



Seismic site effects in Lisbon: the role of complex geological and morphological conditions

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Abstract

Lisbon's historical seismicity, socioeconomic importance and population density contribute to a moderate to high seismic risk. The geological setting of the city includes cases of inclined layers, interbedding sedimentary rock layers in soil deposits, sand and clay layers in the same geological unit, leading to cases of shear wave velocity inversion and a large scatter of geotechnical properties within each geological unit. The morphological setting of the city is characterised by the existence of several hills and relatively shallow, stream-carved valleys filled with alluvial deposits. The seismic site effects in Lisbon were assessed through numerical simulation using the linear equivalent method and adopting the two types of seismic action defined in the Portuguese National Annex of Eurocode 8: (i) one-dimensional subsoil models covering the city, at sites where borehole data and geophysical data were available; (ii) two-dimensional subsoil models along three cross-sections representative of the geological settings and morphology. The distribution of amplification factors in the city revealed a pattern related to ground characteristics that impact seismic soil response, such as the presence of high-thickness cover deposits, significant shear-wave variations, alluvial valleys, a crest or significant slope variations and inclined layers. The 2D/1D spectral ratio highlighted the areas where 2D seismic effects are more important. The soil factor determined in the numerical analyses was consistently greater than the soil factor values indicated in Eurocode 8.

Keywords Seismic site response · Numerical modelling · Amplification factors · Complex geological and morphological conditions · Lisbon

1 Introduction

Lisbon has a moderate to high seismic risk due to its historical seismicity, socio-economic importance and population density. Lisbon's geological setting is characterised by a complex lithostratigraphic structure that includes cases of inclined layers, interbedding sedimentary rock layers in soil deposits and layers of sands and clays that are related to the same geological unit (Moitinho de Almeida 1986; Teves-Costa et al. 2001). These features can result in cases of shear wave velocity inversion and a wide range of geotechnical

properties within each geological unit (e.g., Almeida 1991; Teves-Costa et al. 2011). The morphological setting of the city is characterised by the existence of several hills and relatively shallow, stream-carved valleys filled with alluvial deposits (al).

The combination of these factors requires the characterisation of the seismic site effects to delimit the areas of similar local hazard and contribute to long-term urban planning and seismic risk mitigation.

Local site conditions can significantly modify the main characteristics of the seismic ground motion, including its amplitude, duration, and frequency content. The extent of their influence depends on the geometry and properties of the underlying materials, on site topography, and on the characteristics of the input motion (Kramer 1996).

Site effects are classified into three types: local seismic response or stratigraphic effect, basin or valley effect, and topography effect (Kramer 1996; Stewart et al. 2002). The stratigraphic effect has to do with the amplification of ground motion due to the impedance contrast of the surficial layers with respect to the deeper layers. The basin or valley effect is related to the influence of the two- or tri-dimensional structure of alluvium basins on the seismic motion, including the simulation in large scale of the wave reflection and generation of surface waves in the basin boundaries. The topography effect is related to the influence of surface topography on the generation of wave reflection. Other 2D effects can be associated with subsoil morphology, such as inclined layers.

Over the past decades there has been a large number of studies that have characterised 2D site effects on ground motion (e.g., Bard and Bouchon 1985; Bard 1999; Chávez-García and Faccioli 2000; Raptakis et al. 2004; Cauzzi et al. 2010; Vessia et al. 2011; Pagliaroli et al. 2011; Abraham et al. 2015; Riga et al. 2016; Madiati et al. 2017; Amoroso et al. 2018; Alleanza et al. 2019; Molina et al. 2019; Rodríguez-Plata et al. 2021).

The first pioneering studies on the valley response have been addressed by means of theoretical and experimental approaches in the eighties (e.g., Bard and Bouchon 1985) providing a general framework for studying common valley response characters by means of numerical simulations.

Evidence of topographic effects comes from macroseismic observations, instrumental studies, analytical approaches and numerical modelling that have been significantly expanded since Boore (1972) early work. Bard (1999) provides a comprehensive review of the effects of surface topography on earthquake ground motion.

The concept of aggravation factor was first developed by Chávez-García and Faccioli (2000) to connect 1D and multi-dimension effects.

Pagliaroli et al. (2011) carried out numerical site response analyses on the Nicastro ridge (Italy) and reported that the maximum topographic amplification occurs at the crest of the ridge. The calculated topographic amplification factors were also compared to Eurocode 8 (EC8) and those derived from analytical and numerical studies in the literature. The topographic amplification factors at the crest of the Nicastro ridge satisfactorily match the average trend of literature-derived data, whereas EC8 recommendations represent a lower boundary since the computed peak acceleration amplification factors were between 25 and 35%, which is higher than those suggested by EC8.

Riga et al. (2016) performed extensive numerical analyses of the linear viscoelastic response of trapezoidal sedimentary basins to investigate the sensitivity of their 2D seismic response attributes to parameters related to the geometry of the basin (width, thickness and inclination angles of lateral boundaries) and to the dynamic soil properties (shear and compressional wave velocities, soil density and attenuation).

Rodríguez-Plata et al. (2021) investigated the seismic site response of the Norcia basin in Central Italy using 1D and 2D ground response numerical models. The authors provided

period-dependent aggravation factors that quantified the difference between 2 and 1D site response in two representative cross-sections of the basin. The variability of the period-dependent aggravation factors was explored by considering the effects of frequency content of input motion, damping ratio and alluvial-bedrock interface irregularity. Although the basin sediments are composed of rather stiff soils, the Norcia basin has been shown to consistently modify and enhance ground motion.

In this paper, 1D and 2D numerical analyses were performed. One-dimensional modelling was performed across the city in correspondence with the available geotechnical and geophysical data. Three 2D numerical analyses were performed across the deep (~ 100 m) geological cross-sections given by Moitinho de Almeida (1986). These analyses considered different 2D effects (valleys, hills and inclined layers). Two types of seismic actions, as defined in the Portuguese National Annex of Eurocode 8 (EC8-N.A., IPQ 2010), were considered for a 475-year return period, selecting, from the European Strong-Motion Database (Luzi et al. 2020), two sets of seven accelerograms compatible with the reference spectra. The 1D and 2D results are shown in terms of amplification factors and acceleration response spectra, investigating also the physical phenomena governing the site response. The acquired data were compared to other results from the literature estimated at sites with similar geological-morphological properties to identify a pattern of variation. Furthermore, the estimated soil factors were evaluated and compared to those established in Eurocode 8 (CEN 2004) and the related Portuguese National Annex (IPQ 2010).

2 Geological, geophysical and geotechnical data

2.1 Geological setting

Portugal is located along the Eurasia-Africa plate boundary (Cabral 2012). This offshore region is responsible for large earthquakes generated at Gorringe Bank zone, Horseshoe Fault, and Cadiz Fault, which affect the Portuguese mainland, particularly the Lisbon metropolitan area and the Algarve region. The interaction between these two plates at SW Portugal were the source of large past earthquakes, including the $M_w = 8.2$ – 8.8 Lisbon earthquake on November 1st, 1755 (e.g., Solares and Arroyo 2004).

The geological map of Lisbon County (scale 1:10 000, Moitinho de Almeida 1986) shows a geological setting with a complex lithostratigraphic structure (Fig. 1). Significant contrasts characterise this structure due to long tectonic and depositional processes that have occurred since the beginning of the Upper Cretaceous at approximately 100.5 Ma.

In the southwest area, Cretaceous formations outcrop. These formations are composed of Bica Formation (C3) and Caneças Formation (C2) limestones and marls, as well as neo-Cretaceous basalt rocks from the Lisbon Volcanic Complex (LVC). The Cretaceous formations extend down to 330 m depth. The LVC covers the Monsanto anticlinal as a result of Late Cretaceous volcanic eruptions (~ 72 Ma), reaching 300 m depth in the northern and western areas. The Lisbon Volcanic Complex and the Cretaceous Carbonate Complex identify the rock substratum.

In the northern and eastern areas, the Cenozoic formations emerge, mainly from the Paleogene (in particular the Eocene–Oligocene, 56–23.03 Ma) and Miocene (23.03–5.333 Ma) periods, associated with the genesis and evolution of the Tagus River basin. The Paleogene Benfica Formation (BF), characterised by a heterogeneous composition, includes overconsolidated conglomerates, sandstones, siltstones, claystone, limestone, and marls,

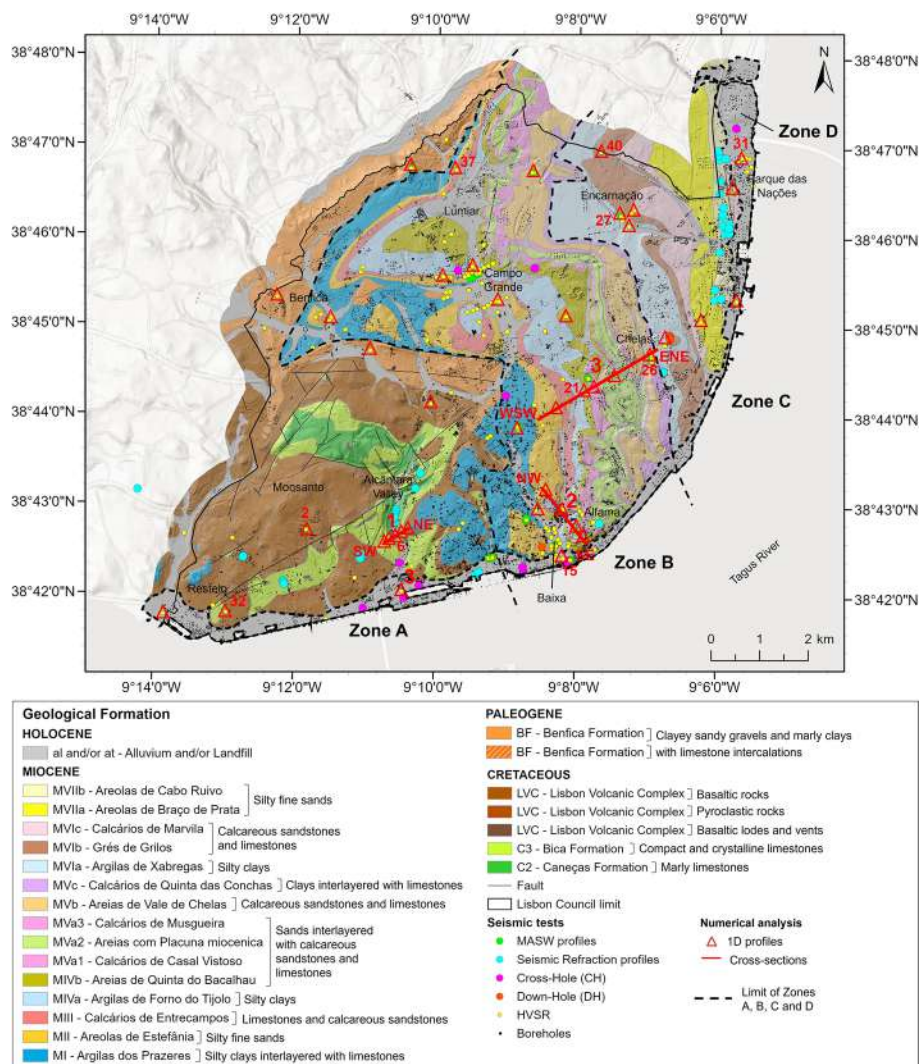


Fig. 1 Geological map of Lisbon County (adapted from Moitinho de Almeida 1986) and spatial distribution of geophysical and geotechnical data available in Lisbon: surface wave seismic profiles, single-station ambient vibration measurements and geotechnical boreholes. The spatial distribution of 1D profiles and cross-sections was also displayed. The lithological description was adopted from Teves-Costa et al. (2001) and the limits of Zones A, B, C and D from Oliveira et al. (2023) and this study

and corresponds to the transition between the Miocene formations and the Lisbon Volcanic Complex (Almeida 1991).

During the Miocene, an open connection with the sea allowed the deposition of a complete estuarine sequence with alternate marine and continental facies. The thickness of the entire series can reach approximately 300 m. As the Miocene units form a monocline dipping east (7° – 10°), the sequence becomes thicker eastwards. As defined by Cotter (1956), the Miocene series is typically divided into different lithostratigraphic units

with varying thicknesses and compositions such as sands, sandstones, clays, siltstones and limestones (see Fig. 1). The Miocene series and the Benfca Formation represent an overconsolidated substratum. Almeida (1991) performed several laboratory tests and showed that Miocene soils have a significant degree of overconsolidation, with sandy soils being highly compacted and hard clays being fissured. The Benfca Formation is composed of highly overconsolidated, predominantly coarse soils with a clay-silty matrix. Surface soils weather due to the erosion of overburden layers, resulting in overconsolidation and loss of the original properties of these geological formations.

The Cretaceous formations are affected by faults and folds, with evidence of extensive diaclasses (e.g., in Alcântara Valley and Monsanto, Fig. 1). The fault groups present in the LVC basalt materials are sub-vertical faults with approximate orientations of NE–SW and NNE–SSW, interrupted by another group with an approximate direction of NNW–SSE. In the contact between the Benfca Formation and the Miocene series, faults in the E–W direction can be observed north of the Monsanto anticline (Moitinho de Almeida 1986). Faults are less common in the Miocene series than in older geological formations. The existing ones have small dimensions and roughly N–S directions. A sequence of faults with variable directions (NE–SW and E–W) in the Alfama region (downtown area) cause the lifting of the Miocene series' base. These faults are responsible for the site's morphology as well as the thermal springs (Almeida 1991). The Tagus River fault discovered along the riverbank area has a NE–SW pattern extending to the north and crosses the whole Miocene with an inverse component (Almeida and Almeida 1997).

The city was divided in the three zones (A, B and C) proposed by Oliveira et al. (2023) based on HVSR peak frequencies (see Fig. 1), which correspond to the transition from the oldest to most recent outcropping geological formations in the SW–NE direction. Zone D was introduced in complement to Oliveira et al. (2023), considering the computed amplification factors corresponding to the riverside area of the city. These results will be shown in Sect. 4.1.

The topography of Lisbon shows a rather rough relief as a result of the structural control imposed by regional tectonics which, combined with the strength contrast of the different formations, intense fracturing, differential erosion, and the installation of the hydrographic system, conditioned the morphology of the city and their occupation over time. The elevation values vary between 0 and 215 m a.s.l., according to the Digital Terrain Model (DTM) (Fig. 2). Figure 2 shows that the lowest altitude classes are found along the riverfront and in the notch zones of the hydrological network. The highest elevations are found in Monsanto (215 m a.s.l.) and the city's northern Sect. (100–150 m a.s.l.).

Lisbon has seven small irregular hills separated by long narrow valleys. These valleys, which are the remnants of old streams (Fig. 2) are now filled with thin alluvial deposits (al) composed of sands, sandy gravels and sandy clays. The Holocene fluvial deposits, identified in the riverside area of the city, are characterised by a sequence of very heterogeneous alluviums (al) and a significant lateral and vertical facies variation, reaching a maximum depth of 30 m (Almeida 1991; Teves-Costa et al. 2001). The landfills (at) are the most heterogeneous layer covering most of the city with a variable thickness. They are present in reclaimed lands, in the Tagus margin, and filling natural or artificial depressions (Almeida 1991; Oliveira et al. 2020). The geological map also presents these surface formations (al and at in grey colour, Fig. 1), characterised by low resistance (Almeida 1991), although they are not distinguished at the map scale.

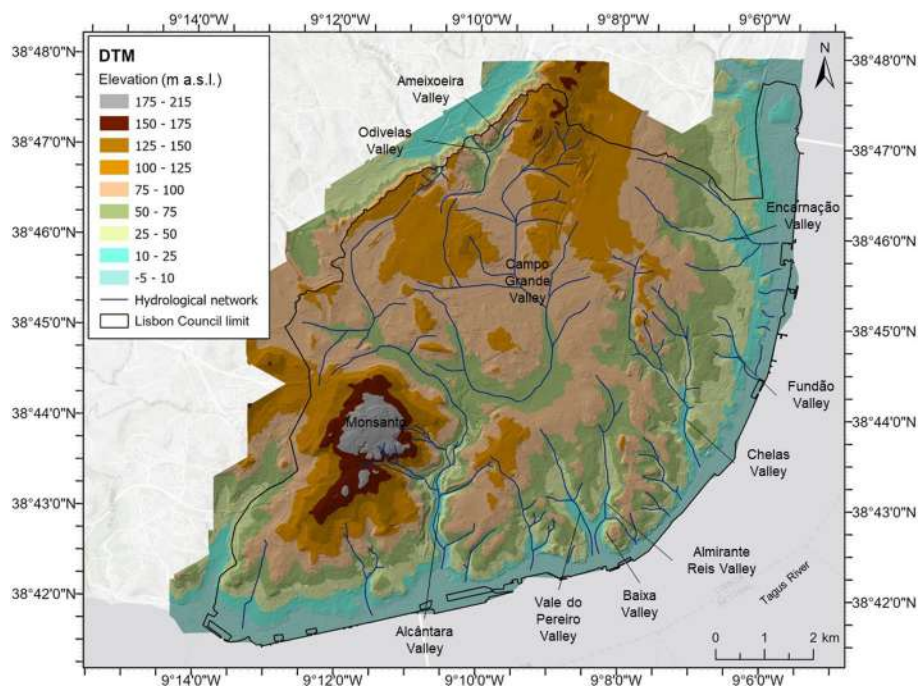


Fig. 2 Digital Terrain Model (DTM) of Lisbon. The main zones with the highest elevation variation, as well as the hydrological network of the city, are identified

2.2 Geophysical and geotechnical data

This work considers all of the geophysical data compiled by Oliveira et al. (2023), in terms of compression-wave (V_p) and shear-wave (V_s) velocities, from geophysical surveys carried out in Lisbon as well as in the city's neighbouring region to supplement the database with profiles performed on less characterised geological units. The geophysical database also includes a frequency dataset computed from ambient vibration measurements carried out at several sites in the city.

