground type B overlapping the rest; B - Boreholes classified as ground type C overlapping the rest; C - detail of the Parque das Nações region.

Due to the irregular distribution of boreholes and ground type, it was decided to add information from the geological map in order to facilitate the creation of the seismic microzonation map.

Statistical analysis was performed to evaluate the dispersion of the ground type classification in each shallow geological formation. The number of boreholes by ground type and the total number of boreholes crossing each geological formation were considered. For example, the ground type distribution founded for Areolas de Cabo Ruivo (MVIIb) and Benfica Formation (BF) is plotted in Figure 8. It can be seen that for Areolas de Cabo Ruivo (MVIIb) (Figure 8A), ground type B and C are clearly predominant and almost equally distributed, while for Benfica Formation (BF) (Figure 8B) ground type B clearly prevails (~85%).

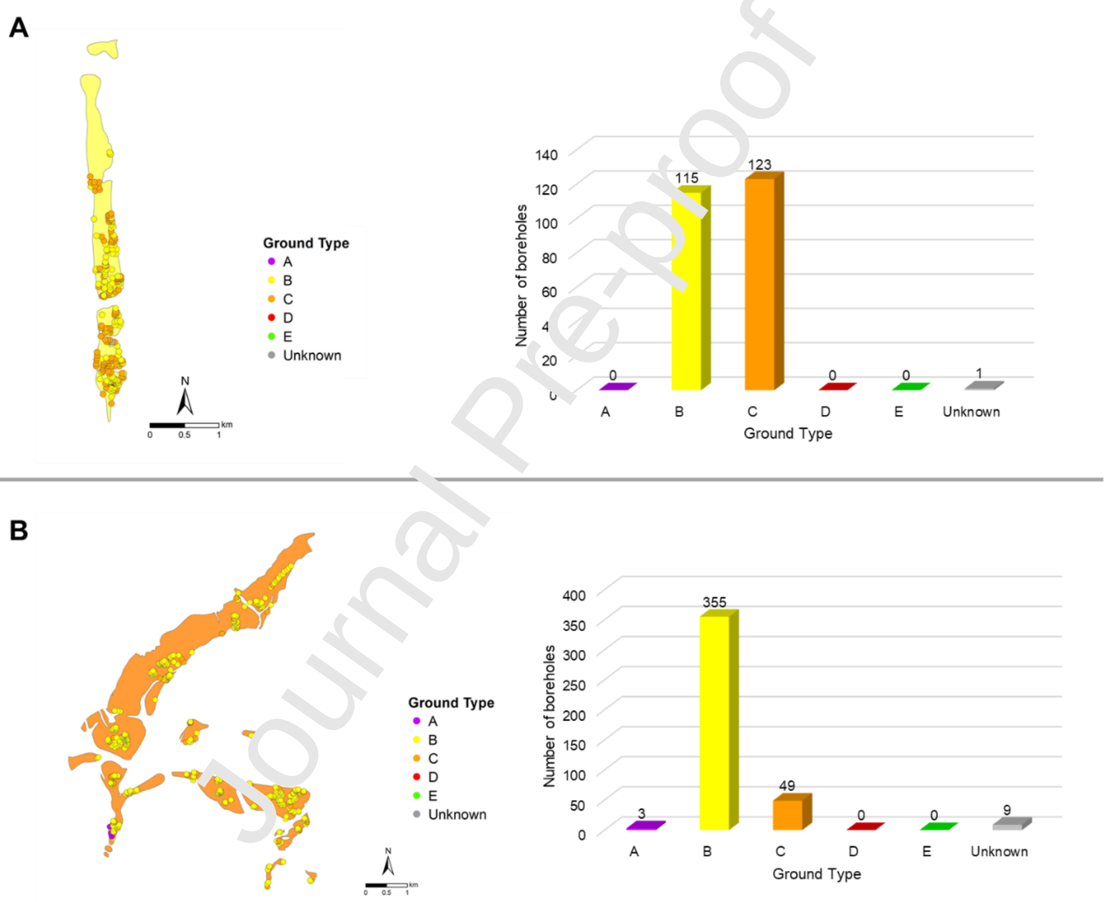


Figure 8. The statistical distribution of ground types for two geological formations: A – Areolas de Cabo Ruivo (MVIIb); B – Benfica Formation (BF).

Table 1 shows the main results of the statistical analysis, relating the predominant ground type(s) in each shallow geological formation. Two predominant ground types are enhanced (in bold) when the difference between them is less than 10%.

Table 1. Statistical analysis results of the predominant ground type(s) for each shallow geological formation.

