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Site seismic hazard mapping at a regional scale: the example of the Emilia-Romagna plain

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ABSTRACT The assessment of seismic ground motion at the surface is a key component for a reliable evaluation of seismic risk and for the development of effective prevention and mitigation policies. Risk prevention and mitigation strategies for natural hazards are most effective when implemented at an early stage. For territorial authorities, such as regions, river basin authorities, and provinces, the availability of up-to-date hazard maps at different spatial scales (regional, basin, and provincial) is, therefore, of paramount importance, as it enables the identification of the most critical areas and supports informed decision-making processes. This study presents a methodology for the zonation and representation of site-specific seismic hazard at the regional scale, and its application to the Emilia-Romagna plain (northern Italy). In particular, data derived from the most recent and representative seismic microzonation studies across the study area enabled the identification of zones characterised by similar seismic response, to which average stratigraphic amplification factors were assigned. Subsequently, peak ground acceleration and hazard seismic microzonation values were computed for the entire Emilia-Romagna plain.

Key words: seismic hazard, site effects, Po Plain alluvial succession, environmental noise (or ambient vibrations), V_S profile, seismic zonation.

1. Introduction

It is well established that local geomorphological conditions can significantly modify the amplitude, frequency, and duration of seismic ground motion (Bard, 1999; Fehr *et al*., 2019; Sudhir Bikram *et al*., 2025). In particular, the seismic response at the surface is influenced by the presence and thickness of soft soils (loose or poorly consolidated sediments, such as recent alluvial deposits and slope debris), by sharp lateral and vertical variations in the depth of stiff bodies that can be assimilated to the seismic bedrock, and by specific landforms such as ridges, peaks, and steep scarps of significant height (at least 30 m). Therefore, for effective seismic risk prevention and mitigation policies, it is essential to identify where such conditions occur and to assess the extent to which amplification phenomena (site effects) may develop.

A reliable assessment of seismic ground motion at the surface, thus, requires a detailed characterisation of local stratigraphic, lithological, and morphological conditions. In particular, it is crucial to determine the depth of the rigid substrate, as well as the shear-wave velocity (V_S) profile within the overlying unconsolidated sediments.

The identification of the rigid substrate, or seismic bedrock, i.e. stiff ground characterised by a V_S at least twice that of the overlying soft sediments, may be challenging in the presence of thick

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sedimentary covers (e.g. thickness H > 50 m), especially considering that available resources typically enable the application of standard geophysical techniques (e.g. Multichannel Analysis of Surface Waves, Refraction Microtremor), which rarely enable subsurface investigations beyond depths of approximately 50 m.

Furthermore, for territorial zoning purposes, it is necessary to account for the spatial variability of the aforementioned geological and geomorphological features.

This paper presents a procedure for the development of a regional-scale site-specific seismic hazard map and illustrates the results of its application to the Emilia-Romagna sector of the Po Plain (northern Italy), an area characterised by numerous densely populated urban centres, significant cultural and historical heritage, and major productive activities, and which has been affected by frequent earthquakes, some of which have reached considerable magnitudes (M_w > 5.5).

2. Geological framework

The Po Plain is the largest alluvial plain in Italy, built by the depositional activity of the Po River and its tributaries. It represents the Quaternary foredeep located between opposing fold-and-thrust belts: the south-verging Southern Alps, which bound it to the north and west, and the north-verging northern Apennines, which bound it to the south. Toward the NE, the Po Plain transitions into the Veneto plain, while to the SE it is bordered by the Adriatic Sea (Fig. 1a). The Emilia-Romagna plain corresponds to the central-eastern sector south of the Po River.

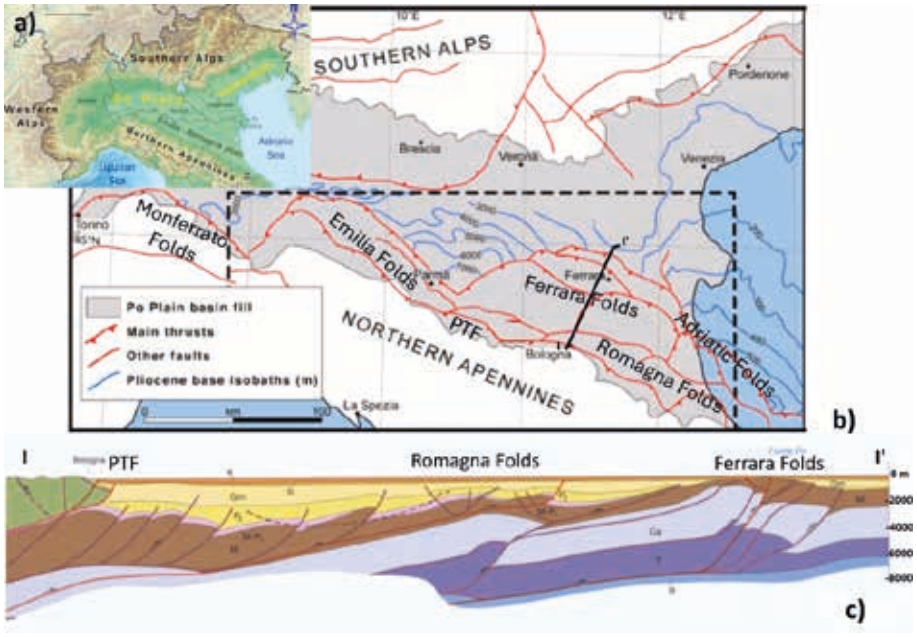


Fig. 1 - a) Geographical-physical sketch of northern Italy, showing the location of the Emilia-Romagna plain. b) Tectonic sketch of the Po Plain, showing the main buried thrust systems and fold arcs, as well as the Pedeapenninic Thrust Front; the location of the geological cross-section I–I' is also indicated (modified from Carloni *et al*., 2025). c) Geological cross-section between Bologna and the Po River, illustrating the buried fold-and-thrust architecture. It shows the main stratigraphic units: (modified from Boccaletti *et al*. 2004, 2011). Quaternary deposits (Qm), Upper Pliocene deposits (P2), Messinian–Lower Pliocene deposits (M–P1), Miocene deposits (M), the Meso-Cenozoic carbonate succession (Ca), Triassic evaporites (T), and the metamorphic basement (B).

The fronts of the Alpine and Apennine chains do not coincide with the morphological transition between hills and plains; rather, they consist of arcuate systems of buried thrusts that propagate for tens of kilometres beneath the plain. As a result, the Po Plain subsurface is structured into antiforms and synforms, which strongly control the thickness of the alluvial sediments.

Specifically, the front of the northern Apennines, which extends beneath the Emilia-Romagna subsurface as far as the Po River and beyond, is represented by the arc of the Emilia folds in the western sector and by the arc of the Ferrara folds in the central and eastern sectors (Pieri and Groppi, 1981) (Fig. 1b).

The Apennines and the Alps are still actively evolving mountain chains, as evidenced by the frequent seismic activity recorded along their fronts (e.g. Boccaletti *et al.*, 2011).

Tectonic activity has also strongly influenced the sedimentation of recent geological units. Within synforms, the thickness of Plio-Quaternary deposits exceeds 7,000 m, whereas it decreases to only a few hundred metres at the crests of anticlines (Fig. 2b). Moreover, alluvial stratigraphic units (Middle Pleistocene–Holocene) are bounded by discontinuity surfaces which, along the basin margins and in structurally elevated areas, are marked by pronounced angular unconformities (Fig. 2).