The geophysical database (see the location of the surveys in Fig. 1) includes 60 seismic refraction profiles, 13 Multichannel Analysis of Surface Waves (MASW) profiles, 14 cross-hole (CH) tests, 2 down-hole (DH) tests and 179 ambient vibration measurements (HVSR).

Based on this dataset, Oliveira et al. (2023) computed a city-scale regression relating the V_s variation with depth for each geological formation, resulting in support for the sub-soil model in the numerical modelling of the present study.

Figure 1 also includes 12,696 boreholes, most of them with SPT test results, obtained from 2296 geotechnical reports that belong to the geotechnical database of the Lisbon Municipality (GDB) (Almeida et al. 2010). These boreholes have been carried out since 1935 by different companies, providing non-homogeneous information (e.g., used equipment, criteria to end the SPT, change of the surface level due to the anthropic activity, lithological interpretation). Therefore, a critical analysis of the borehole logs was performed for the present study, in combination with the geological cross-sections from Moitinho de Almeida (1986), to reconstruct the geotechnical model for the numerical analysis.

The spatial distribution of the subsoil data, shown in Fig. 1, is not uniform, and consequently some areas, such as the northern and western regions of Lisbon, have a large number of boreholes while others have none. Moreover, the deepest boreholes (> 30 m) are located in the riverside area and in certain sections of the Lisbon Metropolitan Area (Oliveira et al. 2023). 56% of the boreholes have a depth between 10 and 20 m, while approximately 22% have a depth of less than 10 m and 14% have a depth between 20 and 30 m. Only about 8% of the boreholes exceed 30 m, with the deepest borehole reaching 261 m (hydrogeological log). Overall, around 90% of the boreholes identified the surface formations, namely alluvium (al) and/or landfill (at).

2.3 Selected input motions

Eurocode 8 (CEN 2004) defines two seismic actions: type 1 for high seismicity regions of southern Europe (AS1), and type 2 for low to moderate seismicity areas of central and southern Europe (AS2). The reference spectra for type 1 are enriched in long period and refers to earthquakes with moment magnitudes $M_w > 5.5$. Conversely, the reference spectra for type 2 exhibit both a larger amplification at short period and a much smaller long period content, being suitable for earthquakes with moment magnitudes $M_w \leq 5.5$. Ground motion amplification, which accounts for local soil and site effects, is expressed through a constant soil factor S , which increases uniformly the normalized elastic response spectra in all periods.

The Portuguese National Annex of Eurocode 8 (EC8-N.A.; IPQ 2010) defines two seismic scenarios, one for interplate earthquakes (Azores-Gibraltar, Atlantic region) and a second one for intraplate seismic events.

Considering the Portugal seismic zonation, the reference peak ground acceleration (a_{gR}) for Lisbon is 1.5 m/s^2 for seismic action type 1 and 1.7 m/s^2 for type 2 (IPQ 2010). The a_{gR} values indicated for Lisbon were used to estimate the reference response spectra considered in this study, which are built with similar equations for the spectral shapes of EC8, but with different cut-off periods.

Given the low-seismicity criterion in Eurocode 8 ($a_{gR} < 1 \text{ m/s}^2$), the two types of seismic action in Lisbon are classified as moderate to high seismicity, corresponding to seismic action type 1 in Eurocode 8 ($M_w > 5.5$; CEN 2004). However, in the EC8-N.A., seismic action is also classified into two types: type 1, which corresponds to interplate seismic events (far field earthquakes), and type 2, which corresponds to intraplate seismic events (near field earthquakes).

The two types of seismic action correspond to the reference return period equal to 475 years, and they are based on a selection of two sets of seven accelerograms from the European Strong-Motion Database (Luzi et al. 2020) that are compatible with the reference spectral shapes. The selected accelerograms (Table 2 in the Supplementary Information) were recorded at rock or rock-like formations (ground type A) and soft rock or stiff soil formations (ground type B), consistent with the seismic bedrock of Lisbon. In detail:

- i. Seismic action—type 1 (AS1): moment magnitude above 7, epicentral distance above 100 km and horizontal peak ground acceleration above $\sim 0.8 \text{ m/s}^2$, to eliminate weak motion records, which may not be considered as representative for high seismic regions. AS1-A and AS1-B refer to AS1 for ground types A and B, respectively;

- ii. Seismic action—type 2 (AS2): moment magnitude ranging from 6 to 7 and epicentral distance between 15 and 35 km. AS2-A and AS2-B refer to AS2 for ground types A and B, respectively.

The following scale factors (SF) were applied to the accelerograms to adjust the median of the selected response spectra with the EC8 response spectrum: $SF_{AS1-A} = 1.88$, $SF_{AS1-B} = 1.96$, $SF_{AS2-A} = 1.70$ and $SF_{AS2-B} = 1.50$. The same SF was applied to all accelerograms from the same set. The 5% damped response spectra of the input motions are presented in Fig. 3, together with its median response spectra and the EC8-N.A. reference spectral shape for ground types A and B. Overall, a satisfactory match can be found between the median response spectra and corresponding EC8-N.A. spectra.

3 Numerical analyses

3.1 Numerical simulations

Numerical simulations were performed to assess seismic site effects across the city.

The linear equivalent method was used for both numerical analyses adopting STRATA code (Kottke and Rathje 2008) for 1D analysis, and 2D analysis were carried out using 2D FEM code LSR-2D (STACEC 2017). The equations of motion in the LSR-2D calculation code are built using the finite element method under the assumption of viscoelastic material in total stresses.

The compliant (elastic) base boundary condition was applied in both the 1D and 2D analyses. A shear stress was therefore applied at the base derived from the outcrop motion according to the approach first suggested by Tsai (1969) and utilised by Joyner and Chen (1975). In 2D analysis, the free-field condition was applied to the lateral boundaries, leading them to operate as a system capable of absorbing reflected waves that would otherwise be artificially reintroduced into the model. In the LSR-2D code, this is accomplished by connecting viscous dampers between the lateral boundary nodes of the model and the nodes of appropriate one-dimensional soil columns (free-field columns) capable of describing motion under free-field conditions. The mesh was defined by triangular elements with sizes corresponding with the shear wave velocity of each geologic unit to ensure accurate wave propagation up to a maximum frequency of 15–20 Hz (Kuhlemeyer and Lysmer

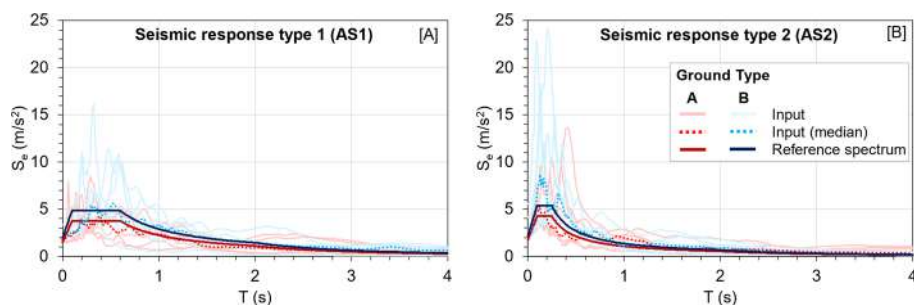


Fig. 3 Response spectra of the four sets of 7 accelerograms selected as input motion for each seismic action and ground type (see Table 2 in the Supplementary Information for the list of records): [A] seismic response type 1 (AS1) and [B] seismic response type 2 (AS2)

1973). Viscous damping was added through a full Rayleigh damping formulation with two control frequencies automatically selected by the program code to minimize significant overdamping in all frequency ranges of interest (Verrucci et al. 2022).

3.2 Subsoil models

The seismic response analyses were performed on the locations represented in Fig. 1.

The 1D subsoil models were prepared with the information available at geotechnical (Almeida, 2010) and geophysical (Oliveira et al. 2023) databases, corresponding to 41 models. Figure 4 shows the 1D subsoil models typifying the geological scenarios identified in the city.

Three 2D geotechnical profiles (Fig. 5) were built using the geological cross-sections provided by Moitinho de Almeida (1986). As illustrated in Fig. 1, cross-section 1 has a SW-NE direction, cross-section 2 is oriented NW-SE and cross-section 3 is aligned WSW-ENE. The geological map of Lisbon and the synthetic lithostratigraphic column (Moitinho de Almeida 1986) were used to estimate the thickness of the various subsoil formations identified in the city when no other information was available.

The transfer function determined through numerical simulations in the linear elastic range was compared with the HVSR curve based on ambient vibration measurements. If the peak frequency of HVSR curve (experimental resonance frequency) matches the peak of the elastic transfer functions (numerical resonance frequency), the physical representativeness of the numerical model is considered satisfactory.

The 1D profiles were then validated by comparing the 1D peak frequencies obtained in the linear elastic domain ($f_{NS,1D}$) to the peak frequencies obtained from the nearest HVSR measurements (f_{HVSR}) (Fig. 6). The validation of the 2D profiles was carried out using the results derived from the 1D profiles that belong to the cross-sections.

Overall, a good fit between f_{HVSR} and $f_{NS,1D}$ can be observed, as 83% of the points fall inside the range ± 0.50 Hz.

Considering the available boreholes and geological cross-sections, the 1D profiles typically were limited to 90 m depth, while the 2D profiles reached maximum depths of approximately 150–200 m, depending on the arrangement of the geological layers.

The seismic bedrock depth on the 2D profiles was calibrated comparing the HVSR fundamental frequency with the resonance frequency computed through 1D seismic response analyses performed at the same point.

In cross-sections 1 and 2 (Fig. 5-A and B), the seismic bedrock depth adopted in the numerical models provided a good match with the HVSR curves.

For cross-section 3 (Fig. 5-C) only for two points at surface it was possible to find a satisfying agreement between the experimental and numerical values. This may be due to higher inclinations of the layering and the uncertainty on the deeper layers' properties and thickness. Peaks at frequencies smaller than 1 Hz were determined in the numerical simulation, but they are outside the seismometer's sensitivity (3D Lennartz Lite seismometer with a 1-s period).

A sensitivity analysis considering a range of seismic bedrock depths (100, 125 and 150 m) showed that the depth of the seismic bedrock position has a residual effect on the surface seismic response, with only minor variations (1–3%) in the period interval during which the acceleration peak occurs. A horizontal layer was adopted in the transition between the overlying units and the seismic bedrock, at the maximum depth of the

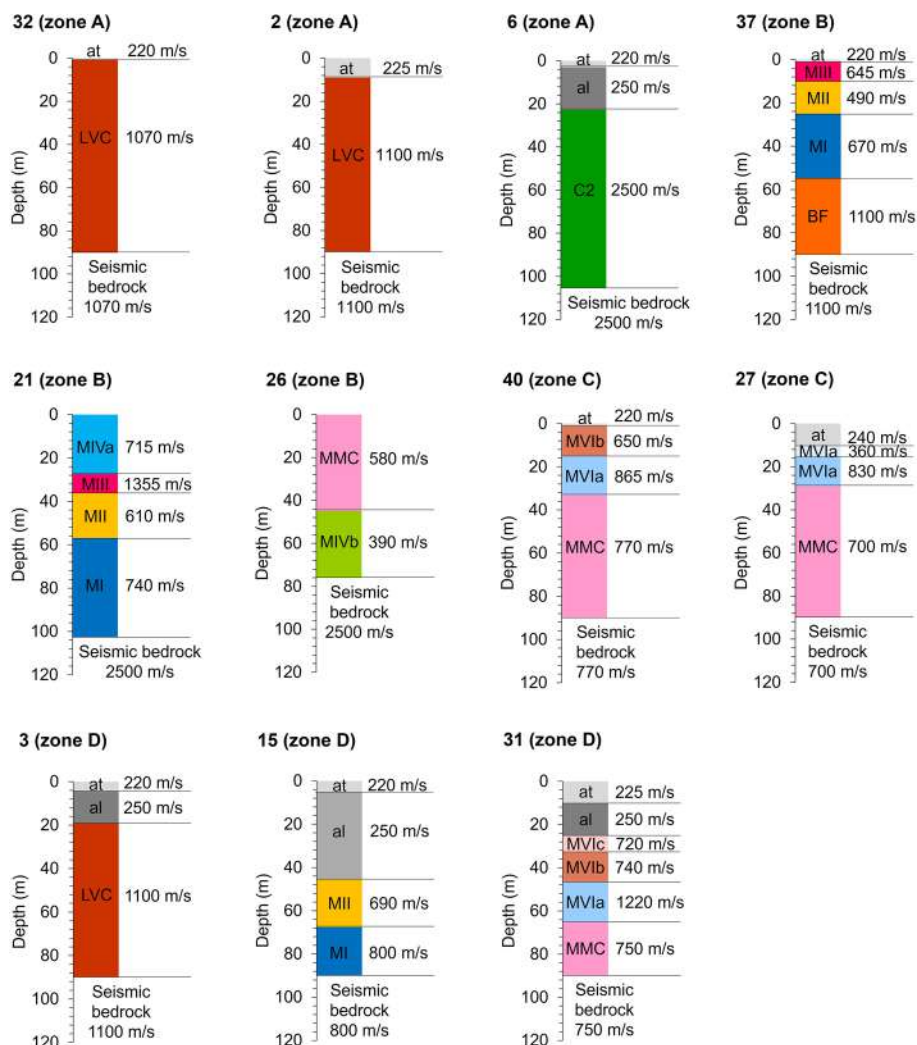


Fig. 4 Typical 1D subsoil models identified in the city grouped by zone (A, B, C and D). The location of each profile is identified in Fig. 1. The geological formations are coloured according to Fig. 1 and their abbreviations are in the legend of Fig. 1. The S-wave velocity of each geological unit is also identified

reference geological cross-section available at the Lisbon's geological map (Moitinho de Almeida 1986).

The seismic bedrock can be associated to the volcanic rocks from the Lisbon Volcanic Complex and Cretaceous limestones from the C3 and C2 formations. Geophysical tests in the SW area of the city (see Fig. 1) found maximum V_S values ranging from 1500 to 2500 m/s until depths of around 35 m. According to the V_S -depth equations derived by Oliveira et al. (2023), shear-wave velocity increases with depth, considering the increase in effective stress.

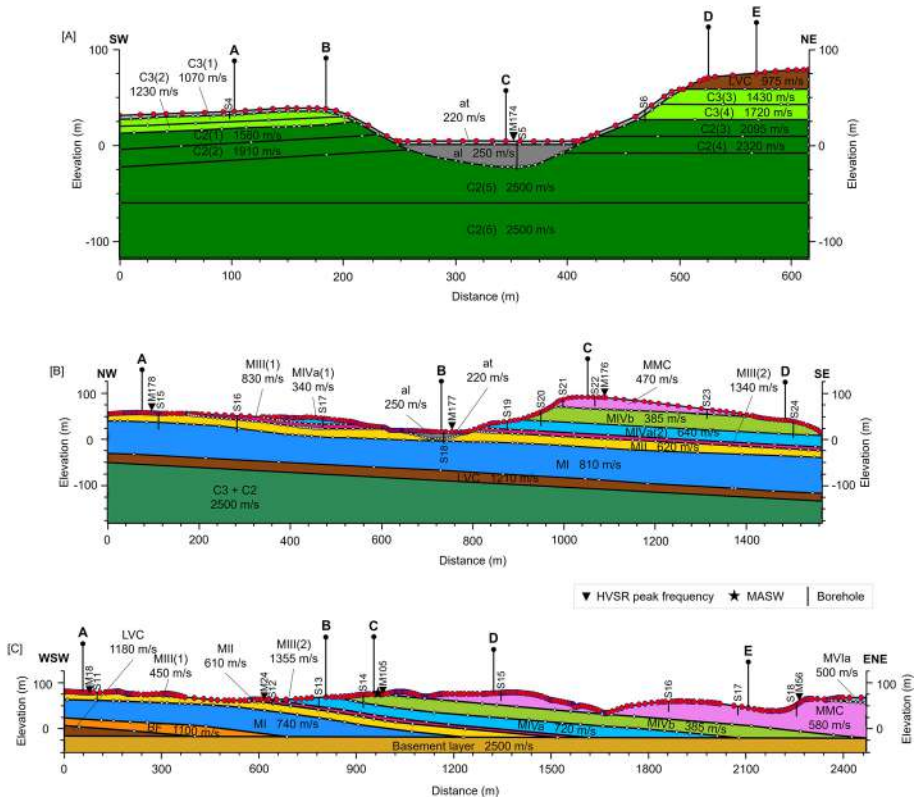
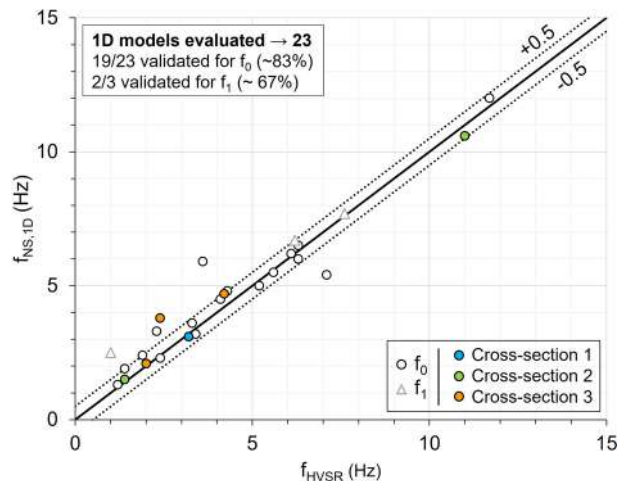


Fig. 5 2D geotechnical profiles: **A** cross-section 1, **B** cross-section 2 and **C** cross-section 3. The location of each cross-section is identified in Fig. 1. The geological formations are coloured according to the legend in Fig. 1 and their abbreviations are in the text. The S-wave velocity of each geological unit is also identified. The final layer C2(6) in cross-section 1 was designed to meet numerical requirements

Fig. 6 1D models validation based on the comparison of the frequency peak obtained from the 1D linear elastic analysis ($f_{NS,1D}$) and the HVSR measurement (f_{HVSr}). f_0 indicates the fundamental or first peak frequency and f_1 the second peak frequency. The colours indicate the 1D profiles included in the corresponding cross-section



In the case of the 1D and 2D models analysed, the seismic bedrock will be at depths larger than 80–90 m, with V_S values estimated based on the V_S -depth equations equal to or greater than 2500 m/s, particularly for the C3 and C2 formations.