Geological Formation	**Number of boreholes**	**Ground Type (%)**					
		A	**B**	**C**	**D**	**E**	**Unknown**
Alluvium (al) and/or Landfill (at)	1666	0.1	33.6	**56.3**	4.6	0.8	4.6
Areolas de Cabo Ruivo (MVIIb)	239	0	**48.1**	**51.5**	0	0	0.4
Areolas de Braço de Prata (MVIIa)	237	0	**62.0**	37.1	0	0	0.8
Calcários de Marvila (MVIc)	160	0	**58.1**	41.3	0	0	0.6
Grés de Grilos (MVIb)	106	0	40.6	**57.5**	0	0	1.9
Argilas de Xabregas (MVIa)	279	0	**44.8**	**54.8**	0	0	0.4
Calcários da Quinta das Conchas (MVc)	58	0	**69.0**	31.0	0	0	0
Areias de Vale de Chelas (MVb)	239	0	**74.9**	22.6	0	0	2.5
Calcários da Musgueira (MVa3)	64	0	**67.2**	31.3	0	0	1.6
Areias com Placuna Miocénica (MVa2)	388	0	**50.5**	**47.4**	0	0	2.1
Calcários de Casal Vistoso (MVa1)	159	0	**42.8**	**52.2**	0.6	0	4.4
Areias de Quinta do Bacalhau (MIVb)	385	0	36.6	**62.1**	0	0	1.3
Argilas de Forno do Tijolo (MIVa)	452	0	**72.6**	25.4	0	0	2.0
Calcários de Entrecampos (MIII)	210	0	**56.7**	41.0	0.5	0	1.9
Areolas de Estefânia (MII)	665	0	**56.4**	42.4	0	2	1.1
Argilas de Prazeres (MI)	1367	0.1	**50.6**	**45.9**	0	1.5	2.0
Benfica Formation (BF)	416	0.7	**85.3**	11.8	0	0	2.2
Lisbon Volcanic Complex (LVC)	605	3.5	**52.2**	26.4	0.2	4.1	13.6
Bica Formation (C3)	221	5.0	28.1	**43.0**	0.9	3.6	19.5
Caneças Formation (C2)	88	0	36.4	**51.1**	0	5.7	6.8

Most of the geological formations have a similar number of boreholes classified as ground type B and as ground type C, as shown for Areolas de Cabo Ruivo (MVIIb) (Figure 8A). Only a small number of geological formations presented a clear predominant classification like Benfica Formation (BF) (Figure 8B).

The ground type D was found mainly in the riverside areas where the thicker surface formations were identified (Figure 4).

For the Cretaceous formations (C), initially classified as ground type A (section 3.2.), the algorithm produced different results. In the case of the Lisbon Volcanic Complex (LVC), most of the boreholes were classified as ground type B, a significant number were classified as ground type C, and only a small number have been classified as ground type A. This may be because in older and harder Cretaceous units (C) just a few boreholes are available. On these formations, it is not usual to perform SPT (N = 60 is obtained very close to the surface and this test is not adequate to characterize such resistant materials) and the boreholes that exist were done in areas covered with surface formations, which can locally modify the site classification. Therefore, to classify the different geological units, particularly the stiffer ones, additional details should be taken into account.

4.2. Introduction of intermediate classes

A large number of geological formations have a similar number of boreholes classified as ground type B and C (see previous section), with highly heterogeneous distribution.

To overcome the difficulty in defining a zonation in these geological formations, an intermediate class BC was introduced, representing a transition ground type from B to C. This intermediate ground type was defined according to the N_{30} value computed with the algorithm and it represents the stiffer profiles of ground type C ($15 < N_{30} < 50$) and the softer profiles of ground type B ($N_{30} > 50$): a ground type is classified as BC when $40 \leq N_{30} \leq 70$.

Figure 9 shows the distribution of ground type classes including the new BC. The results for the Areolas de Cabo Ruivo (MVIIb) are shown in Figure 10. Considering only the two classes, B and C (Figure 8A), it was not possible to observe a predominant class to properly classify this formation. The introduction of class BC leads to the existence of a fairly predominant class (~51%) in this formation (Figure 10B). The inclusion of this new ground type BC on the seismic zonation of Lisbon's soils can be interpreted according to two different situations:

i. A zone (geological formation) where there is an almost equal number of boreholes classify as ground type B and C, showing the large spatial distribution heterogeneity;
ii. A zone (geological formation) with an intermediate behavior between the two classes, B and C, characterized by an N_{30} value close to the transition value of the two ground types defined in EC8.

In both cases, the cause may be due to the random distribution of the surface formations throughout the city presenting variable thickness. These formations, which are not fully mapped in the geological map, can significantly and locally change the geotechnical properties of the ground profiles, and consequently their response to external requests.