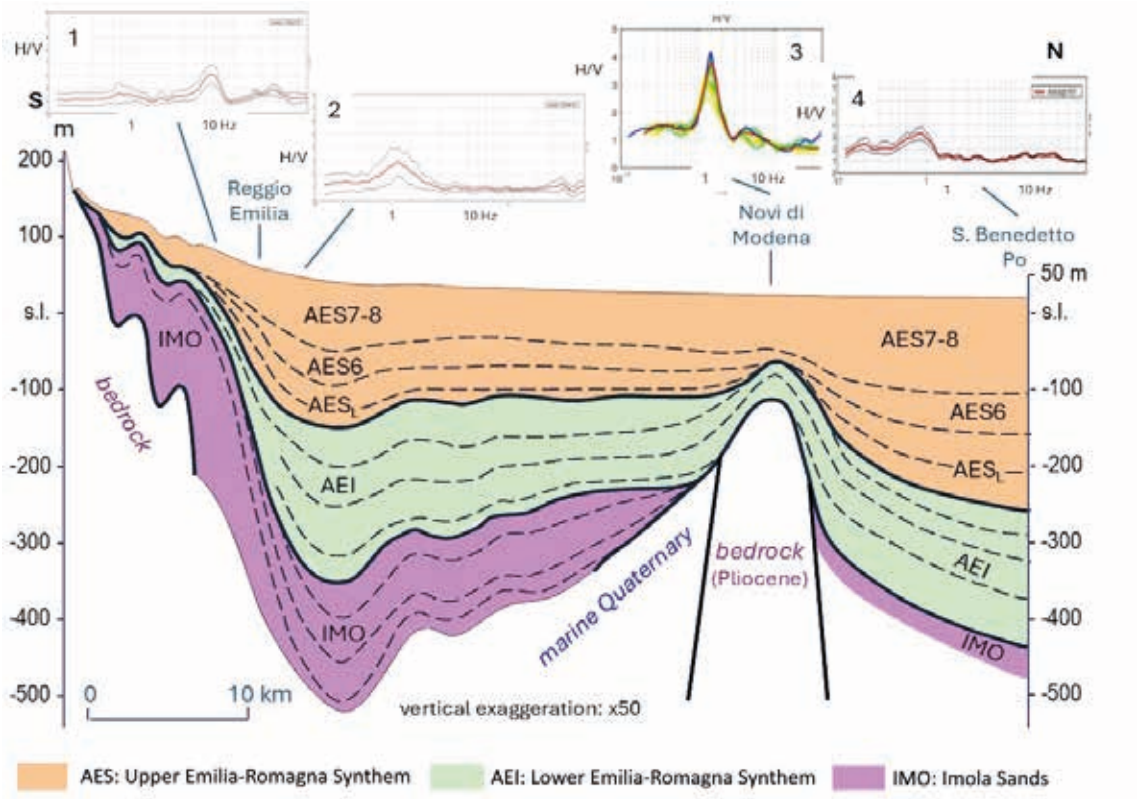


Fig. 2 - Geological cross-section across the Emilia plain, between the Apennine-Po Plain margin, south of Reggio-Emilia, and the Po River (modified from Di Dio, 1998). Dashed lines indicate the main stratigraphic horizons (subsynthems). The locations of the selected horizontal-to-vertical (*H/V*) spectral ratio of the noise measurements are reported above the section (1–4), highlighting the main resonance peaks observed at different sites along the transect, including Reggio Emilia, Novi di Modena, and San Benedetto Po. Panels 1 and 2 are taken from Castagnetti (2013), 3 from Martelli (2021), 4 from Paolucci *et al*. (2013).

The Emilia-Romagna alluvial succession consists of two main stratigraphic units (Fig. 2): the Lower Emilia-Romagna Synthem (AEI, 0.8–0.4 Ma) and the Upper Emilia-Romagna Synthem (AES, 0.4 Ma–Present), both bounded at their base by unconformity surfaces (Di Dio, 1998; Amorosi *et al*., 2026). Both synthems are further subdivided into subunits (subsynthems) composed of alternating coarse-grained sediments (sands and gravels) and fine-grained sediments (clays and silts), also separated by discontinuity surfaces.

In the Emilia-Romagna sector, coarse-grained sediments are mainly confined to the foothill areas, whereas in distal settings, both in synclinal and anticlinal zones, the successions are predominantly composed of fine-grained deposits (clays and silts), with intercalated sandy horizons. The shallowest sediments, of Holocene age, are generally loose or poorly compacted, while the degree of compaction of the underlying deposits increases with depth. However, the alluvial sediments of the Emilia-Romagna plain, even at greater depths, are overall weakly consolidated and compacted and are, therefore, also prone to subsidence.

The substratum of the continental succession consists of transitional sandy deposits (from alluvial plain to beach and lagoon environments) of Middle Pleistocene age (Imola Sands, Yellow Sands, Costamezzana Synthem *Auct.*, IMO in Fig. 2), and of alternations of clays, marls, and sandstones deposited in plain to shelf environments, of Pliocene–Early Pleistocene age, referable to as the Argille Azzurre Formation (Cremonini and Ricci Lucchi, 1982), which widely crops out in the Apennines hills.

3. Methodology

In alluvial plains, the topographic component of amplification, associated with reliefs of at least 30 m in height, can generally be considered negligible. Therefore, in order to produce a regional-scale hazard map of the Emilia-Romagna plain, the focus must be placed on the stratigraphic characteristics of the subsurface. A rapid and effective method for identifying the main stiffness discontinuities in the subsurface is the measurement and analysis of ambient vibrations. It is well known that the processing of ambient noise recordings using the Nakamura (1989) method enables the identification of the main impedance contrasts within recent sedimentary successions (Ibs-von Seht and Wohlenberg, 1999):

$$f_n = \frac{\overline{V}_S}{4H} \tag{1}$$

where f_n is the fundamental frequency of the soil, $\overline{V}_S$ is the average shear-wave velocity above the depth, H, of the resonant interface, and H is the depth of the resonant interface.

Several studies (Paolucci *et al*., 2015; Tarabusi and Caputo, 2016; Mascandola *et al*., 2019; Martelli, 2021) have demonstrated a good correlation between impedance contrasts detected through ambient noise measurements and the main lithological and stratigraphic discontinuities of the Po Plain subsurface. The horizontal-to-vertical (*H/V*) spectral ratio, obtained from measurements of ambient noise, is the ratio between the amplitude of the geometric mean of the two orthogonal horizontal components and the vertical component of the recorded ground motion. The *H/V* ratio is used to identify frequency-dependent amplification effects associated with subsurface impedance contrasts. Peaks in the *H/V* curve indicate frequencies at which the horizontal ground motion is preferentially amplified relative to the vertical component and may, therefore, be associated with resonance phenomena caused by significant contrasts in seismic

impedance between overlying and underlying geological units. Although the *H/V* peak does not provide a direct measurement of the impedance contrast, its dominant frequency can be related to the depth and seismic properties of the corresponding subsurface interface, particularly where the geological and geophysical setting is well constrained. In the Po Plain, this approach has proved effective in identifying major stratigraphic discontinuities and correlating their depth with independent geological and geophysical information. In particular, within synforms and depocenters, low-frequency *H/V* peaks (f_n < 0.5 Hz), generally of modest amplitude (*H/V* ≤ 2), are associated with the basal unconformity of the continental succession, while peaks in the 0.6–1 Hz frequency range, with higher amplitudes (2 < *H/V* ≤ 3), can be correlated with minor internal unconformities (see *H/V* curves no. 2 and no. 4 in Fig. 2).At the top of the buried (or blind) structural highs, a single *H/V* peak of high amplitude (*H/V* ≥ 4) is typically observed at frequencies between 0.7 and 1.2 Hz, which can be associated with the top of the seismic bedrock (see *H/V* curve no. 3 in Fig. 2). The occurrence of a single, high-amplitude peak in these areas can be explained by the shallow depth of the rigid substrate (sometimes less than 100 m) and by the limited thickness separating the bedrock top from the main discontinuities within the continental succession (Paolucci *et al*., 2015). These observations are supported by the availability of numerous seismic microzonation studies (RER, n.d.). In contrast, microzonation studies carried out in foothill areas highlight *H/V* peaks at higher frequencies (2 < f_n < 20 Hz; see *H/V* curve no. 1 in Fig. 2), generally with high amplitudes (*H/V* ≥ 3), which can be related to the top of coarse-grained Pleistocene deposits, typically located at depths shallower than 30 m and in some cases subcropping (Martelli, 2021).

For regional-scale mapping, it is also necessary to account for the spatial distribution and variability of stratigraphic features. The continental succession of the Emilia-Romagna plain was first described and synthesised at the regional scale in a study conducted by the Emilia-Romagna Region and ENI–Agip (Di Dio, 1998), in which the basal surfaces of the AEI and AES synthems were mapped. The base of the AES synthem (0.4 Ma) was subsequently updated by Boccaletti *et al*. (2004, 2011) and Martelli *et al*. (2017a), while the base of the AEI synthem (0.8 Ma) is also reported in Martelli (2021). Martelli *et al*. (2017a) additionally provide the basal unconformity of the AES6 subsynthem (0.25 Ma) (Fig. 3).

For the mapping of the main coarse-grained alluvial fan bodies along the foothill belt, the primary references are the subsurface maps accompanying the plain sheets of the geological map of Italy and studies of the main alluvial fan systems carried out by the Regional Geological Survey (Servizio Geologico d'Italia, n.d.). An initial regional-scale synthesis of the distribution of alluvial fan deposits is provided in the geological map of the Emilia-Romagna plain (RER, 1999). Over the past twenty years, numerous municipal-scale seismic microzonation studies (RER, n.d.) and other local seismic response investigations (e.g. Pergalani *et al*., 2013) have contributed to updating and refining the knowledge of the subsurface in the foothill belt.