To assess the impact of V_S variation of the bottom layer on seismic ground response, a sensitivity analysis was performed considering a range of different V_S values (2000, 2500, 2800 and 3000 m/s) and the 1D profiles which represent the subsoil structure of each 2D profile. Only one seismic input motion was considered for this evaluation.

For the cross-section 1, it was observed that a small variation (1–3%) of the spectral acceleration occurs around the peak value, thus the bottom layer V_S -value tested play a minor role on the seismic response. Based on the results, for the seismic bedrock composed of Cretaceous layers (C3 and C2) a V_S equal to 2500 m/s was adopted.

For cross-section 2 and 3, the peak spectral acceleration varies from 2 to 20%, while in the remaining range of periods the variation is negligible. Due to the uncertainty in the properties and depth of the seismic bedrock layers, a V_S of 2500 m/s was adopted for both cross-sections.

The maximum depth of the 1D profiles is 90 m, not reaching the seismic bedrock with $V_S = 2500$ m/s. In these profiles, the S-wave velocity of the seismic bedrock layer equals the V_S value of the last known layer, considering the sensitivity study results and the lack of data at greater depths.

Almeida (1991) provides a geotechnical characterization of geological formations at the city scale based on in-situ and laboratory tests, giving a range of values for the unit weight (γ), plasticity index (PI) and overconsolidation ratio (OCR). However, this characterization is sometimes based on a small dataset that may not be indicative of the entire geologic unit.

Overall, the unit weight varies from 15 to 21 kN/m³. However, there are no values for this parameter for a significant part of the geological formations (52%). The plasticity index was measured for a large number of geological units (71%). The heterogeneous composition of geological units is reflected in the measured PI values, characterized by values mostly ranging from 7 to 20% with a maximum value of PI=30%. The OCR indicates average values based on laboratory tests performed on very disturbed samples. A limited number of values for these parameters are also included in a few geotechnical reports.

A parametric analysis was performed to assess the impact of the abovementioned geotechnical parameter variations on the stiffness modulus (G) reduction and material damping (D) curves. More details can be found in the Supplementary Information.

The unit weight values were attributed to each geologic unit considering the γ value ranges established by Almeida (1991) and few other geotechnical report results, in accordance with the increase in overburden stress. For the alluvium deposits, an average value was considered regardless of their variable composition.

The plasticity index values were established considering the PI value ranges from Almeida (1991) and other geotechnical reports, as well as the lithological composition of each geologic unit. A non-plastic (NP) behaviour was assigned to the geological units with a predominantly sandy composition, while a PI=20% was considered in the Benfica Formation because of the significant clayey component.

Given the lithological properties of Lisbon, the overconsolidation ratio of each geologic unit was adjusted based on the few laboratory test results.

The soil properties along 1D and 2D profiles were defined according to the available geotechnical data and previous parametric analysis results and they are summarised in Table 1 for each geotechnical unit.

The V_S was estimated through the site-specific V_S -depth equations developed for the Lisbon area (Oliveira et al. 2023), considering the average depth of each soil layer. Due to

Table 1 Selected parameters for subsoil models used for 1D and 2D site response analyses

Geological formation	V_s (m/s) (V_s -depth equation by Oliveira et al. 2023)	γ (kN/m ³)	PI (%)	OCR (-)	ν (-)	Nonlinear decay and damping curves
at	$1.45 \cdot z + 216.26$	17	NP	-	0.40	Rollins et al. (1998) (average)
al	$4.64 \cdot z + 228.86$	16	20	1.5	0.49	Darendeli (2001)
MVIIb	$37.64 \cdot z + 434.38$	18	NP	(1)	0.35	Darendeli (2001)
MVIIa		18	NP	(1)	0.35	Darendeli (2001)
MVIlc	$3.95 \cdot z + 615.39$	18	NP	(1)	0.35	Darendeli (2001)
MVIlb		18	NP	(1)	0.35	Darendeli (2001)
MVIl a	$19.08 \cdot z + 402.32$	18	20	4	0.35	Darendeli (2001)
MMC complex (MVc, MVb, MVa3, MVa2 and MVa1)	$5.57 \cdot z + 426.40$	18	NP	-	0.35	Rollins et al. (1998) (G/G_{0upper} and D_{0lower})
MIVb	$0.25 \cdot z + 376.71$	18	NP	(1)	0.35	Darendeli (2001)
MIVa	$5.93 \cdot z + 342.46$	18	20	6	0.35	Darendeli (2001)
MIII	$63.66 \cdot z + 292.36$	19	NP	-	0.35	Linear $D=2\%$
MII	$6.06 \cdot z + 383.86$	19	NP	(1)	0.35	Darendeli (2001)
MI	$3.98 \cdot z + 509.75$	19	20	6	0.35	Darendeli (2001)
BF	(average value of 1100 m/s)	20	20	8	0.35	Darendeli (2001)
LVC	$2.48 \cdot z + 957.23$	22	NP	-	0.30	Schnabel et al. (1972)
C3	$29.15 \cdot z + 881.01$	22	NP	-	0.30	Linear $D=1\%$
C2	$49.62 \cdot z + 671.60$	22	NP	-	0.30	Linear $D=1\%$

The geological formations are abbreviated in accordance with the legend in Fig. 1. NP indicates non plastic soils (PI=0%)

the lack of sufficient data to estimate the rate of increase of V_s with depth for Benfica Formation, Oliveira et al. (2023) assigned a mean V_s value of 1100 m/s to this geological unit.

According to Oliveira et al. (2023), considering the inherent lithological heterogeneity of most geological formations, the following values of the Poisson's ratio (ν) were adopted: $\nu = 0.49$ for saturated soil, $\nu = 0.35$ for unsaturated soil and $\nu = 0.30$ for rocks.

The non-linear decay and damping curves computed for gravel soils by Rollins et al. (1998) were considered to describe the heterogeneous composition of the landfill deposits and MMC complex (MVc, MVb, MVa3, MVa2 and MVa1) behaviour. The Darendeli (2001) curves were assigned to the alluvial deposits, MVIIb, MVIIa, MVIIc, MVIIb, MVIIa, MIVb, MIVa, MII, MI, and BF formations. The LVC behaviour can be provided by the Schnabel et al. (1972) curves and a linear viscoelastic behaviour with a constant damping $D = 2\%$ was set for the MIII and a constant damping $D = 1\%$ for the C3 and C2 formations.

3.3 Amplification factor (AF), spectral shape ratio (SR) and soil factor (S) estimation

Period-dependent amplification factors (AFs) were computed from 1 and 2D analyses. The AFs are defined by the ratio between the 5% damped acceleration response spectra at the ground surface, $SA(T)_s$, and the corresponding parameter at the outcropping reference bed-rock, $SA(T)_b$, integrated over four period (T) ranges (0.1–0.5 s, 0.5–1.0 s, 1.0–2.0 s and 0.05–2.50 s) (Eq. 1):

$$AF(T) = \frac{SA(T)_s}{SA(T)_b} \quad (1)$$

To compare the S factor computed in the numerical simulations with the values provided in the Portuguese National Annex of Eurocode 8 (IPQ 2010), the amplification was computed in terms of response spectra ratio (Eq. 1).

To estimate the additional effect of the 2D response at different locations at the ground surface with respect to the corresponding 1D response, period-dependent aggravation factors (AGF) are computed as the ratio between the 5% damped acceleration median response spectra at the ground surface from 2D ($SA_{2D}(T)$) and 1D ($SA_{1D}(T)$) numerical analysis (Chávez-García and Faccioli 2000) (Eq. 2):

$$AGF(T) = \frac{SA_{2D}(T)}{SA_{1D}(T)} \quad (2)$$

The amplification factors in this study are denoted as follows: (i) AF_{1D} relates to 1D results; (ii) AF_{2D} refers to 2D results; and (iii) AGF shows the aggravation factor connected to 2D effects (valley, topographic and subsoil morphological effects). The median aggravation factor AGF was computed for the points A to E of cross-section 1, A to D of cross-section 2 and A to E of cross-section 3 (see Fig. 5).

The period-independent soil factor S, which scales the ordinate axis of the Eurocode 8 design response spectrum, are computed for each 1D model using Eq. (3) (Rey et al. 2002):

$$S = \left(\frac{I_{model}}{I_{rock}} \right) \cdot \left(\frac{1}{SR} \right) \quad (3)$$

where SR is the spectral shape ratio, reflecting only the difference between spectral shapes, calculated as the ratio of the normalized elastic median response spectra at the ground surface to the corresponding input motion median response spectra integrated over the period

range of 0.05–2.50 s, while I_{model} and I_{rock} are the spectrum intensities for model and rock respectively, originally defined by Housner (1952) for spectral velocities and here adapted for spectral accelerations (Eq. 4):

$$I = \int_{0.05}^{2.50} \overline{R \cdot S_a(T)} dT \quad (4)$$

where $\overline{R \cdot S_a(T)}$ denotes the log-average of distance-normalized 5% spectral ordinates $R \cdot S_a(T)$ for each model or rock site. The I_{model}/I_{rock} ratio provides a scaling factor for site effect that represents an average amplification globally affecting the whole spectrum (Rey et al. 2002). This ratio corresponds to the AF_{ID} parameter previously described corresponding to the ratio of the output to the input median response spectra integrated over the 0.05–2.50 s range.

4 Numerical simulation results and discussion

4.1 1D site response analysis

The results of a set of typical 1D profiles are shown to elucidate the soil amplification factors distribution.

The outcropping formations in Zone A are the oldest (C2, C3, LVC and BF formations), in general very stiff ($V_s > 1000$ m/s), with a thin cover of alluvium and landfill deposits (cover thickness, $H_c < 5$ m). The Alcântara Valley is the exception, where cover deposits reach ~25 m depth.

Figure 7 shows the site response in terms of median response spectra for input and output motions, as well as median spectral ratio, for seismic action types 1 (AS1) and 2 (AS2) at three selected 1D profiles in Zone A.

The spectral ratio is flat and close to 1 when $H_c < 5$ m (Fig. 7A), while for thicker cover thicknesses the median AF_{ID} are higher than 1, varying between 1.9 (AS2 input) and 2.0 (AS1 input) in the 0.1–0.5 s period range (Fig. 7B).

The Alcântara Valley with cover deposits ~25 m thick lead to a higher median AF_{ID} in the 0.5–1.0 s period range (2.3 for AS1 input and 2.4 for AS2 input) (Fig. 7C).

Zone B has higher geological variety, ranging from Lower to Middle Miocene units outcropping, less stiff than in Zone A ($V_s \leq 750$ m/s).

Campo Grande ($H_c \leq 15$ m) and Baixa valleys (maximum $H_c \sim 45$ m) are the most relevant (see Fig. 1), both filled with cover deposits (landfills and alluvium). In the remaining area, thinner randomly distributed landfill deposits are identified.

The presence of interbedded sedimentary rock layers in soil deposits, such as the MIII formation, leads to a shear wave velocity inversion. Although this geological formation has a very high stiffness, it is highly weathered and fractured at shallow depths. As a result, the V_s values sharply increase with depth, leading to higher impedance contrasts. When compared to other Miocene formations, the sandy MIVb formation has a lower S-wave velocity, which leads to V_s inversion.

Figure 8 displays the site response in terms of median response spectra for input and output motions, as well as median spectral ratio, for AS1 and AS2 at three different 1D profiles in Zone B.

The inversion of V_s leads to amplification factors that increase with the magnitude of the impedance contrast. A V_s inversion at shallower ground levels with a slight impedance

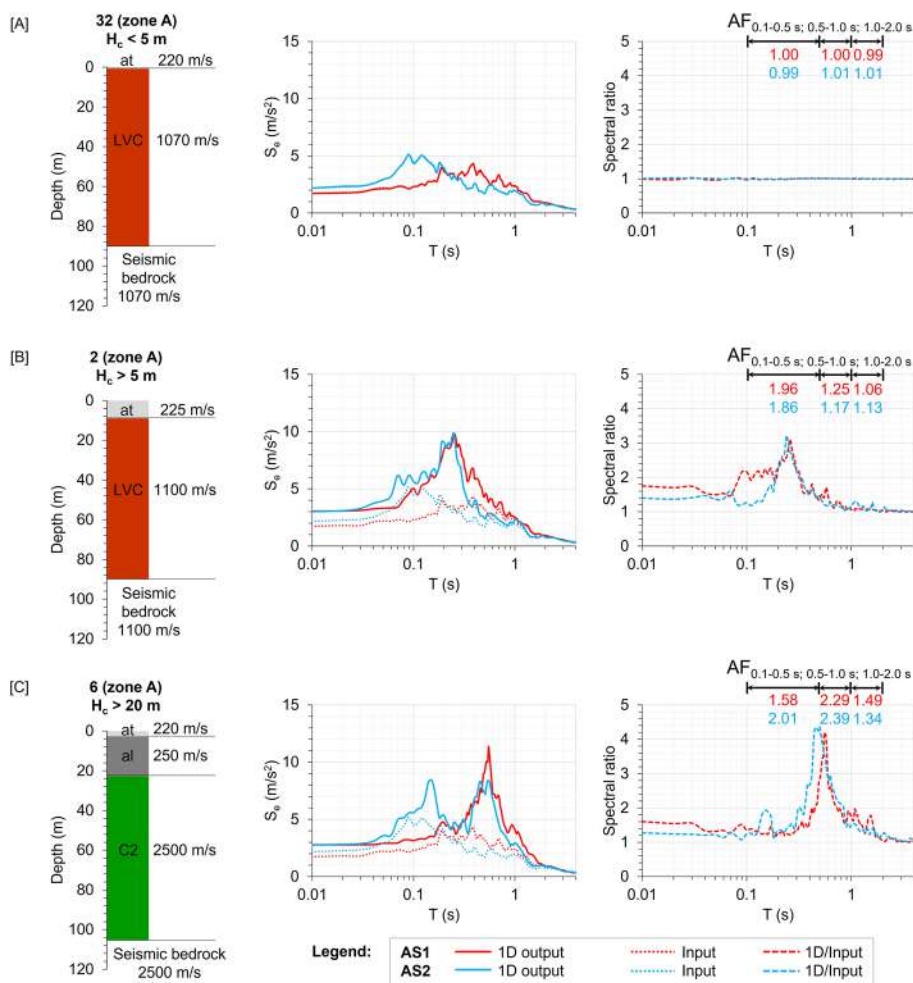


Fig. 7 1D site response analysis results for Zone A: soil profile with cover deposit thickness of **A** $H_c < 5$ m; **B** $H_c > 5$ m; **C** $H_c > 20$ m (Alcântara Valley). The soil profile (left), median response spectra ($\xi = 5\%$) for input and output motions (middle) and median spectral ratio (right) are displayed for each case. AS1 results are in red, while AS2 results are in blue. The amplification factors are shown for each period range and seismic action

contrast results in a median AF_{1D} between 1.5 (AS2 input) and 1.7 (AS1 input) in the 0.1–0.5 s period range (Fig. 8A). In the case of a deeper V_S inversion with a greater impedance contrast, the median amplification factor reaches roughly 2.5 for the period range of 0.5–1.0 s (Fig. 8B). For high impedance contrasts, a median AF_{1D} of 2.3 (AS1 input) to 2.4 (AS2 input) for 1.0–2.0 s period range is observed (Fig. 8C).

Overall, the geological diversity results in higher scatter of the amplification factors in this area.

Zone C is in city's northeast, where Late Miocene geological formations outcrop ($V_S > 600$ m/s). The cover deposits thickness is in general lower than 10 m but in some areas of the stream carved valleys the cover deposits can reach thicknesses until ~15 m. In the riverside area, thicker cover deposits ($H_c > 20$ m) are identified.