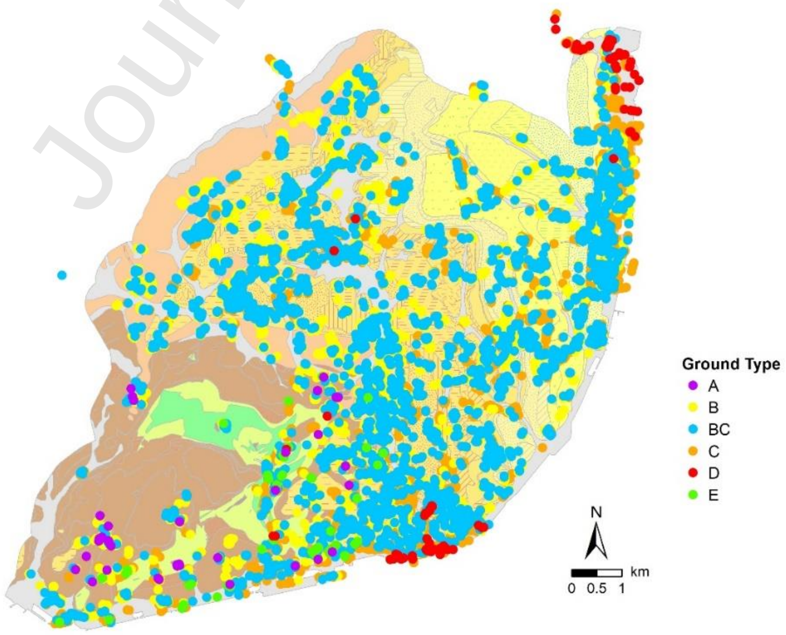


Figure 9. Distribution of ground classification of the Lisbon Municipality, including the ground type BC overlying other ground types.

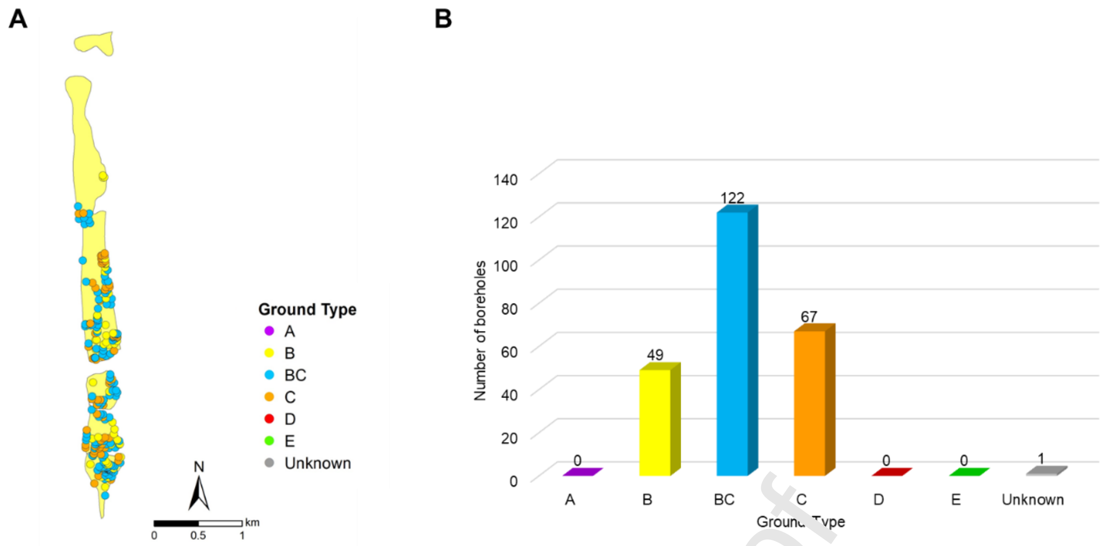


Figure 10. Areolas de Cabo Ruivo (MVIIb). A - Distribution of ground types on the geological formation (all classes considered); B - Histogram with the accounting of ground type, considering the new class BC.

It was also considered necessary to add another intermediate class, AB. Initially, the Cretaceous formations (C) were classified as ground type A. However, the small number of boreholes available for these formations and the inadequacy of using SPT in rock, lead to the inadequacy of the algorithm to classify the ground type in these formations. Besides, the existence of surface formations can also influence the ground response, modifying their characteristics and changing ground type A to ground type B. This fact, together with the impossibility of independently identifying these two ground types in these older formations, justifies the introduction of ground type AB that could correspond to two distinct situations:

i. Ground type A, which response is locally modified due to the existence of surface formations (not mapped and heterogeneous distributed);
ii. Cretaceous geological formations (C) that may be weathered, but where it is not possible to separate unweathered from weathered rock areas.

5. Final ground seismic zonation map of Lisbon

The application of the algorithm, based on N_{30} estimation, identified sites with soil ground types A, B, BC, C, D and E. As mentioned before, the seismic zoning tokes the contribution of the geological map. The soil ground type attributed to each formation was the predominant type identified through statistical analysis.