The foothill belt can be subdivided into two sectors, running parallel to the Apennine–Po Plain margin: a narrow piedmont zone, adjacent to the hilly reliefs and corresponding to the outlets of the main Apennine valleys, characterised by thick, sometimes amalgamated gravel bodies, with tops that are either outcropping/subcropping or generally less than 30 m below the ground surface; and an upper plain zone, where coarse-grained bodies are thinner, interbedded with finer horizons (silts and sands), and with tops generally deeper than 30 m. Fig. 4 presents a cartographic synthesis of the information described above. It is worth noting that the depths of all three surfaces (Figs. 3 and 4) decrease in correspondence with the buried structural arches of the Ferrara and Emilia folds, indicating that these structures remained active at least until the late Middle Pleistocene.

For seismic microzonation studies, numerous borehole geophysical tests have also been

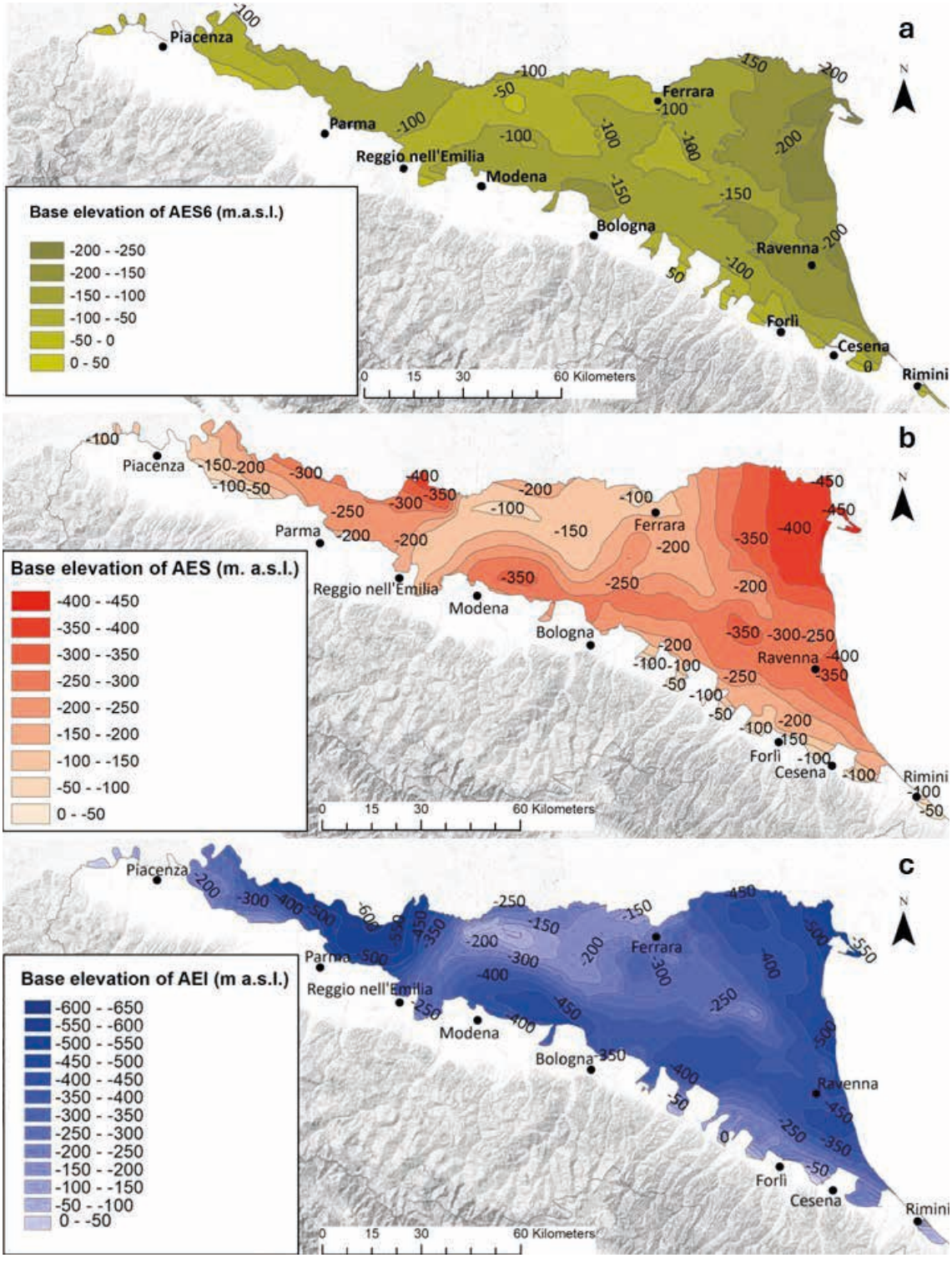


Fig. 3 - Bases of: a) the AES6 subsynthem (Martelli *et al.*, 2017a); b) the AES synthem (from Martelli *et al.*, 2017a); c) the AEI synthem (Martelli, 2021).

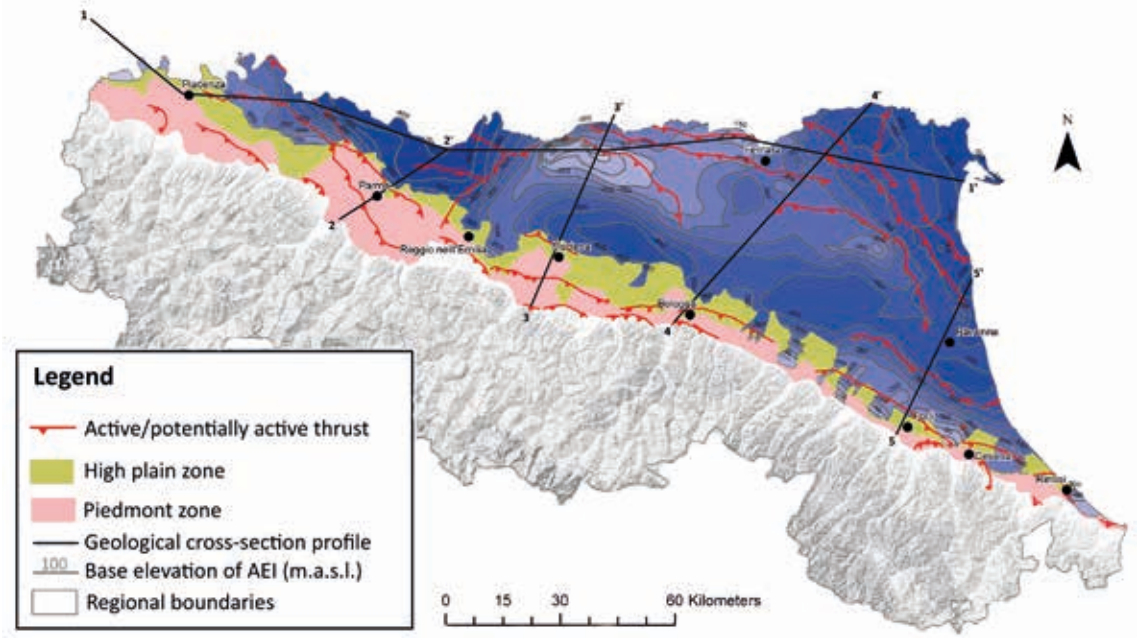


Fig. 4 - Depths (in metres) of the base of the AEI synthem are shown in blue; the main buried active thrusts are shown in red. The piedmont zone and the upper plain zone are also indicated. Black lines represent the traces of the cross-sections in Fig. 5.

performed, including down-hole and cross-hole measurements, some of which reached depths greater than 150 m, as well as ambient noise array recordings that have provided information on V_S down to several hundred metres (Martelli, 2021). In some cases, particularly in areas where the continental succession is thinner, these measurements have allowed the characterisation of V_S within the underlying substrate.

In general, these data indicate that in foothill areas the strongest V_S contrast occurs at the top of Pleistocene alluvial fan gravels, whereas the underlying Plio-Pleistocene marine substratum does not show significant increases in V_S compared to the overlying gravelly succession (see also Pergalani *et al*., 2013). In the plain sectors, significant V_S contrasts are observed at the top of the marine substratum, while only minor increases in V_S are detected at the unconformities within the continental succession (see also Paolucci *et al*., 2015; Garofalo *et al*., 2016; Minarelli *et al*., 2016; Petronio *et al*., 2023; Di Giulio *et al*., 2024; Caputo *et al*., 2025; Gaudiosi *et al*., 2026).

In the Po Delta area and along the Ravenna and Ferrara coasts, no marked V_S contrasts have been identified, and the increase in V_S with depth is generally gradual.