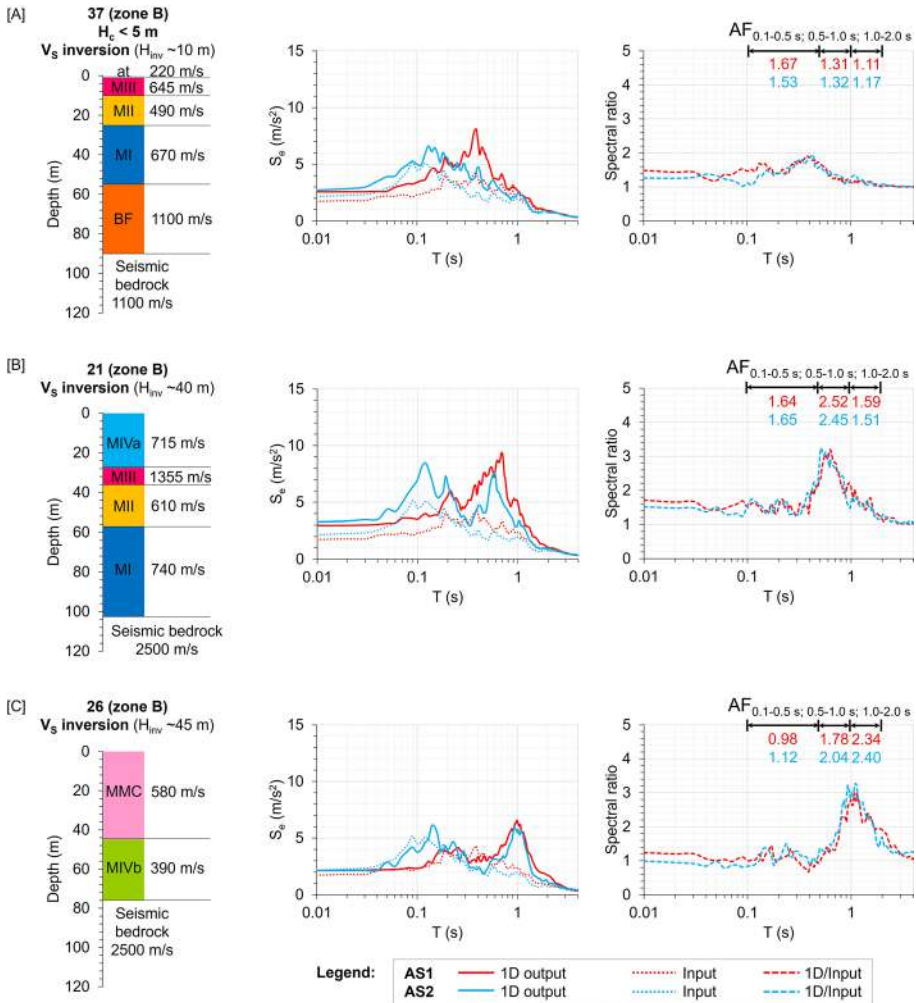


Fig. 8 1D site response analysis results for Zone B: soil profile with **A** $H_c < 5$ m of cover deposits and a V_s inversion at ~ 10 m depth (H_{inv}); **B** V_s inversion at $H_{inv} \sim 40$ m; **C** V_s inversion at $H_{inv} \sim 45$ m. The soil profile (left), median response spectra ($\xi = 5\%$) for input and output motions (middle) and median spectral ratio (right) are displayed for each case. AS1 results are in red, while AS2 results are in blue. The amplification factors are shown for each period range and seismic action

Figure 9 shows the site response in terms of median response spectra for input and output motions, as well as median spectral ratio, for AS1 and AS2 at two selected 1D profiles in Zone C.

The spectral ratio is flat and close to 1 when $H_c < \sim 5$ m for both AS1 and AS2 inputs and whole period range (Fig. 9A), as shown for Zone A (Fig. 7A). For thicker cover thicknesses the median AF_{1D} are higher than 1, reaching 1.6 for both AS1 and AS2 inputs in the 0.1–0.5 s period range (Fig. 9B).

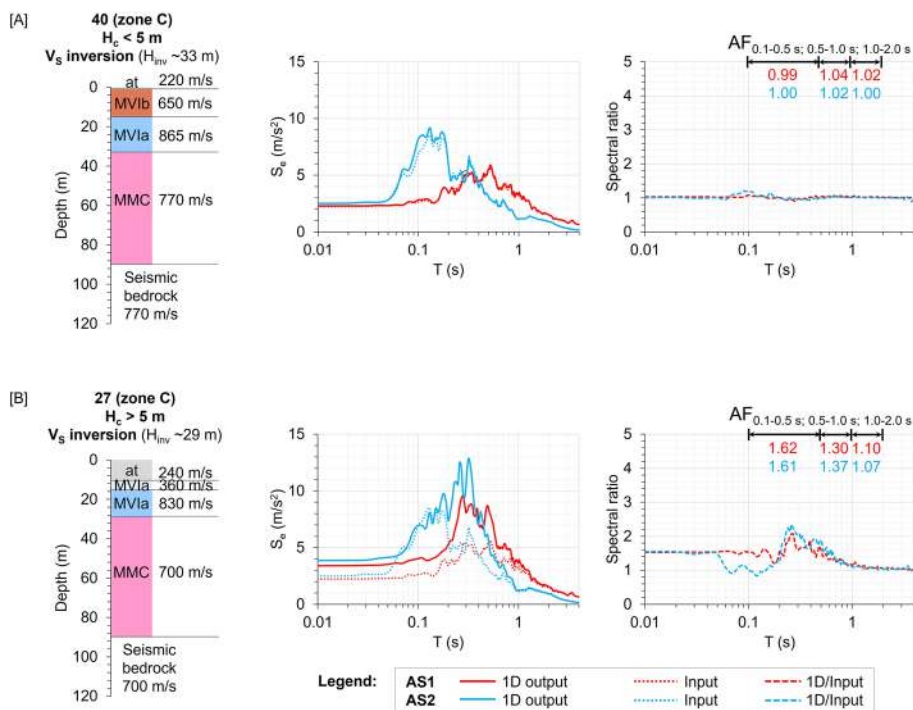


Fig. 9 1D site response analysis results for Zone C: soil profile with **A** $H_c < 5$ m of cover deposits and a V_s inversion at $H_{inv} \sim 33$ m; **B** $H_c > 5$ m of cover deposits and a V_s inversion at $H_{inv} \sim 29$ m. The soil profile (left), median response spectra ($\xi=5\%$) for input and output motions (middle) and median spectral ratio (right) are displayed for each case. AS1 results are in red, while AS2 results are in blue. The amplification factors are shown for each period range and seismic action

Zone D corresponds to the riverside area of the city and is characterized by the presence of significant but varying thickness cover deposits ranging from a few metres to tens of metres, as well as a variable substratum across the city (see Fig. 1).

Figure 10 shows the site response in terms of median response spectra for input and output motions, as well as median spectral ratio, for AS1 and AS2 at three selected 1D profiles in Zone D.

The riverside area with cover deposits ~ 20 m thick lead to a higher median AF_{1D} in the 0.1–0.5 s period range (2.3 for AS1 input and 2.14 for AS2 input) (Fig. 10A). The median AF_{1D} in Baixa Valley is between 2.2 and 2.3 in the 1.0–2.0 s period range (Fig. 10B). The riverside area with cover deposits ~ 25 m thick lead to a higher median AF_{1D} in the 0.5–1.0 s period range with a value of 2.1 for both AS1 and AS2 inputs (Fig. 10C).

The geological formations MIII, MIVb and MVla are likely to cause an inversion of V_s in the soil profile and the impact varies depending on the lithological composition of the soil profile.

A sensitivity analysis was performed to assess the effect of shear-wave velocity inversion on seismic soil response, with the assumption that V_s increases gradually with depth.

If the V_s inversion is disregarded, and the V_s value for the MIII layer is assumed to be the same as the MII layer in profile 37, and the V_s values for the MIII and MII layers

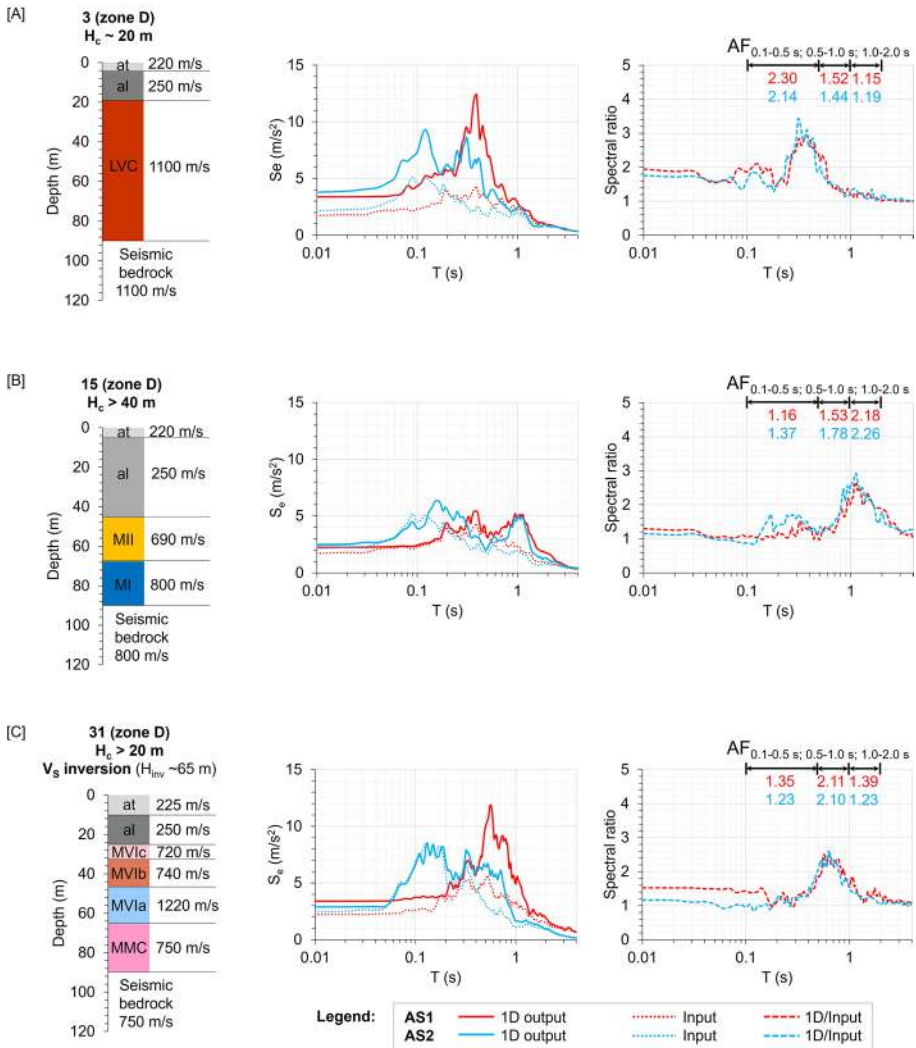


Fig. 10 1D site response analysis results for Zone D: soi profile with **A** $H_c \sim 20$ m of cover deposits; **B** $H_c > 40$ m of cover deposits (Baixa Valley); **C** $H_c > 20$ m of cover deposits and a V_s inversion at $H_{inv} \sim 65$ m. The soil profile (left), median response spectra ($\xi = 5\%$) for input and output motions (middle) and median spectral ratio (right) are displayed for each case. AS1 results are in red, while AS2 results are in blue. The amplification factors are shown for each period range and seismic action

are considered to be equal to the V_s of MIVa layer in profile 21 (see Fig. 8A and B), the median AF_{1D} increases by less than 7%.

If the V_s value for the MIVb layer is considered to be equal to the V_s of the overlying layer (MMC) in profile 26 (see Fig. 8C), the median AF_{1D} reduces by less than 5%.

Using the same V_s value for the MVIa layer as the underlying formation (MMC) in profiles 40, 27 and 31 (see Figs. 9 and 10C), median AF_{1D} varies between 2 and 10%, with a maximum deviation of around 20%.

4.2 2D site response analysis

4.2.1 Cross-section 1

The cross-section 1 intersects the oldest outcropping geological formations (Neo-Cretaceous Lisbon Volcanic Complex (LVC), Cretaceous Bica Formation (C3) and Canaças Formation (C2)). Figure 11 shows the several geological units and the location of in situ investigations (geotechnical boreholes and HVSR measurements).

On the left side of the cross-section 1, Bica Formation outcrops covered by a thin land-fill layer 3 m thick. On the centre, the profile crosses the Alcântara Valley with a slope of $\sim 25^\circ$, ~ 160 m wide and with a 23-m-thick cover deposits. On the right side, the Lisbon Volcanic Complex outcrops forming a hill.

Figure 11A and B summarise the results in terms of median AF_{2D} total amplification factors for seismic action type 1 and type 2, respectively. The median AF_{1D} computed from 1D seismic response analysis along the points A, B, C, D and E was also reported.

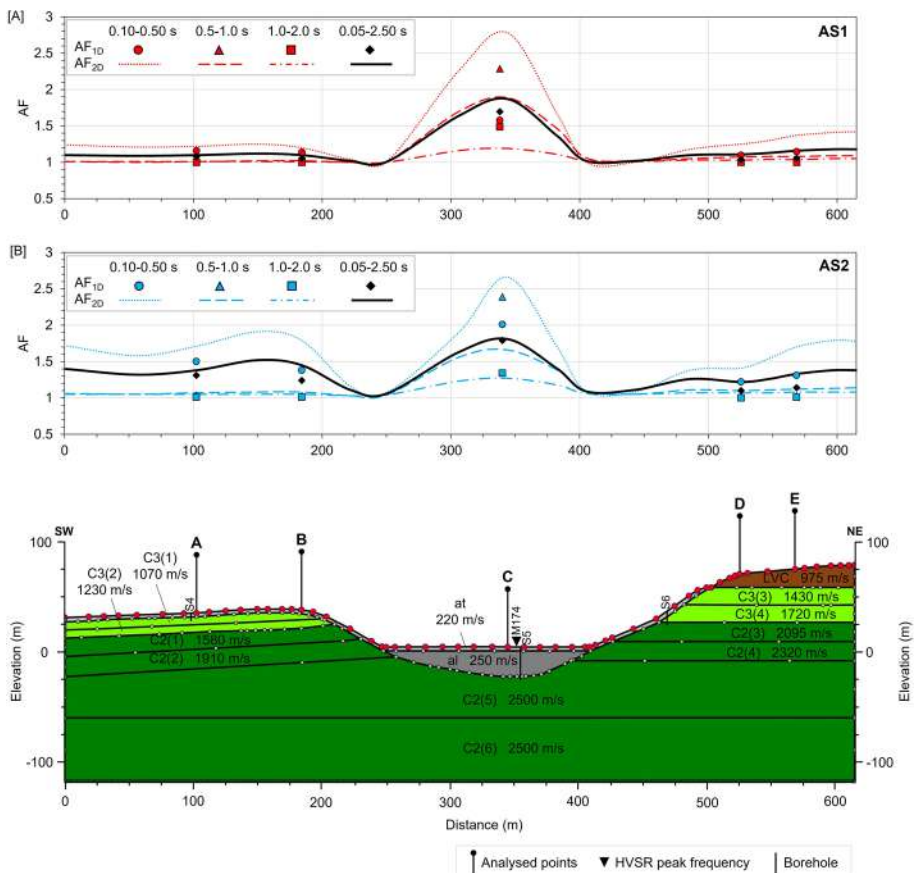


Fig. 11 Variability along the cross-section 1 of the median total amplification factors (AF_{2D}) in the period ranges of 0.10–0.50 s, 0.5–1.0 s, 1.0–2.0 s and 0.05–2.50 s, compared to the values computed from 1D seismic response analysis (AF_{1D}) along the points A, B, C, D and E for A AS1 and B AS2

The peak AF_{2D} occurs in the 0.1–0.5 s period range in the middle of the valley (point C) with median values between 2.8 (AS1) and 2.6 (AS2). The transition between the thin landfill layer lying on rock formations on SW side and the thicker alluvial deposit that fills the valley is identified in the amplification factor behaviour. The median AF_{2D} (1.2–1.3 for AS1 and 1.6–1.9 for AS2) on the SW side of the valley is related to the presence of the thin landfill layer, which has a high impedance contrast with the layer below (C3 formation). On the NE side of the valley, the presence of a basaltic formation with a lower V_s and the slight slope contribute to the median AF_{2D} verified (1.3–1.4 for AS1 and 1.4–1.8 for AS2). At the centre of the valley (point C), a median AF_{2D} of 1.8–1.9 is computed in the period range 0.05–2.50 s.

The median response spectra computed from 1 and 2D analyses are compared with the median input motion spectra at points A, B, C, D and E in Fig. 12A. The comparison confirms that amplification takes place essentially for periods lower than 0.5 s in the valley (point C), more significant for AS1. Spectral accelerations as high as 13–16 m/s² appear at point C in the 0.3–0.5 s period range for both AS1 and AS2, where the 2D spectral acceleration is heavily higher than 1D, evidencing remarkable two-dimensional effects due to the basin configuration; on the contrary, the spectral acceleration is lower than 6 m/s² for AS1 in the whole period range for the other points. At points A and B, the higher spectral acceleration values (~15–20 m/s²) for periods < 0.1 s considering AS2 are related to the thin landfill layer.