Only a few boreholes were classified as ground type A (see Figure 9). Based on local geology the older formations (Lisbon Volcanic Complex (LVC) and Bica Formation (C3)) were classified as soil ground type AB.

Boreholes classified with ground type E are also scarce: only 65 of the 8117 boreholes (see Figure 9). It is not possible to associate a geological formation to this ground type or to define a limited area corresponding to this ground type. So, it was decided to identify these sites on the final map to alert of the possibility of having locally a different ground type.

To classify the alluviums (al) and/or landfills (at) we consider their thickness: the thicker riverside surface formations (on Parque das Nações, Baixa and Alcântara) were classified as ground type D; the remaining surface formations (riverside and interior alluviums (al) / landfills (at)) were classified as ground type C.

The final seismic zonation of the Lisbon town is presented in Figure 11. Seismic homogeneous areas, based on soil ground type classification, were delimitated according to the geospatial delimitation of the geological formations. The surface formations with a thickness greater than 10 meters that are not mapped in the geological map were identified in this map.

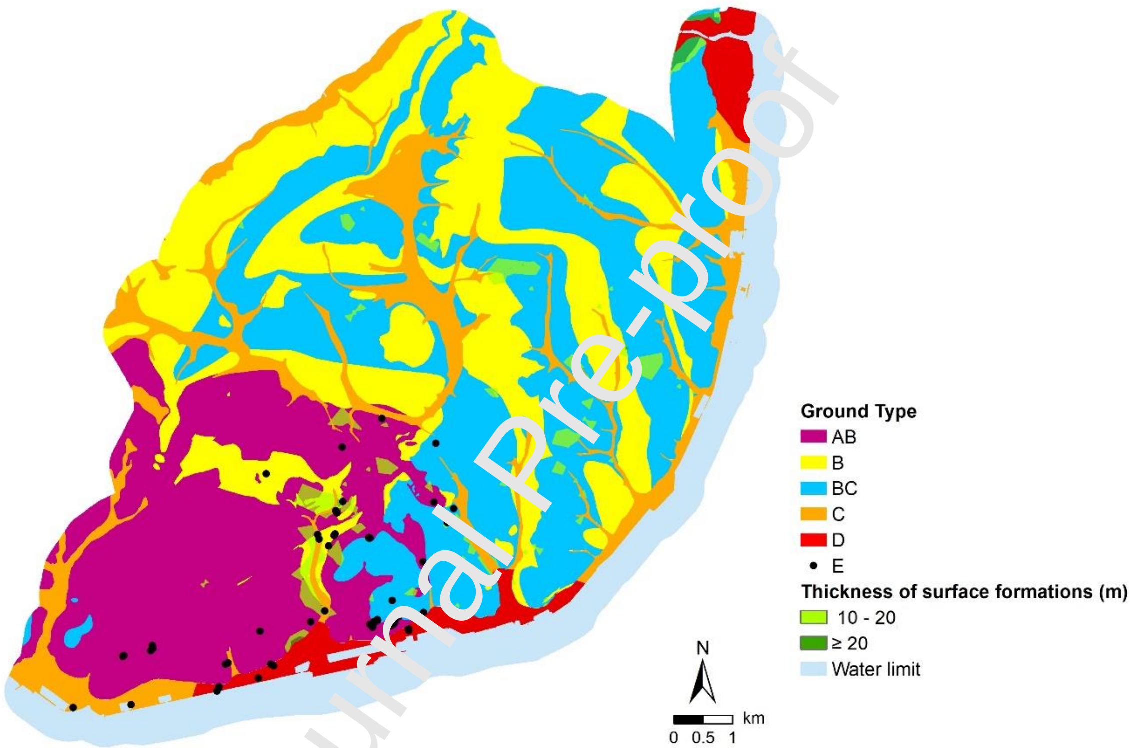


Figure 11. Ground classification map of Lisbon County.

6. Discussion

To check and validate the ground classification field experiments were performed in some sites selected according to their respective ground classification. The field experiments consisted on surface waves seismic profiles and single-station ambient vibrations measurements. The results from these field experiments, together with data collected from independent geophysical reports, were used to locally check and validate the classification algorithm and the options taken for the ground classification. Figure 12 shows the location of the field experiments.