4. The geological zonation of Emilia-Romagna plain in seismic perspective

4.1. Data presentation and discussion

The availability of the large amount of data and information described in the previous chapter has enabled a widespread comparison between stratigraphic and geophysical data across the Emilia-Romagna plain.

Fig. 5 presents five cross-sections through the Emilia-Romagna plain illustrating the geometry

of the main units and stratigraphic surfaces of the continental succession. Based on the currently available knowledge, these stratigraphic elements appear to be those that most strongly influence V_S and, consequently, the local seismic response.

Ambient noise recordings, mostly acquired during seismic microzonation studies, are projected onto the cross-sections. A variability of *H/V* peaks is observed in distribution and amplitude. These variations are related to differences in the thickness of the continental units and to the depth of the main discontinuties. This interpretation is in agreement with previous studies by several other authors (e.g. Paolucci *et al*., 2015; Tarabusi and Caputo, 2016; Mascandola *et al*., 2019; Martelli, 2021) and as summarised in chapters 2 and 3 (Fig. 2).

In sectors close to the reliefs, ambient noise measurements show *H/V* peaks at frequencies higher than 2 Hz (e.g. west of Piacenza in Cross-section 1, Collecchio–Parma in Section 2, Fiorano M.–Modena in Section 3, Bologna in Section 4, south of Forlì in Section 5). Further downstream, *H/V* peaks are observed at frequencies below 2 Hz (e.g. east of Piacenza in Section 1, north of Parma in Section 2, between Bologna and Castel Maggiore in Section 4, and north of Forlì in Section 5).

In the piedmont areas, ambient noise measurements are, thus, primarily influenced by the presence of shallow, rigid bodies, namely, coarse-grained alluvial fan deposits whose tops gradually deepen towards the plain but generally remain within a few tens of metres. In areas near the margin, no additional V_S discontinuities are detected beyond those corresponding to the tops of the coarse-grained bodies, likely due to the substantial thickness of these often-amalgamated bodies and because the marine substrate, composed of Plio-Pleistocene marls and sands, is not very deep and has V_S values similar to, or only slightly higher than, those of the continental succession.

In the plain areas, where coarse-grained deposits are no longer present and the continental succession consists of alternating sands, silts, and clays, ambient noise measurements show *H/V* peaks mostly at frequencies below 1–1.2 Hz, indicative of discontinuities at depths of at least several tens of metres.

In the blind structural high zones (e.g. Mirandola and Casaglia in Section 1, Mirandola in Section 3), where the geological substrate lies between 100 and 150 m depths, a single *H/V* peak is observed at frequencies between 0.7 and 1.2 Hz, generally with high amplitude ($H/V \geq 4$).

In other plain areas, i.e. depocentral areas (synforms) and along fold flanks, where the substrate lies at depths greater than 150 m, the *H/V* curves typically show multiple peaks: one at frequencies between 0.6 and 1 Hz, with amplitudes between 2 and 3, and another at frequencies below 0.5 Hz, usually of lower amplitude (e.g. Boretto and Copparo in Section 1; Sorbolo and Boretto in Section 2; Soliera, Cavezzo, and the area between Mirandola and Poggio Rusco in Section 3; between Minerbio and Voghiera in Section 4; between Gambellara and Ravenna in Section 5).

It is worth noting that in areas where the substrate lies deeper than 350–400 m, the *H/V* peak amplitudes are generally modest ($1.5 < H/V \leq 2$; e.g. Boretto in Section 1, Sorbolo and Boretto in Section 2, Soliera in Section 3, Minerbio in Section 4, between Gambellara and Ravenna in Section 5). Among the deep-substrate areas, a special case is represented by the northern coastal area and the Po Delta (between Codigoro and Lido di Volano in Section 1, and Casal Borsetti in Section 5), where ambient noise curves are practically flat or show only minor peaks ($1.5 < H/V \leq 2$).

A large selection of geological cross-sections across the Emilia-Romagna plain is available on the website of the Geological Survey of the Emilia-Romagna Region (RER Geologia, Suoli e Sismica, n.d.).

Seismic microzonation studies confirm the observations and considerations described above. In particular, local seismic responses vary from one area to another, primarily depending on the

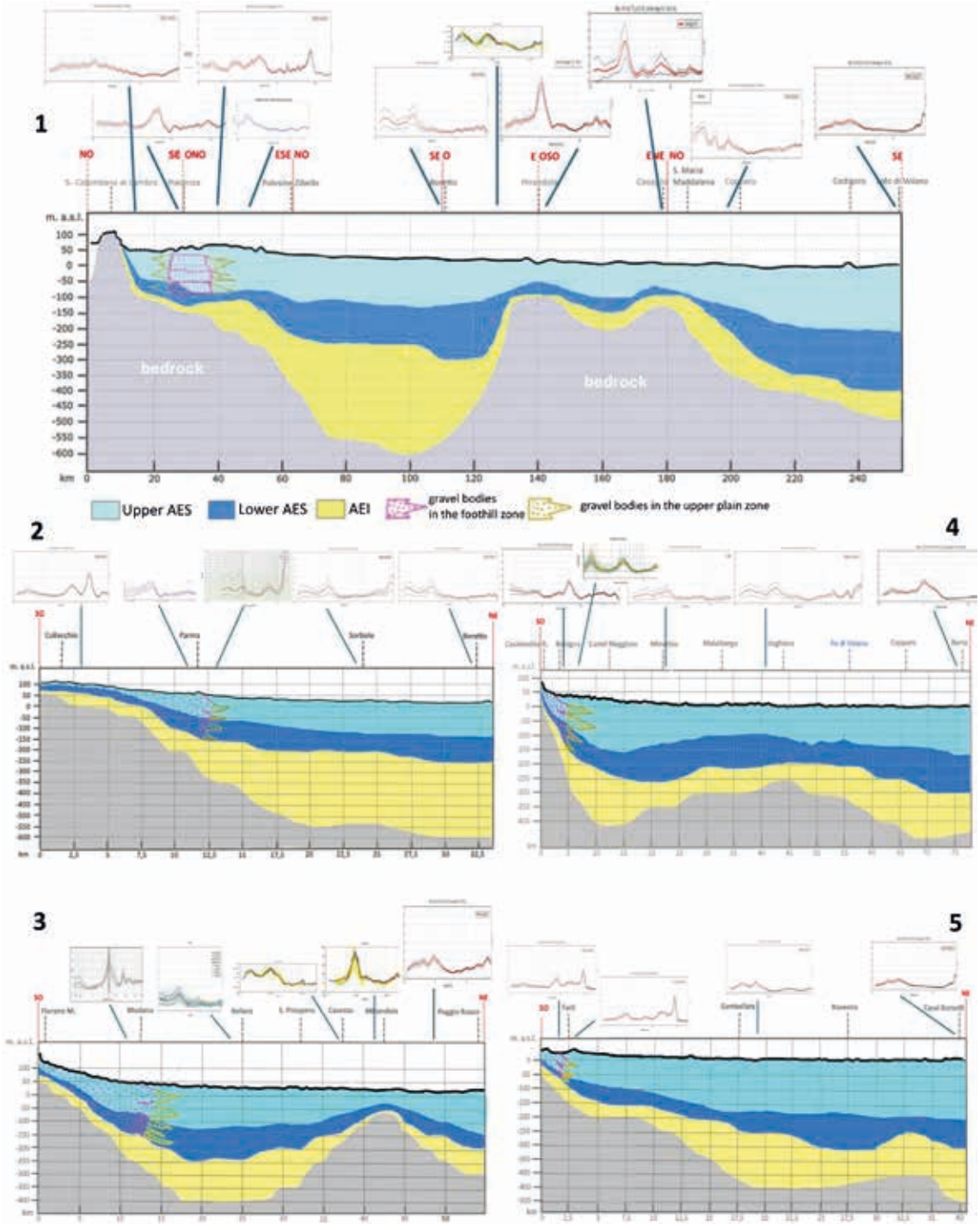


Fig. 5 - E–W (Section 1) and NE–SW (sections 2, 3, 4, and 5) geological cross-sections showing the subsurface trends of the AEI and AES synthems, with their traces indicated in Fig. 5.

depth of the stiffest geological unit; i.e. the unit characterised by an average V_S at least twice that of the overlying succession ($V_{Slower}/V_{Supper} > 2$).

Fig. 6 shows the mean input and output spectra from seismic response analyses (T_R = 475 years, ζ = 5%) conducted at sites considered representative of the different geological contexts of the plain described above. Each graph indicates the estimated acceleration amplification factors[1] (*AF*s) at period T = 0 s, i.e. for peak ground acceleration (*PGA*, i.e. AF_{PGA}), low periods (average value in the interval 0.1 s ≤ T ≤ 0.5 s, AF_{0105}), medium periods (average value in the interval 0.5 s ≤ T ≤ 1 s, AF_{0510}) and high periods (average value in the interval 1 s ≤ T ≤ 1.5 s, AF_{1015}).