To explore the 2D physical phenomena governing the local response, the ratio between the 2D and 1D median response spectra are evaluated for the selected points in Fig. 12B. Figure 13 shows the variation of median aggravation factors (AGF) along cross-section 1 computed at the investigated points for the specified period ranges.

Clear evidence of two-dimensional effects at the valley (point C) is shown, with a maximum amplification at ~0.4 s for both AS1 and AS2 (peaks of the 2D/1D ratio) (Fig. 12B). In the 0.1–0.5 s period range, the median aggravation factors are ~1.8 and ~1.3 for AS1 and AS2, respectively (Fig. 13). At point C, the higher amplification occurs between 0.2 and 0.4 s, matching the H/V peak frequency (about 3.2 Hz), as was also shown by other literature studies (e.g., Pagliaroli et al. 2015, 2020).

The good agreement between the results of the 1D and 2D simulations obtained at points A, B, D, and E suggest small to negligible two-dimensional effects. At points D and E, slight two-dimensional effects (~1.2–1.3) are observed in 0.1–0.5 s period range for both AS1 and AS2, evidencing the topographic effects (Fig. 13). Points A and B generated 1D and 2D results much closer for both AS1 and AS2, leading to a residual amplification factor mainly due to stratigraphic effects, which are well-predicted by 1D seismic response analysis (Fig. 13). The higher amplification verified at point B for AS2 may be related to combination of the inherited characteristics of the accelerograms selected and the subsoil. Thicker cover deposits increased the seismic amplification for AS1 (see point C in Fig. 12).

In the 0.05–2.50 s period range, the median AGF at points C, D and E varies between 1.1 and 1.2 for AS1 and AS2 (Fig. 13).

Overall, the results reported here are consistent with those found by Riga et al. (2016), who conducted extensive parametric 2D numerical linear viscoelastic analyses on homogeneous, symmetric, or asymmetric large alluvial basins. In particular, Riga et al. (2016) found that for a shape ratio of 0.2 and gentle slope angles (similar to the geometry of Alcântara Valley), AGF in the range 1.2–2 are computed at a normalised distance $x/w = 0.50$ (where x is the distance from the edge and w is the length of the valley) corresponding to point C. These values correspond to the period range 0.3–1.5 $T_{0,c}$, where $T_{0,c}$ is the 1D fundamental period at the centre of the valley; in the Alcântara Valley, $T_{0,c}$ is around 0.35 s,

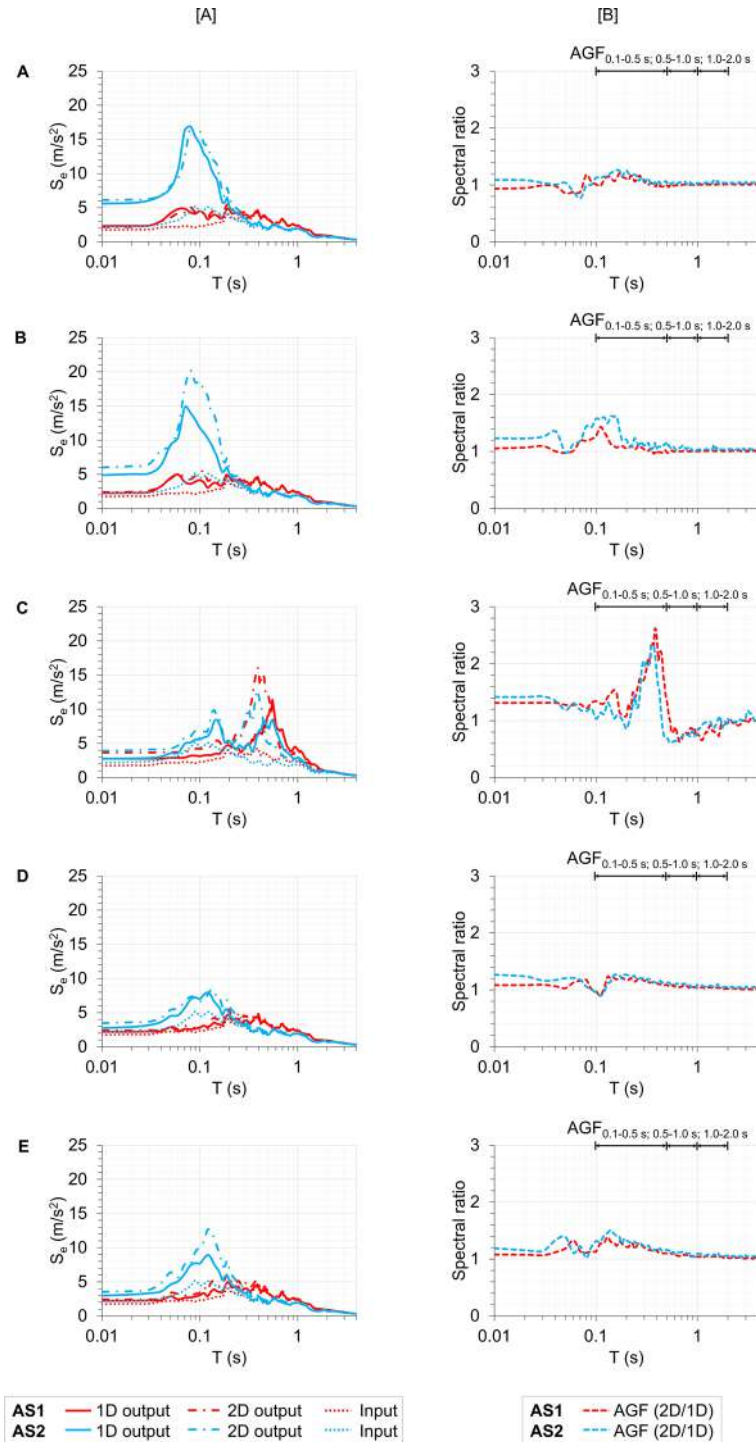
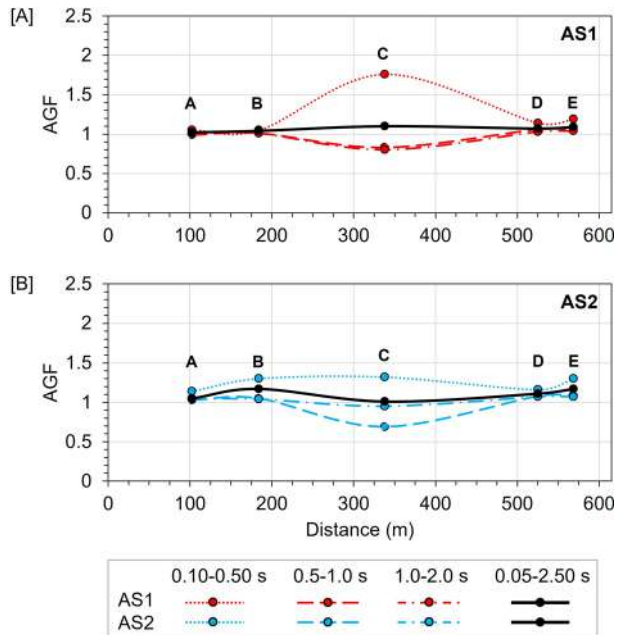


Fig. 12 Cross-section 1 **A** median response spectra ($\xi = 5\%$) for 1D output, 2D output and input motions, and **B** 2D/1D median response spectral ratio computed at five points (A, B, C, D and E) for AS1 (red) and AS2 (blue)

Fig. 13 Variation of median aggravation factors (AGF) along cross-section 1 estimated at the investigated points for the specified period ranges and for **A** AS1 and **B** AS2



leading to a period range of 0.10–0.50 s. It should be noted that the conclusions obtained by Riga et al. (2016) are based on viscoelastic linear analysis, and the role of soil nonlinearity is not addressed.

The median aggravation factors associated with the valley effect are also comparable to the range obtained in other case studies, such as the Mugello (Italy) and Mygdonian (Greece) basins, where values of approximately 1.1–1.5 (Madiati et al. 2017) and 1.25–2 (Raptakis et al. 2004) were obtained for the 0.10–0.50 s period range.

4.2.2 Cross-section 2

The cross-section 2 intersects the Cretaceous and Lower to Middle Miocene formations. Figure 14 shows the cross-section oriented in the NW–SE direction, crossing several geological units and the location of geotechnical boreholes and HVSR measurements.

The geological bedrock below the Miocene formations is composed of Cretaceous formations, namely basalt rocks from the Lisbon Volcanic Complex and limestones from the C3 and C2 formations.

The MII, MIII, and MIVa formations outcrop on the left side. A shallow valley 15-m-thick and 95 m wide lies in the centre. The valley is filled with clayey silt and silty sand alluvial deposits, which are covered by a thin landfill layer of heterogeneous composition. On the right side, a 90-m-high hill arises and the MIVb and MMC formations outcrop.

Figure 14A and B show the key results in terms of median AF_{2D} total amplification factors for seismic action type 1 and type 2, respectively. The median AF_{1D} computed from 1D seismic response analysis along the points A, B, C and D was also reported.

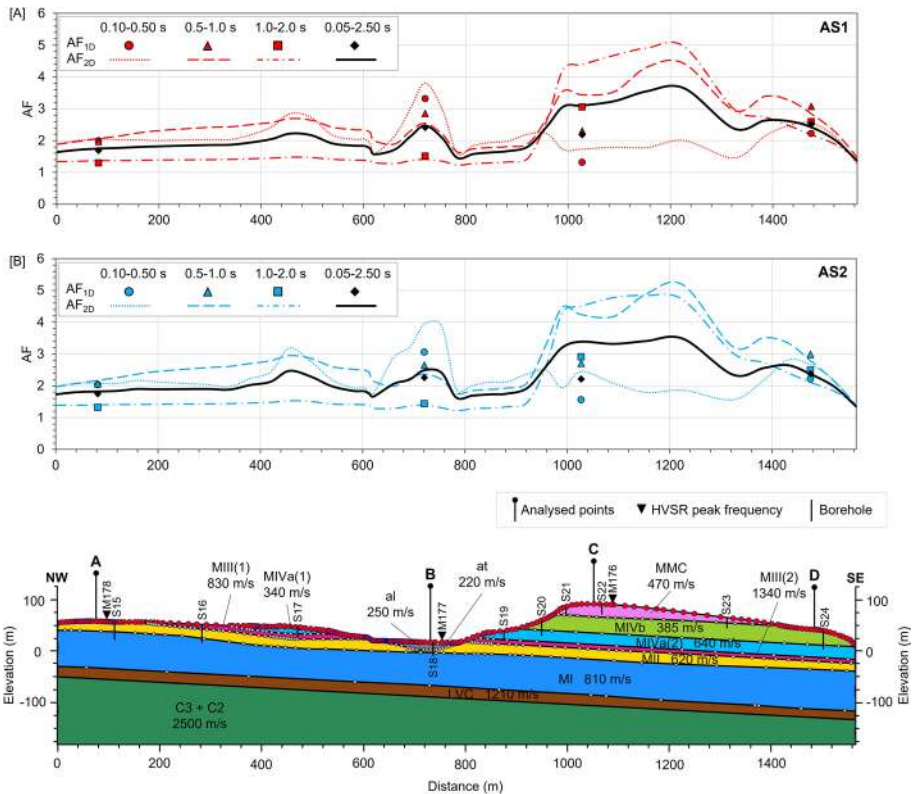


Fig. 14 Variability along the cross-section 2 of the median total amplification factors (AF_{2D}) in the period ranges of 0.10–0.50 s, 0.5–1.0 s, 1.0–2.0 s and 0.05–2.50 s, compared to the values computed from 1D seismic response analysis (AF_{1D}) along the points A, B, C and D for **A** AS1 and **B** AS2

The peak AF_{2D} occurs in the range 0.1–0.5 s in the centre of the valley (point B), varying between 3.8 (AS1) and 4.0 (AS2). The HVSR M177 is flat, which may be because the measurement was performed close to the border of the valley where stiff materials outcrop (MIII formation). On the top of the ridge, the peak AF_{2D} occurs in the range 1.0–2.0 s (point C), varying between 4.4 (AS1) and 4.6 (AS2). Due to the device's sensitivity, HVSR M176 only identifies a higher frequency peak (> 10 Hz), which is related to a superficial impedance contrast (Oliveira et al. 2023). Higher AF_{2D} occurs in the intermediate to lower period ranges at points A and D. This behaviour can be observed in both the AS1 (Fig. 14A) and AS2 (Fig. 14B) results and are related to the subsoil morphology, such as inclined layers. At the top of the ridge (point C) and the centre of the valley (point B), a median AF_{2D} of 3–3.4 and ~2.5 are computed in the period range 0.05–2.50 s, respectively.

The median response spectra computed from 1 and 2D analyses are compared with the median input motion spectra at points A, B, C and D in Fig. 15A, showing higher amplification essentially for shorter periods (< 0.5 s) in the valley (point B), more

significant in AS1, and for longer periods (> 0.5 s) on the top of the ridge (point C), for both AS1 and AS2. At point A, higher amplification occurs essentially for periods higher than 0.3 s for AS1 and for periods lower than 0.3 s for AS2. At point D, the amplification is essentially observed for periods higher than 0.1 s. Spectral accelerations as high as $13\text{--}20\text{ m/s}^2$ appear at point B in the 0.3–0.5 s period range for AS1 and AS2; on the contrary, the spectral acceleration is lower than $10\text{--}12\text{ m/s}^2$ at points A, C and D in the whole period range.

The 2D/1D median response spectral ratios for points A, B, C and D are compared in Fig. 15B, while Fig. 16 shows the variation of median aggravation factors (AGF) along cross-section 2 computed at the same points for the specified period ranges.

Two-dimensional effects are noticed at point B between 0.2 s and 0.4 s for AS1 and AS2 (peaks of the 2D/1D ratio), related to the valley effect and basin configuration (Fig. 15B). In the 0.1–0.5 s period range, the median aggravation factors for AS1 and AS2 are around 1.2 and 1.3, respectively (Fig. 16). At point C, clear two-dimensional effects are observed in 0.5–1.0 s and 1.0–2.0 s ranges for AS1 and AS2, evidencing the topographic effects related to the ridge. In this case, the median AGF varies from ~ 1.5 to ~ 1.6 for AS1 and AS2, respectively (Fig. 16). The spectral ratio shows that the two-dimensional effects are predominant in most of the period range (< 2 s). At point A, AGF is close to 1 for both AS1 and AS2. At point D, a slight two-dimensional effect is identified in the 0.10–0.50 s period range for AS1 and AS2, related to the subsoil morphology (i.e., inclined layers).

In the 0.05–2.50 s period range, the median AGF at points B and C ranges from 1.1 to 1.5 for AS1 and AS2 (Fig. 16).

The aggravation factor obtained at point C (1.5–1.6) for intermediate to longer period ranges is comparable to the values obtained by Pagliaroli et al. (2020) for the ridge in Montedinove (Italy) where this parameter varies from 1.5 to 2. In contrast of what was observed here, the maximum aggravation factor in the Montedinove ridge (maximum AGF ~ 3) is observed at 0.1–0.5 s period range, mainly related to the subsoil structure. The estimated values are also within the average topographic amplification factors estimated by Pagliaroli et al. (2011) for Nicastro ridge (Southern Italy) (1.37–1.85 for AS1 and 1.18–1.89 for AS2).

The median AF_{1D} is higher over the 1.0–2.0 s period range on top of the ridge (point C). The soil shear-strain profiles at the top of the ridge (point C) and on the right side of the profile (point D) shows a concentration of deformation at the MIVb formation. The peak ground acceleration (PGA) profile shows an aggravation in this layer. As shown before, the MIVb formation has a lower V_s , resulting in a V_s inversion in the soil profile. These characteristics imply that the MIVb formation amplifies the seismic motion, affecting surface response.

The V_s value for this layer was assumed to be equal to the overlaying layer (MMC) (see Fig. 14), and new 1D profiles corresponding to points C and D were generated to quantify the impact of the MIVb formation characteristics on the seismic soil response. The new soil shear-strain profiles at the top of the ridge (point C) and on the right side (point D) reveal that the MIVb formation has a reduced shear-strain rate, as does the PGA. At point C, the median AF_{1D} shows a 7% reduction, while point D shows a 19% reduction. As a result, the MIVb formation characteristics have a slight impact on the results.