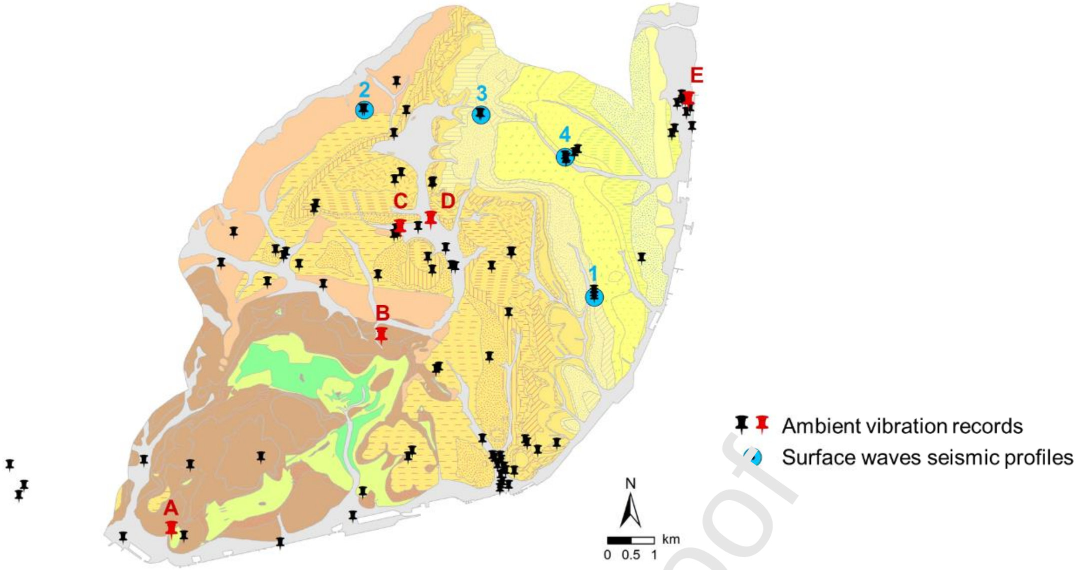


Figure 12. Location of the sites where ambient vibration records and surface waves seismic profiles were performed: A – Restelo; B – Campolide; C – Campo Grande; D – Campo Grande; E – Parque das Nações; 1 – Chelas; 2 – Quinta dos Alcoutins; 3 – Musgueira; 4 – Encarnação.

The surface waves seismic profiles are used to characterize a layered soil, or ground formation, allowing the estimation of the seismic waves' velocities (V_S or V_P) and the thickness (H) of each layer. From these parameters, it is possible to estimate the V_{S30} value, which is useful to ground classification as presented in Eurocode 8 (CEN, 2004).

The surface waves seismic profiles were carried out in areas with variable surface formations thickness settled on different geological formations (Figure 12). The sites selected have nearby geotechnical boreholes.

As an example, Figure 13 shows the results obtained in Musgueira (site 3 in Figure 12) where the Areias do Vale de Chelas (MVb) formation outcrop. The mean V_S profile was obtained by the inversion of the surface waves dispersion curve (Tokimatsu, 1995; Wathelet et al., 2004).

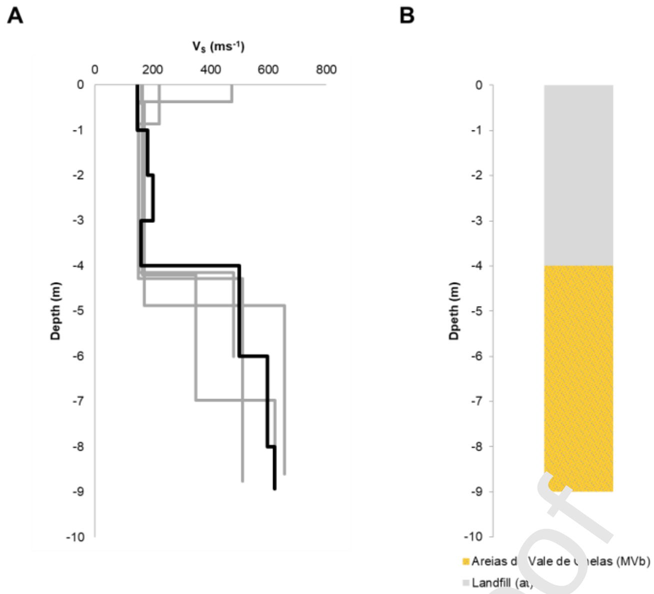


Figure 13. Vs profiles obtained from the analysis seismic profiles of surface waves for Musgueira site: A – obtained V_S profiles (in bold is the mean Vs profile); B – interpretative soil profile derived from the mean V_S profile.

In this site, landfills (at) of variable thickness overlay Areias do Vale de Chelas (MVb) formation. Thus, it is possible to associate the different layers to the ground profile from a nearby borehole (Table 2).

Table 2. Ground profile interpretation obtained from surface waves seismic profiles analysis for two different sites.