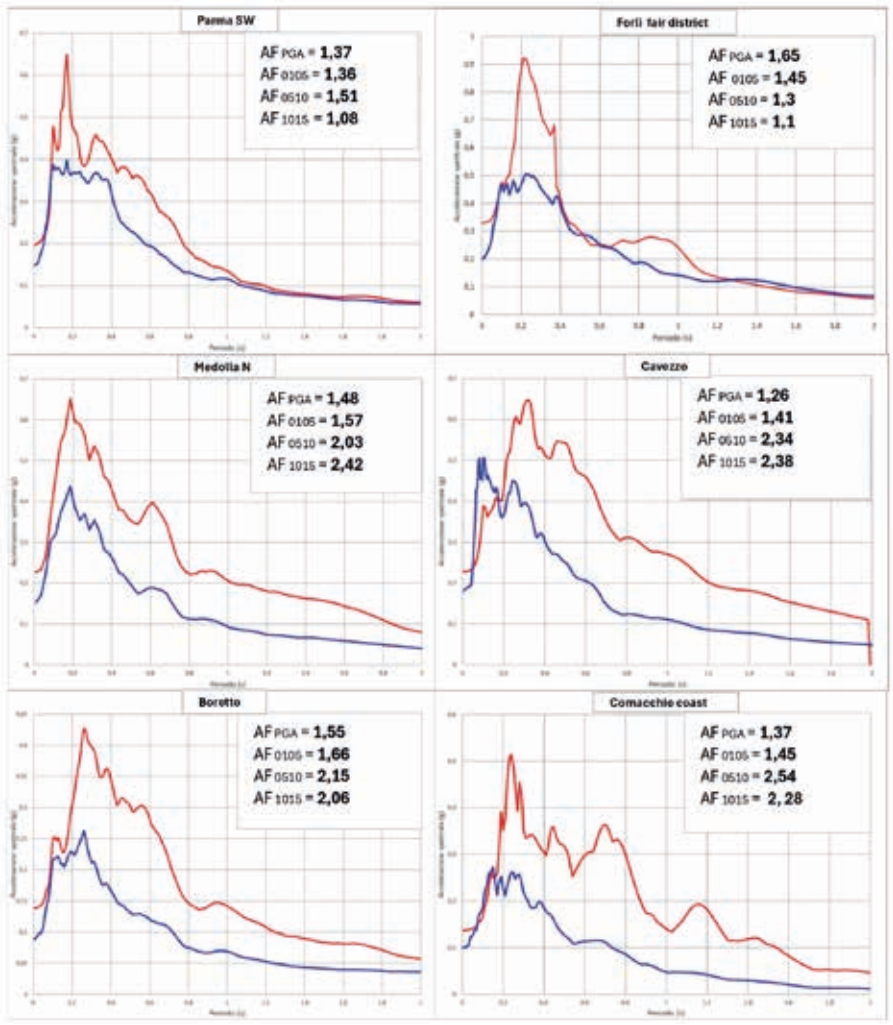


Fig. 6 - Mean input spectra (in blue) and output spectra (in red) for each representative site, derived from local seismic response analyses of the seismic microzonation studies. In the table next to each graph, factors AF_{PGA}, AF_{0105}, AF_{0510}, and AF_{1015} are summarised.

[1] The AF is defined as: $AF = \frac{\int_{T_1}^{T_2} S_a \cdot dT}{\int_{T_1}^{T_2} S_b \cdot dT}$ where S_a is the acceleration elastic response spectrum at the study site (usually at the surface), S_b is the acceleration elastic response spectrum at the reference site (near site where the bedrock, i.e. type A ground, outcrops); T_1 and T_2 represent the extremes of the evaluated interval of T periods.

4.2. Seismic zonation

Based on the considerations described above, the Emilia-Romagna plain was, therefore, subdivided, according to the depth of the top of the stiffest geological unit, into the following six zones (Fig. 7):

- piedmont zone (or foothill zone): characterised by a succession dominated by coarse alluvial fan deposits, whose top is generally at a depth of less than 30 m. The coarse deposits exhibit a markedly stiffer behaviour than the overlying succession, while the marine substrate of the continental succession, consisting of generally fine Plio-Pleistocene marine deposits (marls and sands), does not show a significant increase in stiffness. Therefore, the top of the coarse deposits constitutes the main V_S discontinuity in this zone;
- high plain zone: characterised by a succession of alternating coarse alluvial fan deposits and finer sediments (clays, silts, and sands); the top of the coarse deposits is generally at a depth of at least 30 m. In this zone as well, the top of the coarse deposits represents the main V_S discontinuity. However, other minor deeper discontinuities, such as the internal unconformities and the basal unconformity of the continental succession, are also present;
- buried structural high zone: characterised by the top of the marine substrate at depths between approximately 80–100 m and 150 m. The rigid substrate is provided by the marine deposits, and only modest V_S increases are observed at the main unconformities of the continental succession;
- ridge flank zone: characterised by the top of the marine substrate at depths between 150 m and 350–400 m. The rigid substrate is provided by the marine deposits, with modest V_S increases occurring at the main unconformities of the AES synthem;
- synform (or depocentral) zone: characterised by a marine substrate at depths of at least 400 m. The rigid substrate is provided by the marine deposits, with modest V_S increases also observed at the main unconformities of the AES synthem;
- Po Delta and Ravenna–Ferrara coastal zone: characterised by a marine substrate at depths of at least 400 m and the absence of V_S contrasts within the continental succession. V_S gradually increases with depth, and the rigid substrate is tentatively considered coincident with the marine deposits.

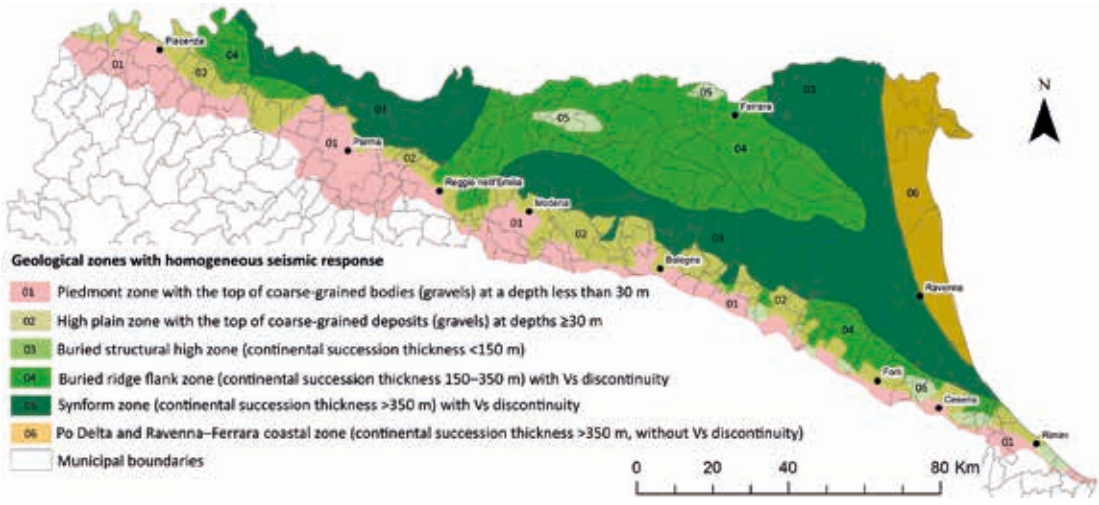


Fig. 7 - Map of the geological zones in seismic perspective of the Emilia-Romagna plain.

4.3. Mean AF *calculation*

Amplification values for specific period ranges (*PGA*, 0.1 s ≤ *T* ≤ 0.5 s, 0.5 s ≤ *T* ≤ 1 s, and 1 s ≤ *T* ≤ 1.5 s) were, then, assigned to each geological zone. These values correspond to the averages of *AF*s derived from the most detailed local seismic responses taken from seismic microzonation studies of the municipalities located within the geological zones shown in Fig. 7.

For the piedmont and high plain zones (zones 1 and 2), the most recent studies of Parma, Fiorano Modenese, S. Cesario sul Panaro, Faenza, Forlì, Rimini, Cattolica, and the Unione della Val d'Enza (S. Polo d'Enza, Bibbiano, Cavriago, Montecchio E.) were considered. For the buried structural high zone (zone 3), the studies of Mirandola (southern sector), Medolla, Bondeno, and Ferrara (western sector) were used as reference. For the buried ridge flank zones (zone 4), the studies of Bellaria, Cesenatico, S. Felice sul Panaro, Finale Emilia, Cavezzo, and Cento were considered. For the synform (depocentral) zones (zone 5), the most representative studies are those of the municipalities of the Unione Bassa Romagna (Alfonsine, Bagnacavallo, Bagnara di Romagna, Conselice, Cotignola, Fusignano, Lugo, Massa Lombarda, and Sant'Agata sul Santerno) and the Unione Bassa Reggiana (Poviglio, Brescello, Boretto, Gualtieri, Guastalla, and Luzzara).

