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Evaluation and representation of the local seismic hazard through the H_{MS} parameter: example in Emilia-Romagna

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ABSTRACT The amplification of seismic motion in seismic microzonation maps is usually done by mapping of amplification factors. These parameters, as proposed by the current national and regional standards, allow for a relative evaluation of the local seismic hazard which are only valid at a local scale. A representation allowing a comparison and classification that is valid at all scales, from local to regional and national levels, would be more useful. To this end, Naso *et al.* (2016) proposed mapping the local seismic hazard through the new H_{MS} parameter. To verify the feasibility and potential of applying this proposal, a test was carried out in four municipalities of Emilia-Romagna. The test demonstrates the simplicity and the highly important advantages of seismic microzonation through the H_{MS} parameter:

- the maps provide ground shaking values resulting from reference seismic hazard and site effects, i.e. show a more realistic representation of the seismic hazard;
- the values of ground motions are absolute; this allows an effective comparison of seismic hazard among areas with different seismicity and geology and, therefore, an exact classification of the territory in terms of seismic hazard.

Key words: urban planning, local seismic hazard, seismic microzonation, amplification factors.

1. Introduction

In order to effectively implement the policies for prevention and mitigation of seismic risk, it is necessary to have technical documents and maps as representative as possible of the local seismic hazard conditions, in terms of extent and type of expected effects (amplification of the seismic motion, failure, subsiding, and displacement due to local instabilities).

According to the national and regional guidelines (see CT, 2015; RER, 2015; SM Working Group, 2015), in the seismic microzonation maps, the amplification of seismic motion is represented by an "amplification factor" (F), the result of the ratio between output and input motion[1]. So, these maps show relative, not absolute, values of the local seismic hazard (see the

1 The amplification factor is the ratio between the output spectrum at the surface, which considers the site effects due to local geological characteristics, and the input spectrum at the reference soil [rigid and flat bedrock, ground type "A": EN 1998-1 (2004), NTC (2008)], calculated for fixed periods intervals; the amplification factors usually applied in the seismic microzoning in Italy (see CT, 2015; SM Working Group, 2015; various regional guidelines) are:

- $F_{PGA} = PGA/PGA_0$, where PGA_0 is the peak ground horizontal acceleration at the period $T = 0$ s at the bedrock and PGA is the peak ground horizontal acceleration at the surface, at the same period $T = 0$ s;

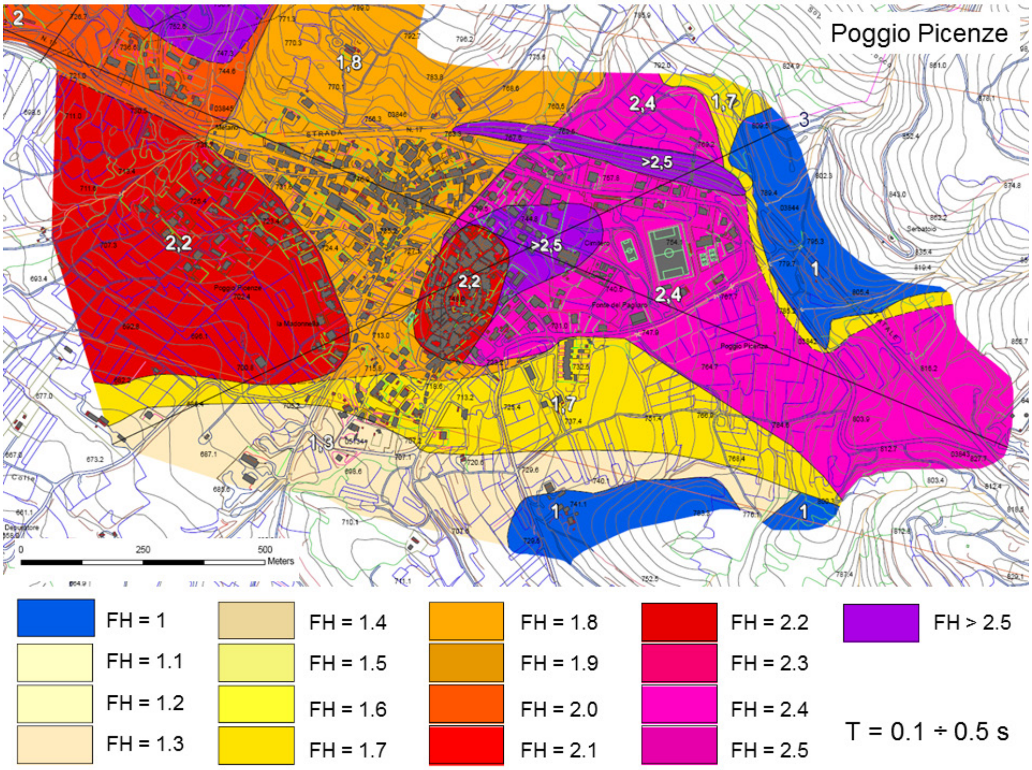

Fig. 1 - Example of seismic microzonation according to the national and regional standards (from Lanzo *et al.*, 2011).

example in Fig. 1) and do not allow comparing the seismic hazard among zones that are far from each other.