Site	Geological Formation	H (m)	V_S (ms^{-1})	V_{S30} (ms^{-1})
Musgueira	Surface formation (Landfill (at))	4	173	449
	Areias do Vale de Chelas (MVb) (weathered)	2	498	
	Areias do Vale de Chelas (MVb) (compacted)	-	604	
Quinta dos Alcoutins	Surface formation (Landfill (at))	4	344	791
	Argilas dos Prazeres (MI)	3	583	
	Benfica Formation (BF)	-	1088	

Considering the V_S profile and the lithological information (Figure 13), it can be inferred that there is a landfill (at) deposit with 4 meters thick and V_S value of 173 ms^{-1}, over a weathered layer of Areias do Vale de Chelas (MVb) with 2 meters thick and V_S value of 500 ms^{-1}, approximately, settled on a more compacted layer of the same formation characterized by a V_S value of 600 ms^{-1}, approximately. For this site, a V_{S30} value of ~ 450 ms^{-1} was obtained. Considering the EC8 ground classification, this V_{S30} value match to ground type B, which agree with the predominant ground classification determined by the algorithm for geological formation of Areias do Vale de Chelas (MVb). This conclusion is also valid for the ground classification obtained for the Benfica Formation (BF) (Quinta dos Alcoutins site, Table 2; site 2 in Figure 12).

It can be seen, by this example, that the surface waves seismic profiles do not always reach the depth of interest for site classification (30 meters). Consequently, to compute the V_{S30} parameter it is necessary to use an estimated value for V_S. For this reason, it is very important to have an idea of the V_S values expected for each geological formation. Several authors (e.g. Oliveira et al., 1997; LNEC, 1998; Lopes, 2005; Lopes et al., 2005; Freitas et al., 2014; Teves-Costa et al., 2014; Gouveia, 2017; Gouveia et al., 2018) estimated S-waves velocities for different geological formations based in different seismic surface field tests.

The horizontal to vertical spectral ratio (HVSR) is widely used to estimate the fundamental frequency of the ground, f_0 (Nakamura, 1989). A first estimate of the average shear wave velocity in the superficial layer (alluviums and/or landfills) can be obtained from:

$$f = \frac{V_S}{4h} \tag{2}$$

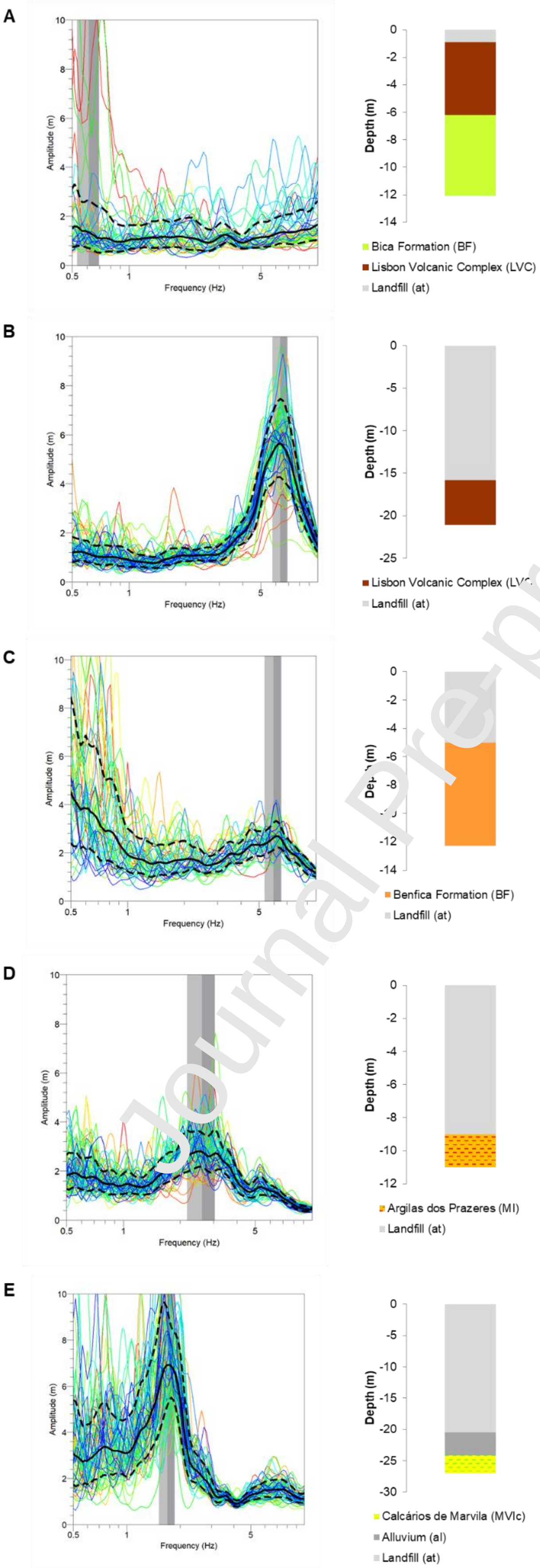
Where f is the natural frequency of ground, Vs is the S-wave velocity and h is the thickness of the surface formation, representative of homogeneous ground with viscoelastic behavior over a rigid substrate (Nakamura, 1989).