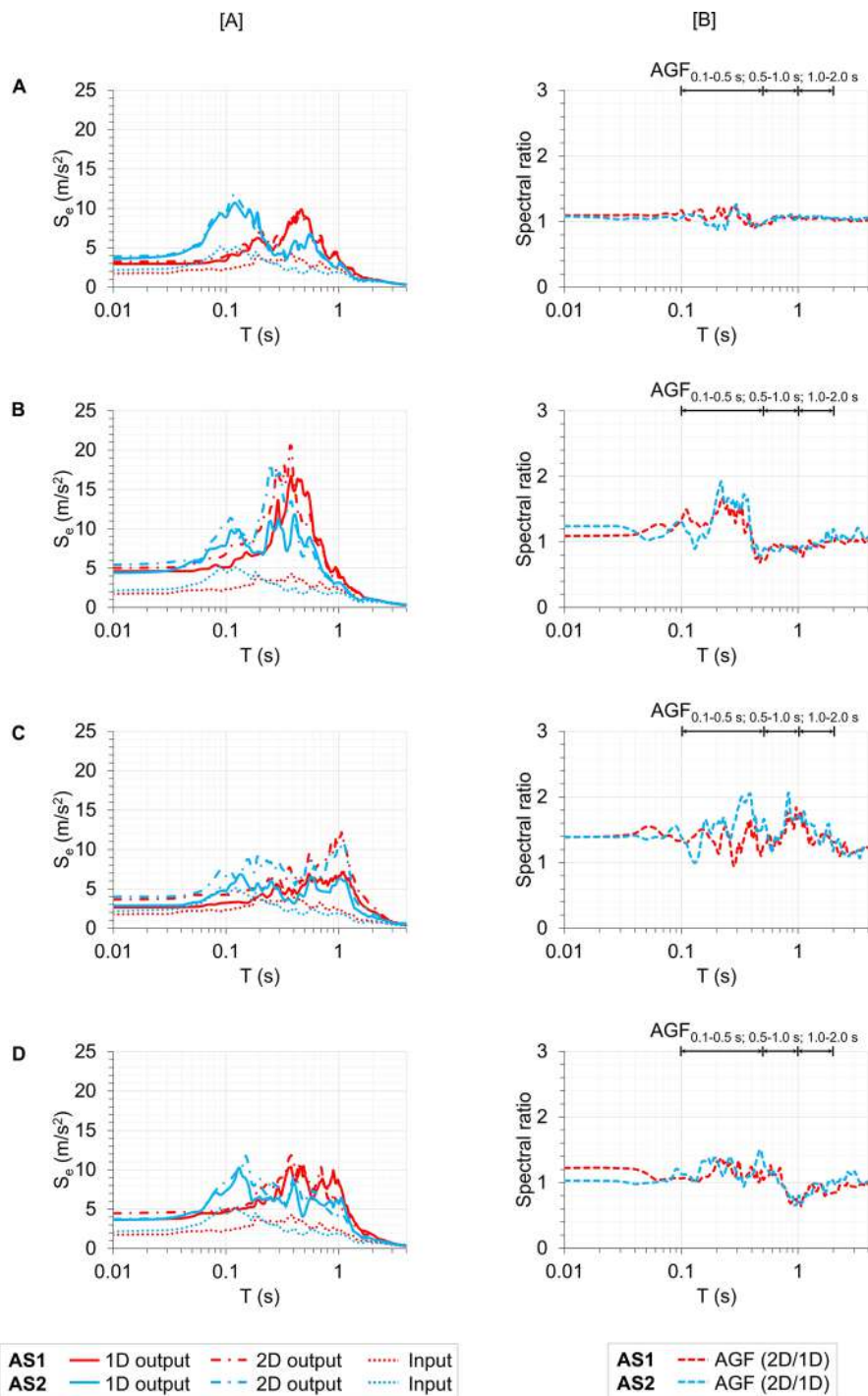
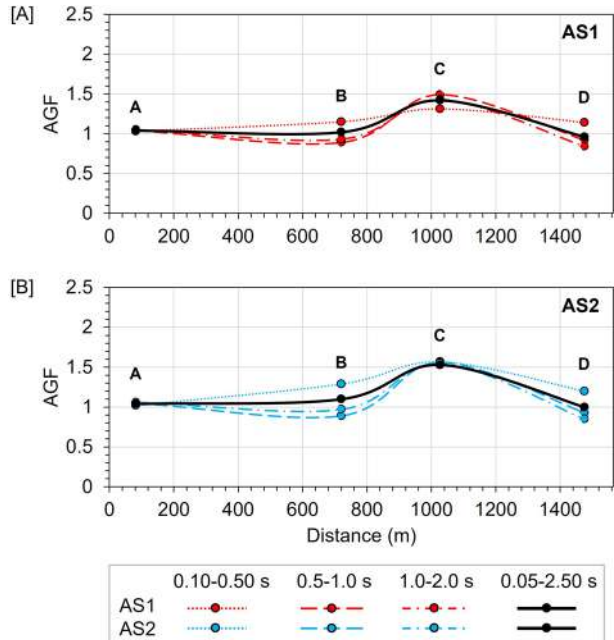


Fig. 15 Cross-section 2: **A** median response spectra ($\xi=5\%$) for 1D output, 2D output and input motions, and **B** 2D/1D median response spectral ratio computed at four points (A, B, C and D) for AS1 (red) and AS2 (blue)

Fig. 16 Variation of median aggravation factors (AGF) along cross-section 2 estimated at the investigated points for the specified period ranges and for **A** AS1 and **B** AS2



4.2.3 Cross-section 3

The cross-section also intersects the Cretaceous and Lower to Middle Miocene formations, but in a transverse direction in relation to the cross-section 2. Figure 17 shows the several geological units as well as the location of in situ investigations (geotechnical boreholes, MASW and HVSr measurements).

In the WSW-ENE direction, the surface topography is gentle. The layers are inclined $\sim 10^\circ$ to the horizontal, and shear wave velocity inversions exist in this cross-section.

Figure 17A and B summarise the results in terms of median AF_{2D} total amplification factors for seismic action type 1 and type 2, respectively. The median AF_{1D} computed from 1D seismic response analysis along the points A, B, C, D and E was also reported.

The median AF_{2D} shows a variation in the predominant period range at which the major amplification effects occur along the profile, identifying the transition between the different geological formations (Fig. 17A and B). On the left side of the profile (first 600 m), where stiffer geological units with approximately horizontal layering are identified, the major AF_{2D} takes place in the 0.1–0.5 s period range with values between 2.2 and 2.4 with a maximum of 2.9 for AS1 (Fig. 17A) and between 2.8 and 3.1 with a maximum of 4 for AS2 (Fig. 17B). In the centre part of the profile (600–1650 m), where an intercalation of soft and stiff formations with an inclined configuration is identified, the major AF_{2D} takes place in the 0.5–1.0 s period range, where maximum amplification is between 3.8 and 4.4. On the right side of the profile (> 1650 m), where more recent and softer formations are identified, the major AF_{2D} takes place in the 1.0–2.0 s period range, where maximum amplification is between 3.4 and 4.0. This behaviour can be observed in both the AS1 (Fig. 17A) and AS2 (Fig. 17B) results. Along the profile, a median AF_{2D} between 2 (AS1) and 2.1 (AS2) is calculated in the period range 0.05–2.50 s.

The median response spectra computed from 1 and 2D analyses are compared with the median input motion spectrum at five points along the profile (A to E) in Fig. 18A and the 2D/1D median response spectral ratios for the same points are compared in Fig. 18B. Figure 19 shows the variation of median aggravation factors (AGF) along cross-section 3 computed at the same points for the specified period ranges.

The higher spectral accelerations round 11 m/s^2 in the 0.3–0.6 s period range for AS1 and 13 m/s^2 in the 0.1–0.3 s period range for AS2 at point A. At point B, the spectral acceleration varies between 8 and 10 m/s^2 for the 0.4–0.8 s and 0.1–0.3 s period ranges for AS1 and AS2, respectively. At point C, higher spectral acceleration values were observed, varying between 10 and 13 m/s^2 for AS1 in the 0.3–0.8 s period range and reaching a maximum of $\sim 11 \text{ m/s}^2$ in the 0.1–0.3 s period range for AS2, where the 2D spectral acceleration is higher than 1D. At point D, a maximum spectral acceleration of $\sim 13 \text{ m/s}^2$ is observed in longer periods ($> 0.8 \text{ s}$) for AS1. The same is observed for AS2, but with a lower spectral acceleration ($7\text{--}9 \text{ m/s}^2$). A spectral acceleration between 7 and 10 m/s^2 was identified in longer periods ($> 0.8 \text{ s}$) at point E for both AS1 and AS2. The spectral acceleration peak moves to longer period intervals from points A to E, with maximum values recorded at points B, C and D where the intercalation and parallel layering of soft and stiff geological formations are more significant.

Slight two-dimensional effects are noticed at point B between 0.1 s and 0.5 s for both AS1 and AS2 (peaks of the 2D/1D ratio); here the median aggravation factors for AS1 and AS2 are around ~ 1.2 and ~ 1.4 , respectively (Fig. 19). At point C, 2D effects are observed in 0.1–0.5 s range for AS1 and AS2. In this case, the median AGF is ~ 1.1 and ~ 1.4 for AS1 and AS2, respectively (Fig. 19). At points D and E, a high median AGF ($\sim 1.3\text{--}1.6$)

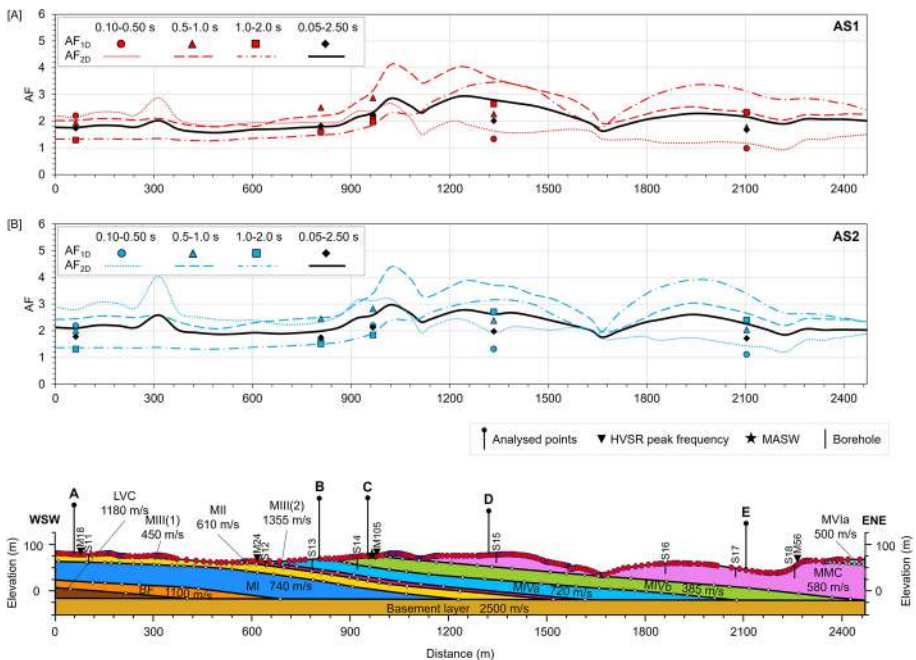


Fig. 17 Variability along the cross-section 3 of the median total amplification factors (AF_{2D}) in the period ranges of 0.10–0.50 s, 0.5–1.0 s, 1.0–2.0 s and 0.05–2.50 s, compared to the values computed from 1D seismic response analysis (AF_{1D}) along the points A, B, C, D and E for A AS1 and B AS2

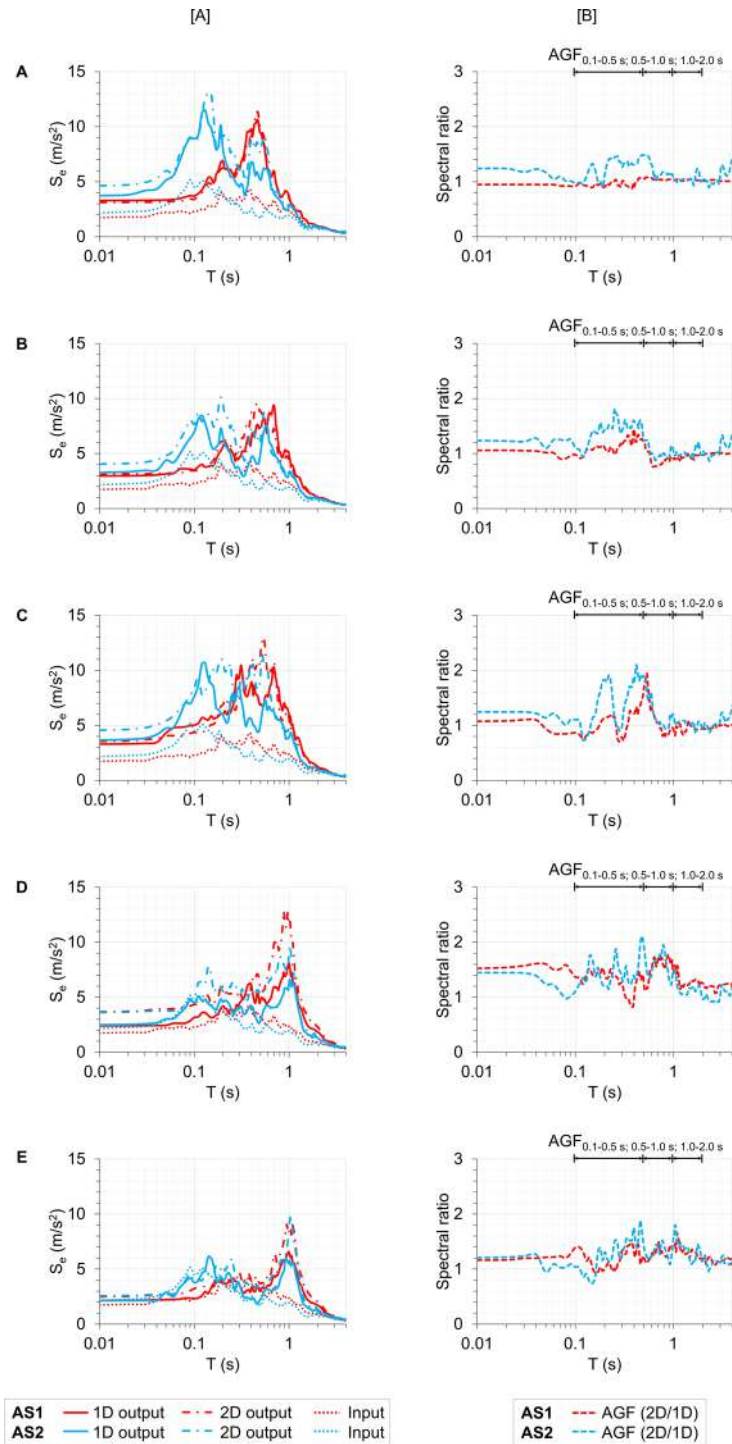
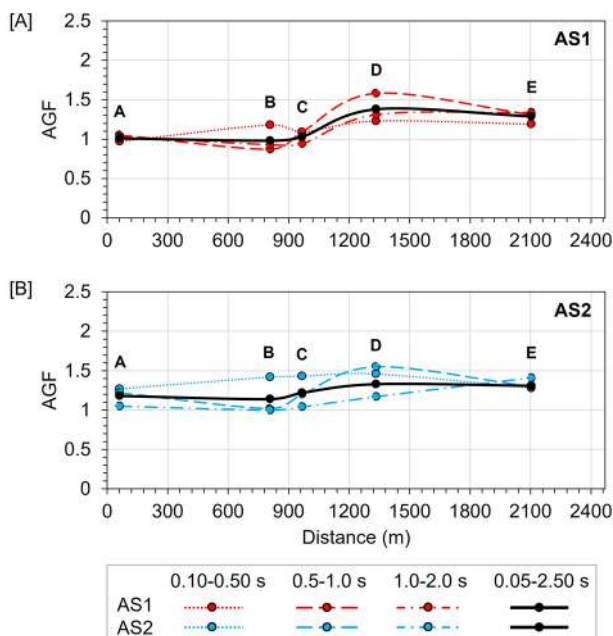


Fig. 18 Cross-section 3 **A** median response spectra ($\xi=5\%$) for 1D output, 2D output and input motions, and **B** 2D/1D median response spectral ratio estimated at five points (A, B, C, D and E) for AS1 (red) and AS2 (blue)

Fig. 19 Variation of median aggravation factors (AGF) along cross-section 3 computed at the investigated points for the specified period ranges and for **A** AS1 and **B** AS2



is obtained for intermediate to long period ranges (>0.5 s). Except for AS2, which has a median AGF of 1.2 for the short to intermediate period ranges (Fig. 18B), the greater agreement between 1 and 2D results observed at point A shows minor two-dimensional effects.

In the 0.05–2.50 s period range, the median AGF at points B, C, D and E vary between 1.1 and 1.4 for AS1 and AS2 (Fig. 19).

In parametric investigations that analyse and quantify two-dimensional effects, homogeneous or heterogeneous models with horizontal layering are used (e.g., Makra et al. 2005; Riga et al. 2016). Two-dimensional valley or topographic effects dominate in case studies where the subsoil geometry displays inclined layering, such as the Thessaloniki basin, Greece (Raptakis et al. 2004) and the Montedinove ridge, Italy (Pagliaroli et al. 2020).

Pagliaroli et al. (2020) found that in Monte San Martino (Italy), which has a gentle slope and inclined subsurface structure, 1D and 2D simulations result in almost the same amplification factors. However, a minor aggravation factor of 1.2–1.3 is reported for shorter to intermediate time ranges. Given the gentle slope at points B, C, D and E in cross-section 3, the observed 2D effects might be attributed to the inclined geometry of the subsoil layers.

The median AF_{1D} is high over the intermediate to long period ranges (0.5–1.0 s and 1.0–2.0 s) due to the local site conditions at points C, D and E. The soil shear-strain profiles at these sites demonstrate that the MIVb formation concentrates deformation and the PGA profile shows a considerable increase in acceleration in this layer as in the cross-section 2.