The current seismic microzonation maps are, therefore, useful for urban planning at town or municipality scale but do not allow comparing (or classifying) the local seismic hazard on a regional or national scale. For this reason, it would be of great interest to have maps that enable classifying the local seismic hazard that is valid at all scales (i.e. absolute values of acceleration, velocity or displacement of the ground).

Moreover, to make use of these documents in the early stages of urban planning, it would be appropriate to draw up maps which consider the seismic hazard for intervals of T periods as representative as possible for the most part of buildings.

For the above mentioned reasons, Naso *et al.* (2016) proposed estimating and representing the local seismic hazard with the new H_{MS} parameter, the product of the Acceleration Spectrum Intensity (Von Thun *et al.*, 1988), integral of the acceleration spectrum between the periods T = 0.1 s and T = 0.5 s (ASI_{PU}), and the acceleration amplification factor FA_{0105} estimated for

- FA, calculated around the period of maximum acceleration response (usually at a low period);
- FV, calculated around the period of maximum velocity response (usually at a higher period);
- $FH = SI/SI_0$, where SI_0 is the Housner Intensity at the bedrock and SI is the Housner Intensity at the surface for the interval of periods 0.1 s ≤ T ≤ 2.5 s o other fixed intervals of T (usually FH_{0105} for 0.1 s ≤ T ≤ 0.5 s; FH_{0510} for 0.5 s ≤ T ≤ 1.0 s and FH_{0515} for 0.5 s ≤ T ≤ 1.5 s);
- FA_{0105}, ratio between the acceleration output spectrum at the surface and the acceleration input spectrum at the bedrock for the interval of periods 0.1 s ≤ T ≤ 0.5 s.

the same interval of periods (for T_R = 475 years, return time usually considered for seismic microzonation studies): $H_{MS} = ASI_{PU} \cdot FA_{0105}$.

The zonation of the territory through H_{MS} allows a representation of the local seismic hazard with absolute values (cm/s in this case) and therefore a comparison, and classification, valid at local, regional and national scale. This kind of seismic microzonation is therefore a key element for a more realistic assessment of the seismic risk.

To verify the feasibility and potential of this procedure, we have carried out a mapping test of H_{MS} in four municipalities of Emilia-Romagna (Fig. 2), located in different geo-morphological environments (mountain, foothills, alluvial plain), with consequently different local geological conditions (outcropping bedrock, slope debris, terraced alluvial sediments, very thick alluvial deposits), and seismicity (from low to high).

2. Case studies

Estimation and representation of the local seismic hazard using the H_{MS} parameter have been tested in urban areas of Bagno di Romagna, Zola Predosa, Mirandola and Luzzara (Figs. 2 and 3).

2.1. Geological and seismological framework

Bagno di Romagna is a municipality of the high Romagna Apennines; this area is characterised by one of the highest reference seismic hazard in the northern Apennines (0.204 g < *PGA* < 0.210 g; Fig. 2). In fact, the town and the villages have often been seriously damaged (intensity = VIII) by earthquakes of estimated magnitude close to 6 (Locati *et al.*, 2016).

The study has been carried out in the three largest urban areas: Bagno di Romagna, San Piero in Bagno, and Acquapartita (including the villages of Valgianna and Selvapiana). The first two urban areas are located in the valley floor of the Savio River and the soil foundation is, therefore, made up of terraced alluvial sediments, varying in thickness from a few metres to about 30 m; the bedrock is made up of a turbiditic succession of sandstone and clayey marl (Marnoso-Arenacea Formation, Langhian-Serravallian age). On the sides of the valley slope debris and landslide bodies are present, with thickness from a few metres to over 20 m. Acquapartita is located on a