The ambient vibration recordings were carried out in several sites to obtain additional information to characterize the ground seismic behavior (Figure 12). Sites were selected based on the surface formation thickness (e.g. in the Parque das Nações) settled on different geological substrates (e.g. in the Lisbon Volcanic Complex (LVC)). In addition, the results obtained by Teves-Costa et al. (2014), as well as the reanalysis of ambient vibration records collected before (Teves-Costa et al., 2011) were considered (Figure 12). To analyze and interpret the obtained results the ground profile lithostratigraphy of each borehole located near the recording sites were considered.

On the Lisbon Volcanic Complex (LVC), two sites were analyzed: the first one (Restelo, site A in Figure 12) has a very thin landfill (< 1 m) (Figure 14A) and the second one (Campolide, site B in Figure 12) has a surface landfill 16 m thick (Figure 14B). The first curve shows no evident peak, which is characteristic of a rock behavior, corresponding to a ground type A (SESAME, 2004). The second curve shows a peak of 6.3 Hz associated with surface landfill. Using eq. (2) V_S for these landfills will be 401 ms^{-1}, approximately. This example shows that the existence of a superficial formation on a ground type A can convert it into a ground type B, supporting the assignment of ground type AB to the Lisbon Volcanic Complex and Bica Formation.

In Campo Grande, two sites were selected: the first one (site C in Figure 12) presents a surface landfill of 5 m (Figure 14C) and the second (site D in Figure 12) presents a landfill of 9 m (Figure 14D). The HVSR curve at the first site presents a peak at a frequency close to 6.0 Hz and at the second site a frequency peak of 2.6 Hz was obtained (Figures 14C and 14D). Both peaks must be associated with landfill deposits. This example shows the influence of the landfill deposits thickness on the soil natural frequency. Using eq. (2) we obtained V_S values of 120 ms^{-1} and of 94 ms^{-1}, respectively at the first and the second site, for the landfill deposits. These values can result from the heterogeneous composition of these deposits. This example also shows that two close sites, settled on the same geological formation, can be classified in two different classes, evidencing the difficulty of attributing a classification to each geological formation.

In Parque das Nações (site E in Figure 12) a site with a very thick surface formation (20 - 25 m), composed of landfills and alluviums, was selected. The obtained HVSR curve shows a clear peak at a frequency close to 1.7 Hz (Figure 14E). This value can be interpreted as the natural frequency of the ground profile. Using eq. (2) the S wave velocity is around 165 ms^{-1} in the highly weathered formations. This value, together with the thickness of these surface formations, supports the classification of the riverside sites as ground type D.



A

Geological Formation	Thickness (m)
Landfill (at)	0.9
Alluvium (al)	0
Landfill (at) + Alluvium (al)	0.9
f_0 (Hz)	-
A_0 (m)	-

B

Geological Formation	Thickness (m)
Landfill (at)	15.8
Alluvium (al)	0
Landfill (at) + Alluvium (al)	15.8
f_0 (Hz)	6.3
A_0 (m)	5.6

C

Geological Formation	Thickness (m)
Landfill (at)	5
Alluvium (al)	0
Landfill (at) + Alluvium (al)	5
f_0 (Hz)	6.0
A_0 (m)	2.6

D

Geological Formation	Thickness (m)
Landfill (at)	9
Alluvium (al)	0
Landfill (at) + Alluvium (al)	9
f_0 (Hz)	2.6
A_0 (m)	2.8

E

Geological Formation	Thickness (m)
Landfill (at)	20.5
Alluvium (al)	3.7
Landfill (at) + Alluvium (al)	24.2
f_0 (Hz)	1.7
A_0 (m)	6.9

Figure 14. HVSR curves obtained from the analysis of ambient vibration recordings: A – Restelo; B – Campolide; C – Campo Grande; D – Campo Grande; E – Parque das Nações.

The results of the field experiments performed are in agreement with the ground classification obtained by the algorithm application. However, more tests are needed, in particular in the areas where there are no or few boreholes, to test the proposed zonation and to investigate in more detail the transition between the different soil classes.

7. Conclusions

In this study, a map with the classification of Lisbon's soils is presented. A first attempt was made to classify the soils according to the EC8's ground type classes (A, B, C, D, and E). However, for a better definition of the seismic zonation it was necessary to introduce two additional intermediate ground classes, AB and BC. It seems, as proposed by some authors, that the single classification into A, B, C, D and E classes, is not enough to take into account the diversity of the soil seismic behavior.

In the absence of Vs values, the zonation was based on the characteristics of the surface geology using the N_{30} parameter obtained from the analysis of a large GDB controlled by Lisbon Municipality. This parameter allowed the implementation of an expedited computing method to define the soil ground type. This work, which was the first exhaustive exploitation of the GDB, allowed the identification of some gaps that are currently being corrected to improve the quality and the applicability of the GDB in future projects.