When the V_s value for the MIVb layer was assumed to be equal to the overlying layer (MMC) (see Fig. 17), the new soil shear-strain profiles at these points reveal that

the MIVb formation has a reduced shear-strain rate, as does the PGA. At point C, the median AF_{1D} shows a 29% reduction, point D shows an 18% reduction, and point E shows a small reduction (3%; Fig. 8C). As a result, the MIVb formation characteristics have a slight impact on the results as in the cross-section 2.

5 Amplification factors (AF) and soil factors (S)

5.1 Amplification factor distribution

Figure 20 shows the distribution of median amplification factors and median aggravation factors (AGF) grouped in four zones for the 0.05–2.50 s period range. All of the points analysed were projected along the SW-NE axis.

In detail, Fig. 20A shows the median amplification factors computed through the 1D numerical simulations (NS_{1D}).

Figure 20B shows the median amplification factors calculated through the 1D (NS_{1D}) and 2D (NS_{2D}) numerical simulations for points where only stratigraphic effects were identified, i.e., the median AF_{1D} from the 1D numerical simulations plus the median amplification factors from the 2D numerical simulations in sites where two-dimensional effects are negligible. In these cases, the amplification factor is mainly due to stratigraphic effects, which are well-predicted by 1D seismic response analysis, as seen in Fig. 20B, where 1D and 2D numerical simulations give similar results.

Figure 20C plots the median aggravation factors derived using the 2D/1D spectral ratio.

In general, Zone A is distinguished by low 1D amplification factors (<1.4) due to impedance contrasts caused by the presence of thin landfill layers (Fig. 20A). When the geological bedrock outcrops, the AF_{1D} is close to 1. As a result, the median AF_{1D} of this zone is close to 1 (1.1) for AS1. In the case of AS2, the presence of thin cover deposits amplifies the seismic motion, leading to a higher median AF_{1D} (~ 1.2). In Alcântara Valley a higher amplification factor is observed (1.7–1.8) due to the contrast between the cover deposits (landfill and alluvial deposits) and the C2 formation (Fig. 12B).

Zone B is characterized by a median AF_{1D} of ~ 1.8 for both AS1 and AS2, which is higher than in Zone A (Fig. 20A). The amplification factors obtained in this zone are more variable, which is attributed to greater geological variety (geological formations from the Lower to Middle Miocene) and different impedance contrasts.

Zone B has significant stratigraphic amplification factors (Fig. 20A). These results are derived from 1D profiles that belong to the cross-sections, with a geological bedrock shear-wave velocity (V_s) of 2500 m/s assumed. A sensitivity analysis was performed to determine whether these higher values are related to the V_s value of geological bedrock. The analysis was carried out at points A to D of cross-section 2, A to E of cross-section 3 and point C of cross-section 1 (see Fig. 5). The remaining 1D profiles of the cross-section 1 classified as ground type A (points A, B, D and E in Fig. 5) were not investigated due to the existence of highly stiff layers and the fact that the ground type does not change (ground type A at the base and on the surface). A V_s value of 1500 m/s was investigated for the seismic bedrock. According to the new AF_{1D} distribution with $V_s = 1500$ m/s, the observed median is 11–15% lower than the median AF_{1D} with $V_s = 2500$ m/s.

Zone C is mostly composed of competent formations with minor impedance contrasts, leading to low amplification factors for both seismic actions ($AF_{1D} \sim 1$). Amplification factors for 1.3–1.4 are identified in the presence of landfill and alluvial deposits (Fig. 20A).

Fig. 20 Median amplification factors (AF) and median aggravation factors (AGF) distribution in the 0.05–2.50 s period range along the SW-NE axis: **A** all points (1D numerical simulations, NS_{1D}); **B** stratigraphic effect (1D and 2D numerical simulations, NS_{1D} and NS_{2D}); **C** aggravation factors (valley, topographic and subsoil morphology). The results for AS1 are in red, whereas the results for AS2 are in blue. The median, 16th and 84th percentiles of AF for each zone are also shown. The map (bottom) shows the distribution of all points and identifies Zones A, B, C and D, with a horizontal axis indicating the order of the 1D profiles. The sequence of the 1D profiles in Zone D is 1, 3, 15, 30 and 31. *A.R. Valley* indicates the Almirante Reis Valley

In Zone D, the 1D amplification factors range from 1.4 to 1.7, with a median of ~ 1.6 for both AS1 and AS2 (Fig. 20A).

Taking into account the points where only stratigraphic effects were identified (Fig. 20B), the median AF remains or decreases when compared to the previous results shown in Fig. 20A, regardless of seismic action or zone analysed. The median amplification factor in Zone B has slightly decreased from 1.8 to 1.7.

According to the Bard and Bouchon (1985) approach, the relationship between shape ratio, h/l (where h is the soil thickness at the centre of the valley and l is the half of valley width) and bedrock–sediment velocity contrast, C_V , in the Encarnação Valley suggests that stratigraphic effects may be predominant. However, Makra et al. (2005) observed that 2D valley amplifications still play a role in shallow basins. For this reason, Fig. 20B does not include the results for profiles 27 and 28 in Encarnação Valley.

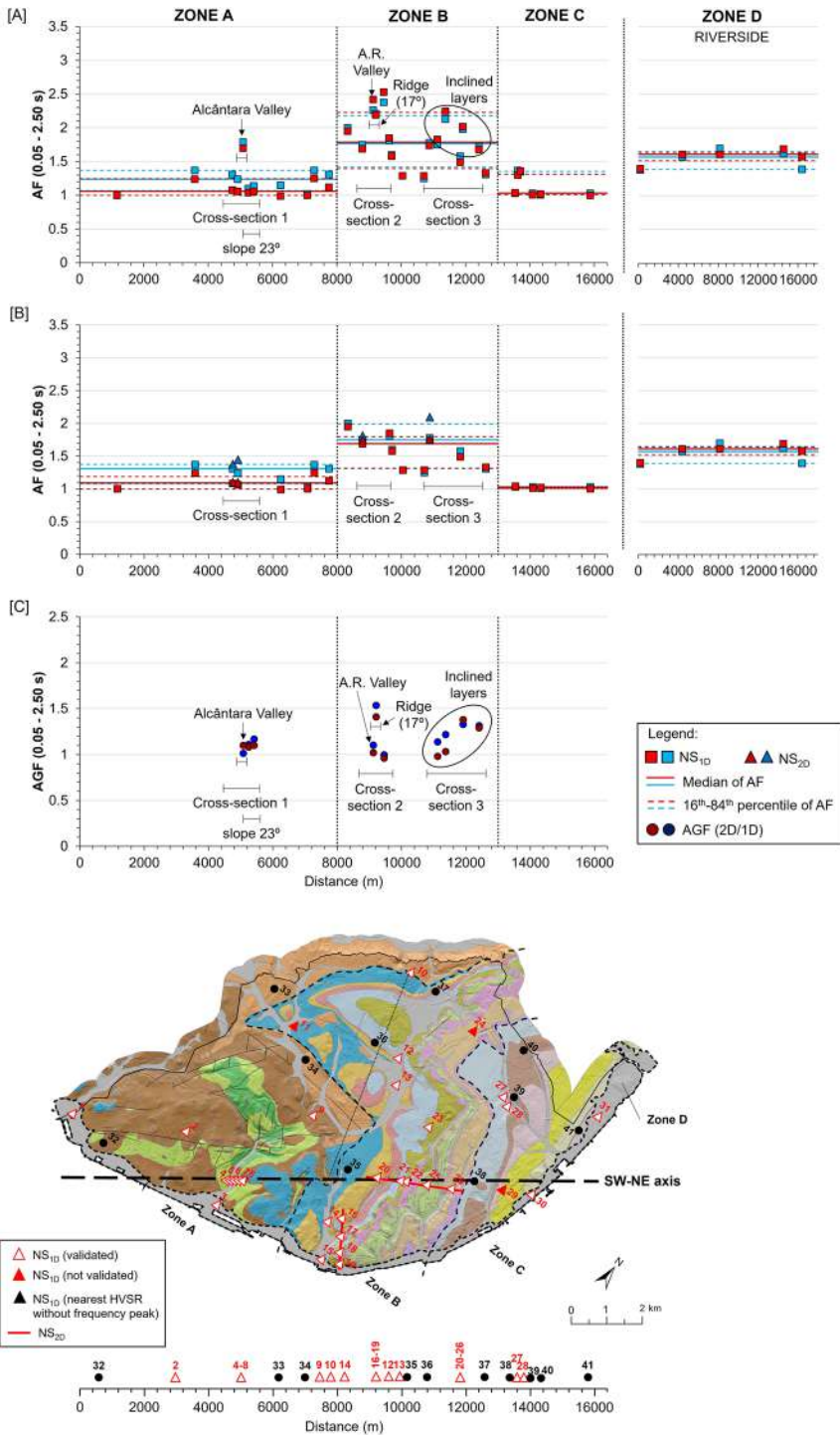
The two-dimensional amplification factors are greater than the stratigraphic amplification factors at the same point. The difference between them is shown by the aggravation factors (Fig. 20C). The differences correspond to the valley effect observed in the Alcântara Valley (Fig. 12B) and Almirante Reis Valley (Fig. 15B), the topographic effect observed on the top of the ridge (Fig. 15B) or on the Alcântara Valley's right margin (Fig. 12B), and 2D effects mostly related to subsoil morphology (inclined layers) (Fig. 18B). The AGF at the Alcântara Valley and Almirante Reis Valley is around 1.1 for the 0.05–2.50 s period range, 1.4–1.5 at the top of the ridge, and 1.1–1.4 for the inclined layers feature.

In general, the valley effects are important in the shorter periods (Fig. 21A), while topographic and subsoil morphology effects are dominant in intermediate to longer periods (Fig. 21B and C) for both AS1 and AS2.

The valley effect is important in the 0.1–0.5 s period range (AGF ~ 1.8 for AS1 and 1.3 for AS2) and residual in the remaining periods (Fig. 21). Considering its geometry, the right margin has a slope of around 25° and a height of more than 30 m above the surface of the valley (50–60 m). According to EC8, a topographic effect exists when topographic irregularities are higher than 30 m in height and have a slope angle greater than 15° (CEN 2004). Thus, the topographic variation was responsible for the 2D effects identified on the right margin of Alcântara Valley (AGF ~ 1.1 –1.3).

The Almirante Reis Valley (cross-section 2) has a slight valley effect when compared with the Alcântara Valley; however, it is also significant in the shorter periods (AGF ~ 1.1 –1.3). In this case, the observed amplification effect is mainly due to stratigraphic effects (Fig. 21A). The topographic effect observed close to the top of the ridge is important in the intermediate to longer periods (AGF ~ 1.4 –1.6) (Fig. 21B and C).

Given the gentle slope of the cross-section 3, the 2D effects are primarily due to inclined layers, being predominant in the intermediate (AGF ~ 1.2 –1.6) to longer periods (AGF ~ 1.3) (Fig. 21B and C). The same was observed at point D of cross-section, but for shorter periods (Fig. 15).



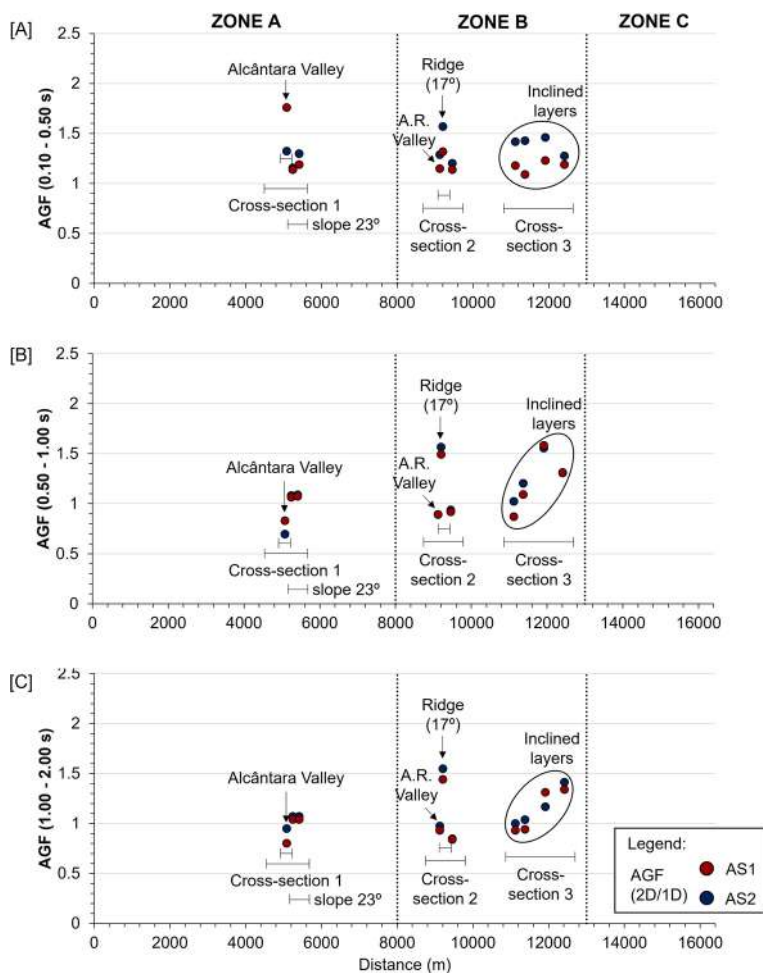


Fig. 21 Median aggravation factors (AGF) variation (valley, topographic and subsoil morphology effects) along the SW-NE axis over the **A** 0.1–0.5 s, **B** 0.5–1.0 s and **C** 1.0–2.0 s period ranges

In the transversal profile along a NW–SE axis (Fig. 22), only the closest 1D subsoil models (37, 12, 13, 20, 16, 17, 18 and 19) were projected. The results show an increase in amplification factor in Zone B in the NW–SE direction (Fig. 22-A). According to the points analysed, the geological formations are more competent in the northwest part of the profile and without cover deposits, where the ground elevation is higher. The southeast part of the profile includes valleys related to old water streams and a ridge, where topographic effects were observed.

Figure 20 shows the heterogeneity of estimated amplification factors in Zone B, which is linked to geological lateral variation. In the NW–SE axis (Fig. 22), the lateral variation associated with geology is minimized, indicating a tendency connected to ground elevation.

Zones A and C include fewer points and are more dispersed and settled on different geological formations, making it harder to project them onto a transversal profile. Then, no transversal profiles were developed in these zones.

Vessia et al. (2011) investigated the influence of shape ratio, input accelerograms, and soil/bedrock impedance contrast on some simplified examples of alluvial valleys. The authors demonstrated that the shape ratio is one of the most important factors for recognising 2D valley effects. Shallow (shape ratio < 0.2) and deep (shape ratio > 0.2) valleys behave quite differently: the shallow valley has higher amplification at the edges, whereas the deep valley has higher amplification at the centre, as seen in the Alcântara and Almirante Reis valleys (Fig. 20).

Riga et al. (2016) showed that maximum values of aggravation factors less than one may occur above the sloping edge of the basin, implying that the 2D response is attenuating in comparison to the corresponding 1D response, particularly in steep slopes. Maximum aggravation factors strongly depend on the basin shape ratio at the nearly constant-depth part of the basin. The shape ratio shows a general increase, which is more pronounced in the centre part of the basin, where median values as high as 1.8 and 84th percentiles around 2.3 are found for the highest shape ratio, i.e., deep and narrow valleys.

When AS1 is considered, the median amplification factor found in the 0.10–0.50 s range for the centre of Alcântara Valley (~ 1.8) fits the data mentioned above (Fig. 13). AS2 has a median amplification factor of about 1.3. For both AS1 and AS2, the median amplification factor in Almirante Reis Valley (1.2–1.3) is lower than in Alcântara Valley (Fig. 16). This tendency for a shallower valley was also noticed by Riga et al. (2016).

Alleanza et al. (2019) also conducted a parametric analysis to explore the impact of 2D subsoil morphology on seismic motion amplification at the surface. To achieve this, a series of linear viscoelastic analyses were performed on simplified 2D models, considering the valley shape, edge inclination, excitation frequency, and impedance ratio. The authors compared the parametric study's amplification factors to those estimated based on a real-case history of alluvial valleys in Central Italy.

Alleanza et al. (2019) showed that the impedance ratio plays an important role in defining the 2D response of the valley and is almost independent of the edge slope. According to Alleanza et al. (2019) approach, the shape determined by the ratio of the wavelength (λ) of the median input motions to the thickness (H) of the deformable soil column at the centre of the valley (λ/H) for the Alcântara Valley is approximately 3.2 for AS1 and 3.7 for AS2. This indicates that the frequency of the input motion is higher than the fundamental frequency of the valley (2.7 Hz), surface wave propagation is dominant, and the valley effect is significant.

The estimated topographic amplification factors were compared with those derived from the analytical and numerical studies compiled by Pagliaroli (2006), the results obtained by Pagliaroli et al. (2011) and those proposed by EC8.

The slope on the right side of the Alcântara Valley (cross-section 1) has a shape ratio (H/L) of 0.48 and a topographic amplification factor of around 1.1–1.2 (Fig. 13). The ridge in cross-section 2 has a H/L ratio of 0.43 and a topographic amplification factor of approximately 1.4–1.5 (Fig. 16).