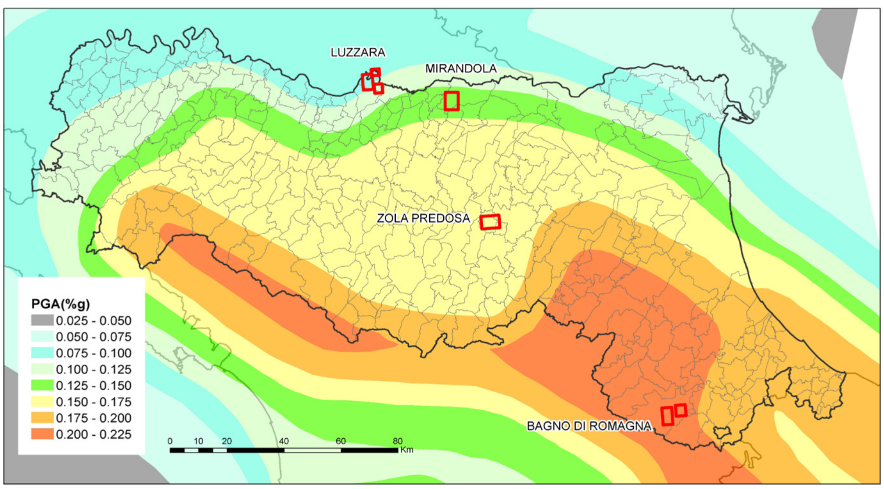

Fig. 2 - Map of the reference seismic hazard [*PGA* on the bedrock: ground type A: EN 1998-1 (2004), NTC, (2008)] for T_R = 475 years (from MPS04: http://zonesismiche.mi.ingv.it/), with location of the study areas.

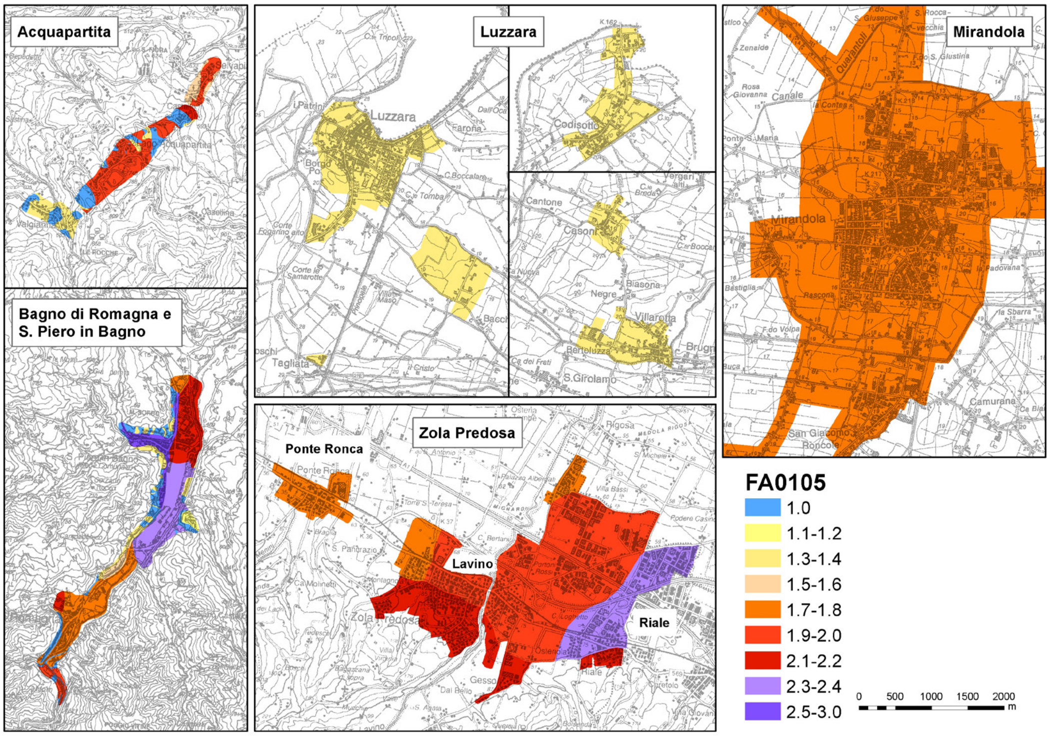

Fig. 3 - Maps of amplification factors FA_{0105} of the study areas (T_R = 475 years).

large landslide (the thickness of the landslide body is several tens of metres) detached from the northern slope of the Comero Mount; the bedrock is made up of turbidite sandstones (Mt. Comero Sandstone, Eocene-Oligocene age), locally fractured and weathered.

Zola Predosa is a municipality located along the Apennine-Po Plain margin, west of Bologna. This area is characterised by a medium reference seismic hazard (0.160 g < PGA < 0.164 g; Fig. 2). The town and the Ponte Ronca village were seriously damaged by the 1505 earthquake, intensity = VII (M_w=5.62), and by the 1929 seismic sequence, intensity = VI÷VII [main shock: M_w=5.36; Locati *et al.* (2016)].