The proposed classification was punctually checked with field experiments based on surface seismic methods. The experimental results showed a good agreement with the classification obtained through SPT analysis. However, more experiments are needed to cover all the geological situations present in the town.

Although the good agreement with the few experimental results, this methodology, mainly based on the results of SPT and available geological information, presents several limitations:

- The spatial distribution of the geotechnical boreholes is very heterogeneous, with areas with a high concentration of boreholes and areas with no data;
- The depth of the boreholes is generally lower than the 30 m needed to apply the EC8 ground type classification (about 56% does not exceed 15 m depth);
- The 8792 geotechnical boreholes used were carried out between 1935 and 2016 by several companies. The recent and older reports were analyzed in the same way and some of the information contained in these studies may already be outdated, especially concerning the surface formations (Dias, 2013);
- The geological map of Lisbon County, edited on 1986 (Moitinho de Almeida, 1986), was based on field works carried out at the end of the 19th century and on surveys performed in the early 1980s. Considering the urbanization changes it is likely that part of the information presented on the geological map is outdated, especially concerning the surface formations;
- The uncertainty associated with the estimation of the N_{30} value cannot be quantified due to all options that were necessary to take to overcome the different difficulties that have arisen.

However, the weaknesses associated with the use of the GDB (composed of non-reproducible data acquired over several years by different companies) are compensated by the large volume of available data which is its strength.

Due to these limitations, it should be noted that the seismic zonation of Lisbon (Figure 11) identifies only the predominant ground class in a given zone. It is also important to point out that the proposed map is plotted at the city scale, so its use for punctual assessment of site seismic behavior is discouraged (as evidenced by the site analysis in Campo Grande). The analysis and/or any use of the seismic zonation map should consider these constraints.

This work presents a starting point for a detailed microzonation of Lisbon town. It has been very useful for the seismic resilience-building estimation project under development in the Lisbon Municipality. However, it is necessary to estimate Vs profiles, through seismic surface waves experiments, and the fundamental frequency of the ground deposits, with small spacing. Thereafter, the new proposals to define the ground type, like the ones under preparation for the next generation of Eurocode 8, can be tested and eventually adopted.

Acknowledgments

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Figure Caption

Figure 1. Spatial distribution of available geotechnical boreholes.

Figure 2. Statistical analysis of the depth of the boreholes and the number of SPT results per borehole.

Figure 3. Geological map of the Lisbon County (adapted from Moitinho de Almeida, 1986).

Figure 4. Distribution of surface formations (alluvium and landfill) in Lisbon, applying a data interpolation for thicknesses > 5 m. A – Parque das Nações; B – Baixa; C – Alcântara.

Figure 5. Reference cross-section: definition of variables used in the classification algorithm.

Figure 6. Flow chart of the proposed classification algorithm to ground seismic zonation.

Figure 7. Ground classification obtained from the application of the algorithm. A - Boreholes classified as ground type B overlapping the rest; B - Boreholes classified as ground type C overlapping the rest; C - detail of the Parque das Nações region.

Figure 8. The statistical distribution of ground types for two geological formations: A – Areolas de Cabo Ruivo (MVIIb); B – Benfica Formation (BF).

Figure 9. Distribution of ground classification of the Lisbon Municipality, including the ground type BC overlying other ground types.

Figure 10. Areolas de Cabo Ruivo (MVIIb). A - Distribution of ground types on the geological formation (all classes considered); B - Histogram with the accounting of ground type, considering the new class BC.

Figure 11. Ground classification map of Lisbon County.

Figure 12. Location of the sites where ambient vibration records and surface waves seismic profiles were performed: A – Restelo; B – Campolide; C – Campo Grande; D – Campo Grande; E – Parque das Nações; 1 – Chelas; 2 – Quinta dos Alcoutins; 3 – Musgueira; 4 – Encarnação.

Figure 13. Vs profiles obtained from the analysis seismic profiles of surface waves for Musgueira site: A – obtained V_S profiles (in bold is the mean Vs profile); B – interpretative soil profile derived from the mean V_S profile.

Figure 14. HVSR curves obtained from the analysis of ambient vibration recordings: A – Restelo; B – Campolide; C – Campo Grande; D – Campo Grande; E – Parque das Nações.

Table 1. Statistical analysis results of the predominant ground type(s) for each shallow geological formation.

Table 2. Ground profile interpretation obtained from surface waves seismic profiles analysis for two different sites.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- Seismic microzonation map based on large geotechnical database
- Automatic algorithm to classify each profile based on a proxy of V_{S30} EC8 ground classification
- The final zonation joins the profile classification with geological data