Finally, for the Po Delta and Ravenna–Ferrara coastal zone (zone 6), the studies of Comacchio, Goro, Mesola, Lagosanto, and Codigoro were used. All these studies are available on the Emilia-Romagna Region website (RER, n.d.).

In these studies, seismic responses analyses were performed under one-dimensional conditions; the nonlinearity of the dynamic properties of the soils was considered using a linear equivalent numerical model. Regarding the dynamic characterisation of the soils, in order to obtain decay curves of shear modulus (G/G_0) and damping (D%) representative for the area, curves derived from laboratory experimental analyses, conducted on local soil samples, for depths up to 50–70 m, were used. For greater depths, curves from literature, depending on the different soil types, were used (Seed and Idriss, 1970; Seed *et al*., 1986; Sun *et al*., 1988; Idriss, 1990; Vucetic and Dobry, 1991; EPRI, 1993; Darendeli, 2001). As already described, the V_S profiles applied for the seismic response analyses were reconstructed based on direct geophysical investigations (down-hole and cross-hole type) up to a depth of 150 m and seismic lines and arrays for ambient noise measurements (Extended Spatial Autocorrelation/Spatial Autocorrelation) up to the marine substratum. The largest V_S contrasts have been detected at the top of the coarse Pleistocene deposits in the marginal areas and at the top of the marine substratum in the plain areas; therefore, the Pleistocene gravels have been considered as the seismic bedrock in the marginal areas and the marine substratum has been considered as the seismic bedrock in the plain. Minor V_S discontinuities have been associated with the main stratigraphic unconformities in the continental succession. It was, thus, possible to produce the regional maps of *AF*s shown in Fig. 8.

We also took into account variations in amplification within the same geological macrozone, reporting the range of variability (i.e. the maximum and minimum amplification values calculated in the studies conducted for the various municipalities falling within the macrozone).

In the piedmont areas (e.g. SW Parma, Fig. 6), where the soft soil/rigid substrate interface is shallow (H < 30 m), medium-low *AF*s are expected at short periods (AF = 1.4±0.2 for T < 0.5 s), while at longer periods (T > 0.5 s) they decrease slightly, averaging around 1.3 ± 0.2 up to 1 for T > 1 s.

In the high plain areas, where the soft/rigid interface lies at depths between 30 and 50–60 m (e.g. the Forlì fair district) and the geological substrate, although rapidly deepening, is less than

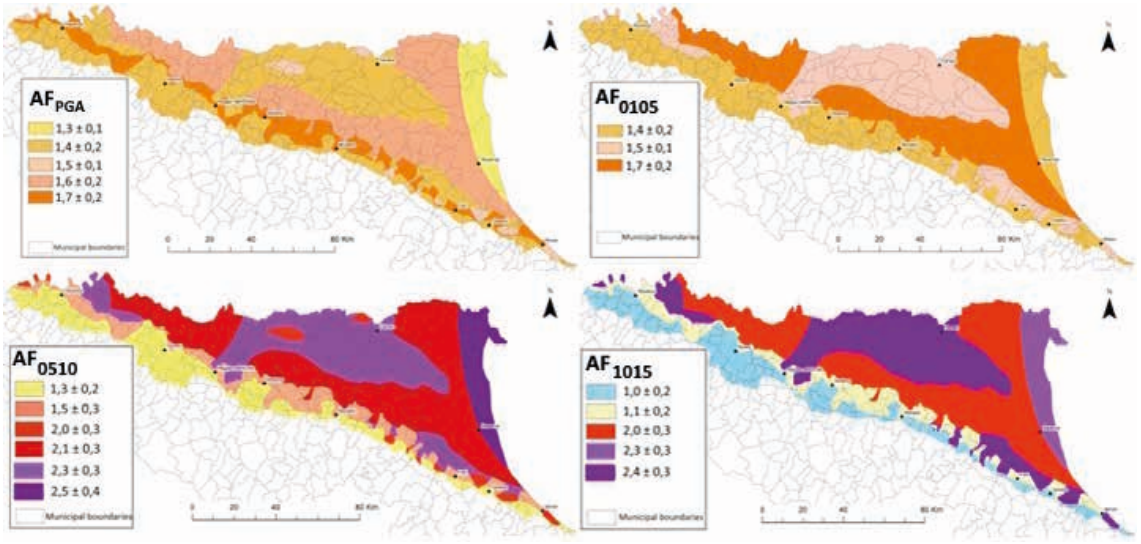


Fig. 8 - Maps of the AF_{PGA}, AF_{0105}, AF_{0510}, and AF_{1015}, obtained by selecting representative values for each zone from the results of third-level municipal SM analyses.

350 m deep, expected *AF*s are medium for short periods (1.4±0.2 for $T \leq 0.5$ s) and medium–high (*AF* = 1.5±0.3) for $0.5 < T \leq 1$ s. For $T > 1$ s they decrease significantly up to 1.1±0,2.

At the top of buried structural highs (e.g. northern Medolla), where the rigid substrate is shallower than 150 m, the largest *AF*s are expected at medium and long periods (*AF* > 2 for $T > 0.5$ s), while medium *AF*s occur at short periods (*AF* = 1.5±0.2 for $T \leq 0.5$ s).

Even in plain areas, where the rigid substrate lies at depths of 150–350/400 m (e.g. Cavezzo), with minor V_S discontinuities in the overlying succession, medium *AF*s are expected at short periods (*AF* =1.5±0.1 for $T \leq 0.5$ s), while very high *AF*s are expected at long periods (*AF* ≥ 2.3 for $T > 0.5$ s).

In plain areas where the rigid substrate is deeper than 350–400 m (e.g. Boretto) and minor V_S discontinuities are still present in the overlying succession, medium–high *AF*s are expected at short periods (*AF* = 1.7±0.2 for $T \leq 0.5$ s) and high *AF*s at long periods (*AF* > 2 for $T > 0.5$ s).

In the Po Delta and along the Ravenna-Ferrara coast, where the rigid substrate lies deeper than 350–400 m and no V_S discontinuities are present in the overlying succession (e.g. Comacchio), low *AF*s are expected at short periods (*AF* ≤ 1.4±0.2 for $T \leq 0.5$ s), while high *AF*s are expected at long periods (*AF* > 2.3 for $T > 0.5$ s).

4.4. PGA - H_{SM} *calculation and comparison of seismic hazard models*

The *AF*s, however, do not provide absolute seismic hazard values (e.g. site-specific ground acceleration) and do not enable a direct comparison, or a real ranking, of seismic hazard between different areas. According to technical standards, among which EC8 (European Committee for Standardization, 2004), NTC08 (MI, 2008), and NTC18 (MIT, 2018), the parameter for local seismic hazard is *PGA* at the site, PGA_{site} [a_{max} in the Italian technical standards (MI, 2008; MIT, 2018)], calculated as:

$$PGA_{site} = PGA_0 \times AF_{PGA} \quad (2)$$

where PGA_0 represents the basic seismic hazard, i.e. the expected acceleration on stiff, flat ground (soil Type A), and AF_{PGA} is the local amplification coefficient for T = 0 s. In the plain areas, since the topographic component of amplification is negligible, *AF* is given solely by stratigraphic amplification. To facilitate estimates of local seismic hazard in Italy, a reference map of the basic seismic hazard for the national territory [MPS04; INGV (2006)] has been produced using a grid of points spaced at 0.05° [INGV, 2006; see chapter C3.2 in MIT (2019)].For each grid point, the PGA_0 value, expressed as a percentage of gravitational acceleration "g", has been calculated and made available (Fig. 10a).

Thus, by combining the average amplification factor AF_{PGA} for each macrozone (Fig. 8a) with the PGA_0 grid (Fig. 9a), it was possible to calculate the site-specific seismic hazard [PGA_{site} in Eq. (2)] at every MPS04 grid point (Fig. 9b) (return period T_R = 475 years, i.e. 10% probability of exceedance in 50 years).