The average trend of literature-derived data reported by Pagliaroli et al. (2011) shows that the topographic amplification factors for these shape ratios range from 1.42 ($H/L = 0.43$) to 1.47 ($H/L = 0.48$). The topographic amplification factors for ridge in cross-section 2 satisfactorily match the value predicted by the average trend. Because the average trend is calculated using analytical and numerical data from ridges and isolated cliff structures, comparing it to the topographic amplification factor for the slope in cross-section 1 is improper.

Fig. 22 Median amplification factors (AF) and median aggravation factors (AGF) distribution in the 0.05–2.50 s period range along the NW–SE axis: **A** all points (1D numerical simulations, NS_{1D}); **B** stratigraphic effect (1D and 2D numerical simulations, NS_{1D} and NS_{2D}); **C** aggravation factors (valley, topographic and subsoil morphology). The results for AS1 are in red, whereas the results for AS2 are in blue. The map (bottom) shows the distribution of all points, with a horizontal axis indicating the order of the 1D profiles. A.R. Valley indicates the Almirante Reis Valley

When compared to the results obtained by Pagliaroli et al. (2011), the predicted topographic amplification factors at the top of the hill (cross-section 2) appear to fall within the authors ranges for AS1 (1.37–1.85) and AS2 (1.18–1.89).

According to the EC8, the topographic amplification factor for ridges with a substantially smaller crest width than base is 1.4 for average slope angles $i > 30^\circ$ and 1.2 for gentler slope angles ($15^\circ < i < 30^\circ$). A topographic amplification factor of 1.2 is recommended for isolated cliffs and slopes near the top edge (CEN 2004). The average slope angles on the right side of cross-section 1 and the ridge in cross-section 2 are approximately 25° and 20° , respectively. The estimated values for the slope in cross-section 1 are in good agreement with the EC8 proposed values. In contrast, the topographic amplification factors observed at the top of the ridge are 15% to 25% higher than the EC8 suggested values.

The underestimation is due to the fact that EC8 values are frequency independent, disregarding the fact that, at least for ridges and isolated hills, topographic amplification is generally band-limited and centred around the fundamental vibration frequency of the ridge, according to the 2D resonance phenomenon (Pagliaroli et al. 2011).

5.2 Soil factors

The soil factor, S , was estimated using the previously calculated stratigraphic amplification factors (AF_{1D}) from 1D numerical simulations and the spectral shape ratio (SR) over the period range of 0.05–2.50 s.

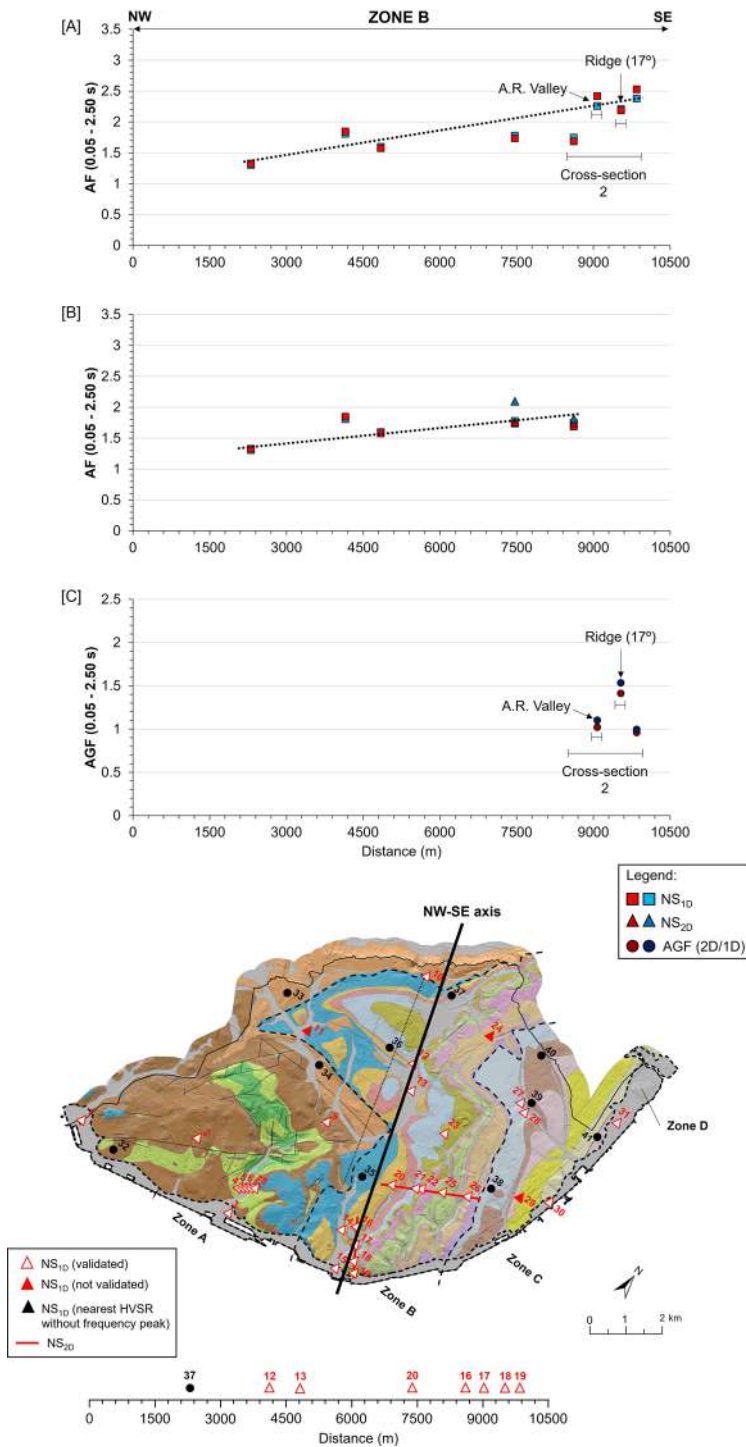
The spectral shape ratio was compared to the EC8 and EC8-N.A. reference SR values. In the EC8 Portuguese National Annex, the SR value equals to 1 for both seismic actions (AS1 and AS2) and all ground types except ground type D (1.18). When the estimated median SR values are compared to the EC8 reference values, they both have the same value ($SR = 1$) for ground type A, regardless of whether AS1 or AS2 is used. The difference between them, however, is higher for ground types B and C.

The observed median for the distribution of points corresponding to ground type B is 23% and 6% lower than the EC8 and EC8-N.A. reference values for AS1, respectively. The median for AS2 is 7% higher than the EC8 and EC8-N.A. reference values. When ground type C and AS1 are employed, the difference in medians is 27% smaller than the EC8 reference value and almost like the EC8-N.A. reference value. The median for AS2 is 20% greater than the EC8 and EC8-N.A. reference values.

The median SR value for the five-ground type E soil profiles is 0.83, which is 45% and 25% lower than the EC8 and EC8-N.A. reference values for AS1. The median for AS2 is roughly equivalent to the EC8 and EC8-N.A. reference values.

Based on the results, we can conclude that using the EC8-N.A. reference values improves the adjustment between the calculated SR values and the reference values.

Figure 23 plots the S factors for each seismic action (AS1 and AS2) by ground type. The median and 16th–84th percentiles of the estimated S values for each ground type were calculated using the classification of each site based on the value of VS30.



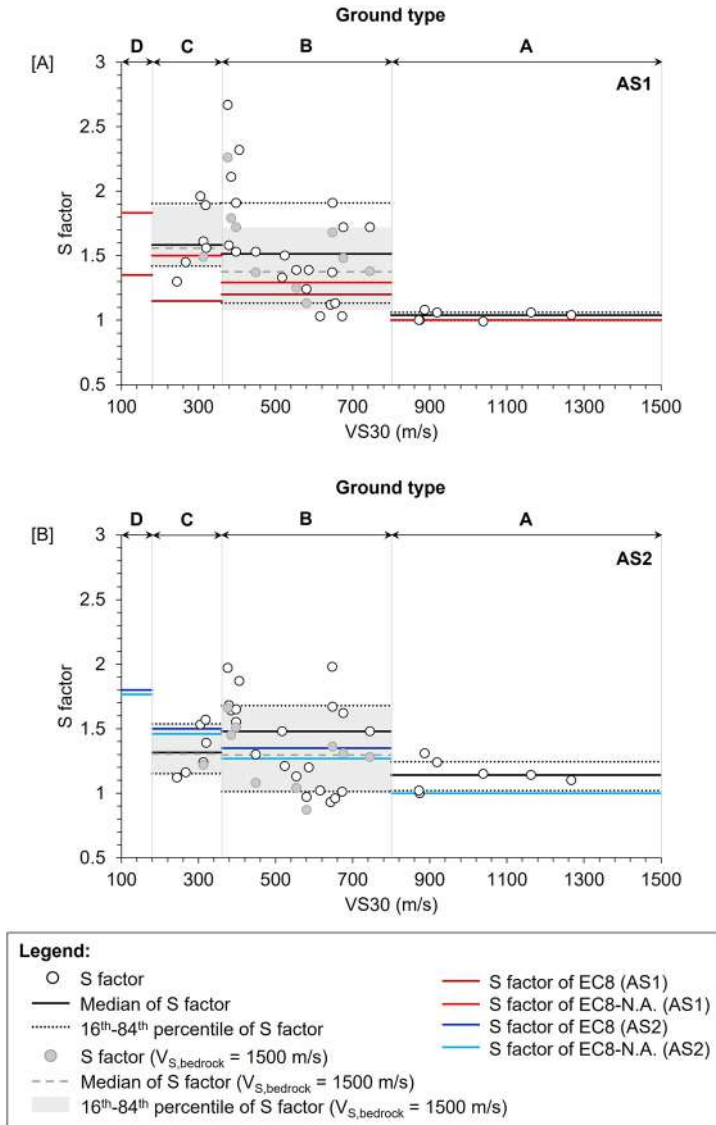


Fig. 23 S factor distribution against VS30 value for **A** seismic action type 1 (AS1) and **B** seismic action type 2 (AS2). The median, 16th and 84th percentiles for each ground type (A, B and C) are shown. The EC8 and EC8-N.A. S factors are also displayed

In general, regardless of ground type or seismic action, the reference values of EC8 and EC8-N.A. underestimate the median S value. The exception is ground type C (AS2), where the reference values exceed the calculated median S factor (Fig. 23B). When the EC8-N.A. values for AS1 are considered, the difference between the estimated and reference values is smaller than when considering the EC8 reference values. In the case of AS2, the EC8 and EC8-N.A. reference values are quite similar. When the median S value computed for AS1 is compared to the EC8 and EC8-N.A. reference values, it is found to be slightly higher

for ground type A (4%) (Fig. 23A). The difference between the median and the EC8 and EC8-N.A. reference values for AS2 is 12% (Fig. 23-B). The difference is greater for ground types B and C.

The median S-factor for AS1 is 21% and 15% higher than the EC8 and EC8-N.A. reference values, respectively, according to the distribution of points corresponding to ground type B (Fig. 23A). The discrepancies are lower for AS2, with the median being 9% and 14% higher than the EC8 and EC8-N.A. reference values, respectively (Fig. 23B). The difference between medians for ground type C and AS1 is 27% and 5% larger than the EC8 and EC8-N.A. reference values, respectively (Fig. 23A). Differences in AS2 range from 11% (EC8) to 14% (EC8-N.A.) (Fig. 23B).

The median estimated value for AS1 for the five soil profiles classified as ground type E is 1.83, which is 23% and 9% higher than the EC8 and EC8-N.A. reference values, respectively. The predicted median values for AS2 are 18% lower than the reference values.

Ground type B has rather high S factor values (Fig. 23). These values are correlated with the higher stratigraphic amplification factors analysed before (Fig. 20A) derived from 1D profiles with a V_s of 2500 m/s estimated for the seismic bedrock layer.

A sensitivity analysis with V_s of seismic bedrock equal to 1500 m/s indicates that seismic bedrock V_s variation may influence S-factor estimation (Fig. 23). A lower V_s value corresponds to a lower S-factor. The new median S value for ground type B is closer to those defined in EC8 and EC8-N.A. than the previous median values. Because only one individual S value differed slightly, the difference in the median S value derived with V_s equal to 2500 m/s or 1500 m/s for ground type C is minimal. According to the distribution of points corresponding to ground type B for AS1, the observed median is now 13% and 6% higher than the EC8 and EC8-N.A. reference values, respectively (Fig. 23A). For AS2, the computed median differs from the reference values only slightly (2–4%) (Fig. 23B).

Pitilakis et al. (2012) proposed improved S factors and normalized shapes for EC8 elastic response spectra for the different ground type classes described in EC8, based on a large dataset of ground motion records from a worldwide strong motion database.

Considering seismic action type 1, the estimated median S factor for ground type B (1.52) is greater than the value proposed by Pitilakis et al. (2012) (1.30). For ground type C, the estimated median S factor (1.59) is lower than the value proposed (1.70).

For seismic action type 2, the estimated median S factor for ground type B (1.48) is comparable to the value suggested by Pitilakis et al. (2012) (1.40). For ground type C, the recommended S factor (2.10) is much larger than the median S factor found in this study (1.32).

Pitilakis et al. (2012) decided to keep the same S factors as in EC8 for ground types D and E due to limited datasets, despite the fact that the EC8 factors might be inadequate based on the few available records. Despite the limited data for ground type E, the estimated median S factor differs from the EC8 and EC8-N.A. S-factors in both AS1 and AS2.

6 Conclusions

This paper characterises the seismic site effects at the city scale.

The stratigraphic amplification factors (AF_{1D}) were distributed according to zones A, B, C and D, as shown below:

- Zone A – the median of AF_{1D} is close to 1, consistent with outcrop of stiffer geological formations (note for a higher median of $AF_{1D} \sim 1.2$ for AS2 related to the presence of thin cover deposits);

- Zone B – the median AF_{1D} is around 1.8, but with higher scatter due to greater geological variety and different impedance contrasts;
- Zone C – low amplification factors for both seismic actions ($AF_{1D} \sim 1$), due to the outcrop of stiff layers with minor impedance contrasts, excepting in the presence of cover deposits ($AF_{1D} \sim 1.3$ to 1.4);
- Zone D – in the riverside, 1D amplification factors range from 1.4 to 1.7 related to the presence of alluvial deposits with varied thickness, as well as a varying substratum across the city.

A sensitivity analysis on the V_S value of seismic bedrock of 1D profiles with higher values (2500 m/s) was performed to assess the uncertainty associated with its value. Assuming $V_S = 2500$ m/s and $V_S = 1500$ m/s led to a variation of the median AF_{1D} in the range 11–15%.

1D analysis highlight the effects of stratigraphic characteristics on local seismic amplification. In general, the presence of cover deposits increases seismic motion at the surface, for both seismic actions. Zone B highlights the effect of geological heterogeneity and associated geotechnical characteristics, specifically variations in the S-wave velocity profile, on the surface ground response. The amplification factor variability is generally consistent with the zones identified by peak frequency variation.

2D effects were observed in valleys filled with alluvial deposits and at the hill crest. There are also minor 2D effects related to the inclined layers. In general, the valley effects are important in the shorter periods, while topographic and subsoil morphology effects are dominant in the intermediate to longer periods for both AS1 and AS2.

The ground motion is significantly aggravated in the valley (cross-section 1) by a factor of 1.3–1.8 when compared to 1D prediction considering the shorter periods. When compared to 1D prediction, topographic effects aggravate ground motion near the top of the ridge (cross-section 2) by a factor of 1.3–1.6. The 2D effects related to the subsoil morphology predominant in the cross-section 3 aggravate the ground motion by a factor of 1.2–1.6 when compared to 1D prediction.

When two-dimensional effects are detected using 1D and 2D numerical simulations, the associated amplification factors are greater than the corresponding stratigraphic amplification factors, corresponding to the valley effect observed in the Alcântara Valley, the topographic effect observed on the top of the ridge in the cross-section 2, and the 2D effects mostly related to subsoil morphology.

The SW-NE axis shows the heterogeneity of estimated amplification factors in Zone B, which is linked to geological lateral variation. Considering the NW-SE axis, the lateral variation associated with geology is minimized, showing a tendency connected to ground elevation.

Finally, the S factor was estimated and compared with those suggested by EC8. In general, independent of ground type or seismic action, the reference values of EC8 and EC8-N.A. underestimate the median S factor. The exception is ground type C (AS2), where the reference values exceed the calculated median S factor. When the EC8-N.A. values for AS1 are considered, the difference between the estimated and reference values is smaller than when considering the EC8 reference values. In the case of AS2, the EC8 and EC8-N.A. reference values are quite similar.

Ground type B has rather high S factor values that are correlated with the higher stratigraphic amplification factors. When comparing the previous to the new median S factors, the median value obtained with a lower V_S is closer to those defined in EC8 and EC8-N.A.

This methodology can be applied to quantify the impact of 2D effects in other parts of the city where important geomorphological conditions could be identified.

It is important to note that the presented approach could be enhanced by (i) adding new site data, such as deeper geotechnical boreholes and V_s results, to better assess the geotechnical cross-section in depth; (ii) increasing the number of 1D numerical analyses for a more detailed evaluation of amplification factor variation in the city; and (iii) improving the analysis.

The results obtained in the presented study show that in complex geomorphological settings, such as that of Lisbon, the identification and quantification of seismic soil amplification are essential to delimit areas of greatest risk, thereby becoming a valuable asset for ground characterization and seismic microzonation studies. The computed amplification factors can also be compared with those prescribed by the next generation of Eurocode 8.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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