PGA calculation for the Emilia-Romagna plain was carried out also considering models developed after the MPS04 map, as the model proposed by Martelli *et al*. (2017b), for the northern Apennines and surrounding areas, and the MPS19 model (INGV, 2023; data available for download from the website https://zenodo.org/records/7032251) (Fig. 10). In particular, the seismic hazard model proposed for the Emilia-Romagna plain (Martelli *et al*., 2017b) was developed using both horizontal and inclined seismogenic sources (ER 2D in Fig. 10b and ER 3D in Fig. 10c, respectively). It should be remembered that both MPS04 and MPS19 models were developed considering horizontal seismogenic sources. The same calculation methodology was applied to all models.

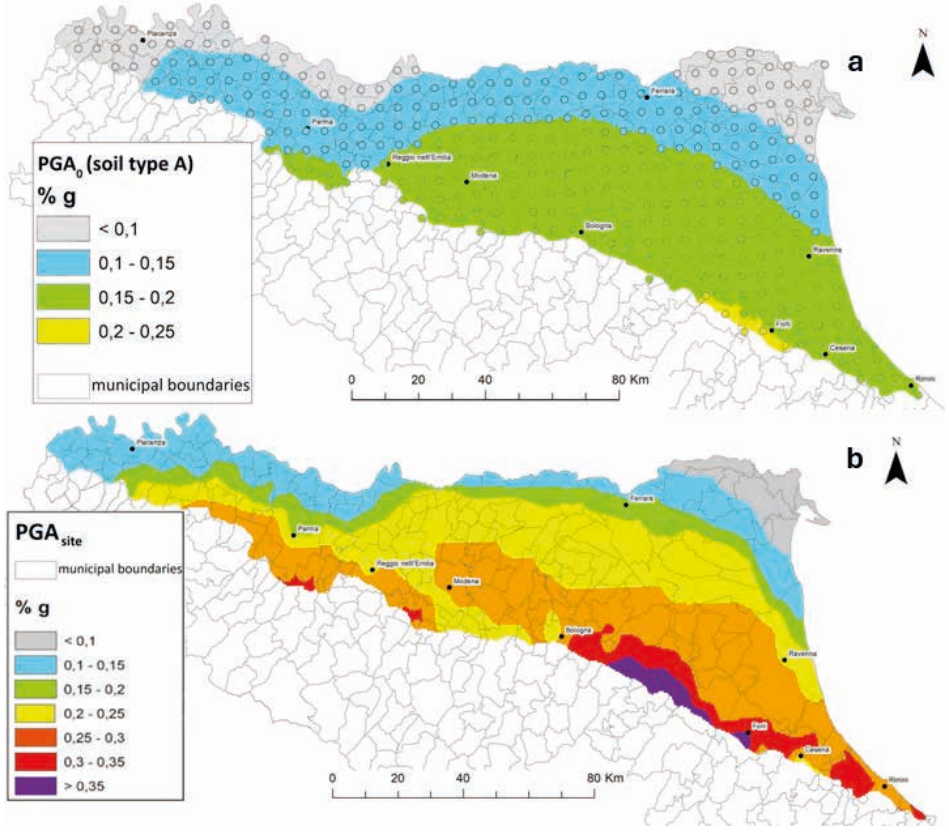


Fig. 9 - *PGA* maps for the Emilia-Romagna plain: a) on the reference ground (INGV, 2006), b) at the surface.

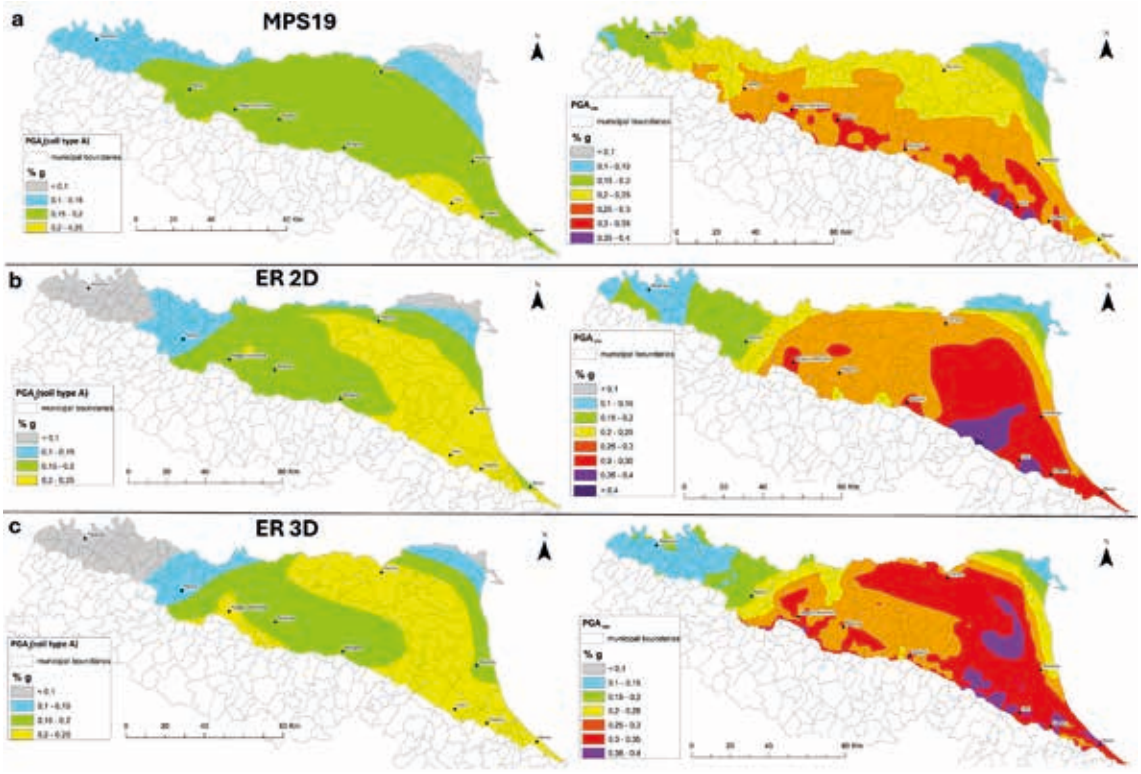


Fig. 10 - Site *PGA* maps for the Emilia-Romagna plain according to the MPS19 model (a) and to the Martelli *et al*. (2017b) model, horizontal seismogenic sources (b) and inclined seismogenic sources (c). For each model, the corresponding map of the reference ground acceleration on Type A soil is reported on the left.

It is worth noting that, compared with the results obtained from the MPS04 model, the maximum accelerations predicted by the other three models are slightly higher, reaching values above 0.4 g in the case of the ER 2D model, particularly in the foothill area of Romagna (Fig. 10b). The MPS19 model (Fig. 10a) is broadly consistent with the MPS04 model, although it yields higher acceleration values also in the northern Po Plain, while maintaining values below 0.15 g in the Piacenza area and the Po Delta. In contrast, the models developed by Martelli *et al*. (2017b) show acceleration values exceeding 0.25 g as far as the Ferrara plain and the border with the Veneto plain. In particular, the ER 3D model (Fig. 10c) more clearly highlights the correlation between seismic hazard and tectonic structures, such as buried arcs. In the western sector of the Po Plain and in correspondence of the Po Delta, these models also show a marked decrease in seismic hazard.

However, for earthquake prevention and seismic risk assessment, it is far more useful to evaluate the effects of a quake at frequencies close to those of the built environment. Therefore, Naso *et al*. (2016) and Mori *et al*. (2019), drawing on the acceleration spectrum intensity (*ASI*) parameter of Von Thun *et al*. (1988), proposed the hazard seismic microzonation (H_{SM}) parameter as a more meaningful indicator of local seismic hazard, defined as:

$$H_{SM} = (ASI_{UHS}/\Delta T) \times AF_{\Delta T} \quad (3)$$

where ASI_{UHS} is the value of the integral over interval ΔT of the response spectrum in acceleration

on stiff, flat ground (soil Type A, EC8 and NTC), representing the basic seismic hazard in that interval, and $AF_{\Delta T}$ is the average AF over the same period interval ΔT. In summary, H_{SM} represents the mean acceleration of the output spectrum within interval ΔT.

Since the regional urban fabric consists overwhelmingly of buildings with natural vibration periods T between 0.1 s and 0.5 s, in accordance with Naso *et al*. (2016) the ASI_{UHS} for 0.1 s ≤ T ≤ 0.5 s was calculated and made available online for every MPS04 grid point in Emilia-Romagna, with a 5 km buffer (Martelli and Ercolessi, 2017, 2020; Naso *et al*., 2019). Fig. 11a shows the map of basic seismic hazard for 0.1 s ≤ T ≤ 0.5 s (ASI_{UHS}/0, 4 s), while Fig. 11b shows the site-specific seismic hazard map in terms of H_{SM}, according to the MPS04 model.

As shown in Fig. 11b, the strongest ground shaking (H_{SM} > 0.7 g) is expected along the Apennine foothills SE of Bologna. Moderate but still significant shaking (0.55 ≤ H_{SM} ≤ 0.7 g) is expected along the Apennine foothill belt between the area west of Parma and the area SW of Modena, as well as in the central part of the plain between the provinces of Modena and Ravenna, extending to the coast. Values gradually decrease towards the north, reaching the lowest levels (H_{SM} < 0.39 g) in the northernmost areas of the region, in the Po Delta and along the Ferrara coast.

With the aim of further comparing the results obtained from different modelling approaches, the calculation of H_{SM} was also performed using the MPS19 model (Fig. 12)[2]. The resulting map shows that the distributions obtained from the MPS04 (Fig. 11b) and MPS19 (Fig. 12b) models are substantially identical, with only marginal differences.

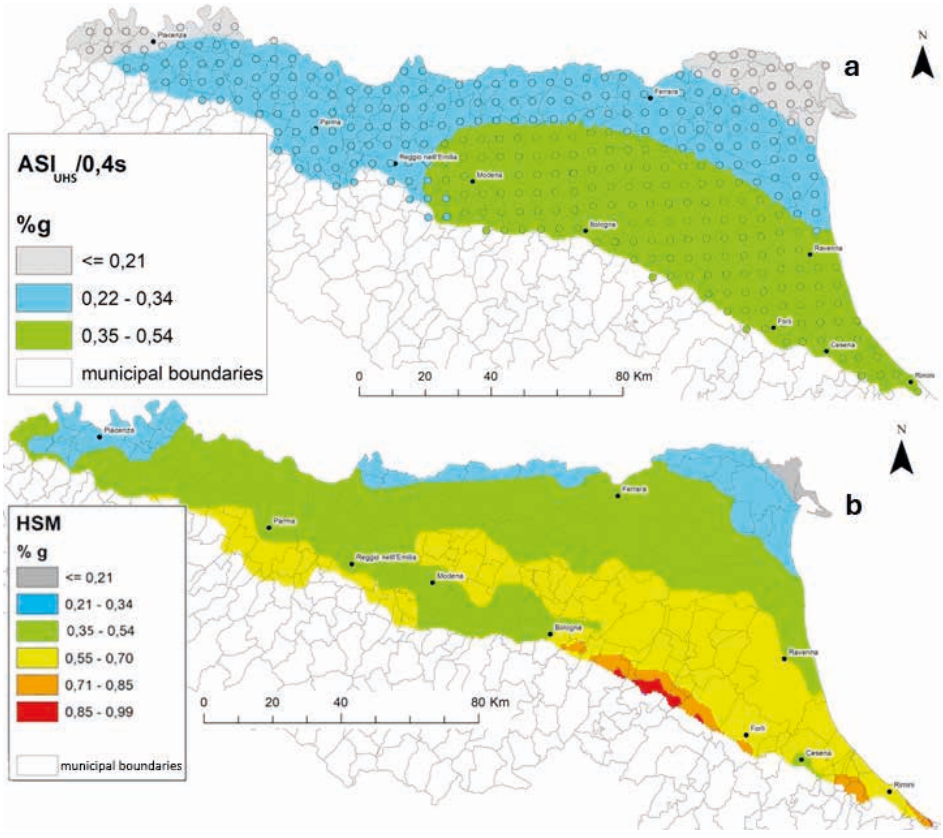


Fig. 11 - ASI_{UHS}/0, 4s (a) and H_{SM} (b) maps for the Emilia-Romagna plain based on the MPS04 model.

[2] Martelli *et al.* (2017b) calculated the basic seismic hazard only in terms of PGA.

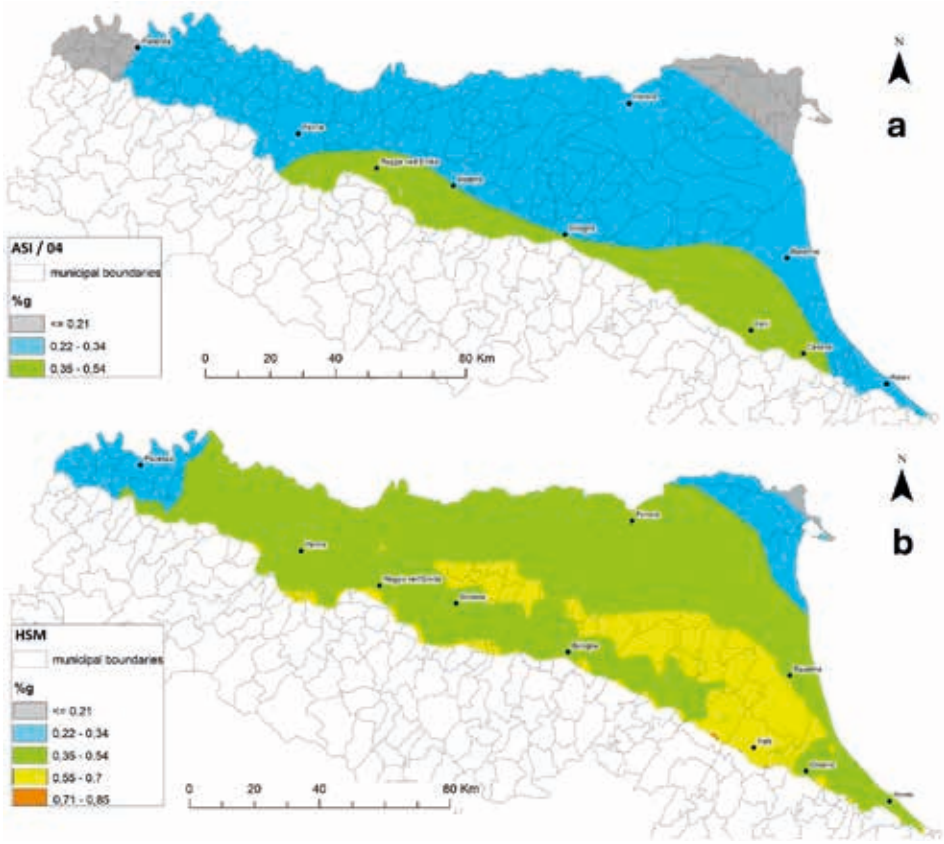


Fig. 12 - MPS19 reference seismic hazard map for 0.1–0.5 s (a) and H_{SM} map (b) for the Emilia-Romagna plain based on the MPS19 model.

5. Conclusions

Reviewing stratigraphic knowledge and comparing it with geophysical data (especially ambient noise measurements and V_S profiles) enables us to divide the territory into geologically homogeneous units for seismic zoning, even at a regional scale. An example of the proposed procedure was applied to the Emilia-Romagna plain, which was, thus, divided into six geological macrozones.

On the basis of the most recent and in-depth seismic microzonation studies (seismic actions calculated through specific local seismic response analyses) conducted in the six zones, it was possible to estimate the average *AF*s, for different intervals of periods *T*, in each of the identified zones. The *AF*s quantify the expected site effects but do not enable a true evaluation and a realistic comparison of the seismic hazard.

By multiplying the values of the *AF*s by the basic seismic hazard values (*PGA* on rigid and flat ground) the expected acceleration at the surface was estimated and, thus, a seismic hazard map in absolute (acceleration), rather than relative (*AF*s), values was obtained. The calculation was performed using four different seismic hazard models: i) MPS04, ii) MPS19, iii) ER 2D, and iv) ER 3D. Overall, the results show a good degree of consistency among the different models, although some differences can be observed, particularly for the regional horizontal and inclined source models, which indicate higher hazard levels in the Po Plain, especially in areas corresponding to

structural highs and buried arcs. H_{SM} values were calculated using both the MPS04 and MPS19 models, yielding almost identical results.

This study, therefore, confirms that, within the Emilia-Romagna plain, the piedmont areas between Bologna and Forlì are characterised by the highest seismic hazard, whereas the westernmost part of the plain and the Po Delta exhibit the lowest hazard levels. The results also highlight, particularly in the central and eastern sectors of the plain, significant spatial variations in seismic hazard associated with structural highs and lows, and consequently with variations in sedimentary cover thickness, as well as with buried active tectonic structures.

Finally, the comparison between the reference ground maps (Figs. 9a, 10, 11a, and 12a) and the final maps (Figs. 9b, 10, 11b, and 12b) highlights the great influence of geological conditions on the local seismic response, regardless of the base model.

This geological-seismic macrozonation and the site seismic hazard maps are documents of great importance since, considering both the basic seismic hazard and the geological conditions, they enable the Regional Authority to make more informed territorial planning choices and implement more targeted policies for the reduction of seismic risk.

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