The study has been carried out in the three largest urban areas: Zola Predosa (also known as Lavino), Riale, and Ponte Ronca. The southern part of the study area is located on hills made up of the Pliocene-Middle Pleistocene marine succession, clays with sands (Argille Azzurre, Pliocene-Early Pleistocene, and Imola Sand, Middle Pleistocene), and terraced alluvial sediments Middle and Late Pleistocene age. The central and northern part of the study area is located in the plain and the soil foundation is made up of alluvial deposits on a bedrock (the clayey and sandy Plio-Pleistocene succession) dipping to the north; since the study area is located above the pede-Apennine Thrust [see for instance Boccaletti *et al.*, (2010)], the thickness of the alluvial deposits increases rapidly toward the north, from a few tens to several hundred metres.

Mirandola is a municipality located in the Po Plain, Modena province, between the Secchia and Panaro rivers. This area is characterised by a medium-low reference seismic hazard (0.111 g < PGA < 0.147 g; Fig. 2). Nevertheless, the town and the villages were strongly affected by the 2012 seismic sequence (main shock: M_w= 6.09), which produced serious damage (intensity = VII÷VIII) (Locati *et al.*, 2016).

The study has been carried out in the municipality town.

The subsoil is made up of an alluvial succession, alternation of sand and silt, Middle and Late Pleistocene and Holocene age, varying in thickness from about 100 to over 200 m; the bedrock consists of the Pliocene-Early Pleistocene marine succession (Argille Azzurre or Santerno Formation). The thickness variability of the alluvial deposits is due to the presence, in the southern area of the town, of a buried ridge, the most southern anticline of the Ferrara Folds (Pieri and Groppi, 1981).

Luzzara is a municipality located along the right bank of the Po River, in the Reggio Emilia province. This area is characterised by a low reference seismic hazard (0.091 g < PGA < 0.100 g, Fig. 2). In the past, the town and the villages have suffered significant damage (intensity = VII) during earthquakes originating in the Parma area and Reggio Emilia Plain [$4.7<M_w\leq5.5$; Locati *et al.* (2016)].

The study has been carried out in the most important urban areas.

The subsoil is made up of alluvial sandy-silt deposits of the Middle-Upper Pleistocene and Holocene, several hundred metres thick; the bedrock consists of Pliocene-Early Pleistocene marine succession (Argille Azzurre or Santerno Formation). The high thickness of the alluvial succession is due to the fact that Luzzara is located in the syncline between the buried Ferrara Folds and south-Alpine thrust-front (Pieri and Groppi, 1981).

2.2. H_{MS} calculation

In the abovementioned urban areas, seismic microzonation studies for urban planning have been carried out by the Regional and local authorities according to national and regional guidelines (CT, 2015; RER, 2015; SM Working Group, 2015); so, maps of amplification factors (F_{PGA}, FH_{0105}, and FH_{05-10}) are available.

For this study, acceleration amplification factors for 0.1 s ≤ T ≤ 0.5 s (FA_{0105}) have also been calculated and represented (Fig. 3).

For the calculation of $ASI_{PU,}$ we have used the data on reference response spectra (T_R = 475 years, 50th percentile) available at http://esse1.mi.ingv.it/d3.html. ASI_{PU} values have been calculated for each point of a regular grid spaced 5 km and, by interpolating these results, we produced a map for the Emilia-Romagna region and its surrounding areas (Fig. 4).

Furthermore, the corresponding amplification factor (FA_{0105}, Fig. 3) was associated to each ASI_{PU} estimation point (Fig. 4).

At each point of the grid, the product of the amplification factor (FA_{0105}, Fig. 3) for the ASI_{PU} value has been calculated (Fig. 4), thus obtaining the H_{MS} value. By interpolating the H_{MS} values of each point of the grid, the seismic microzonation maps in Fig. 5 have been created.

3. Analysis of the results

As shown in Fig. 5, the highest values of local seismic hazard, H_{MS}> 300 cm/s, result in Bagno di Romagna, where the reference seismic hazard is higher (0.204 g < PGA < 0.210 g; Fig. 2; ASI_{PU} > 175 cm/s; Fig. 4); in particular, the highest H_{MS} values (H_{MS}> 350 cm/s) are found in the valley floor and in the slope areas, where the thicknesses of the debris cover are considerable (greater than 20 m) and the amplification factors are therefore high (FA_{0105} ≥ 2; Fig. 3).

The lowest values of local seismic hazard, 100 cm/s < H_{MS}< 150 cm/s, result in Luzzara

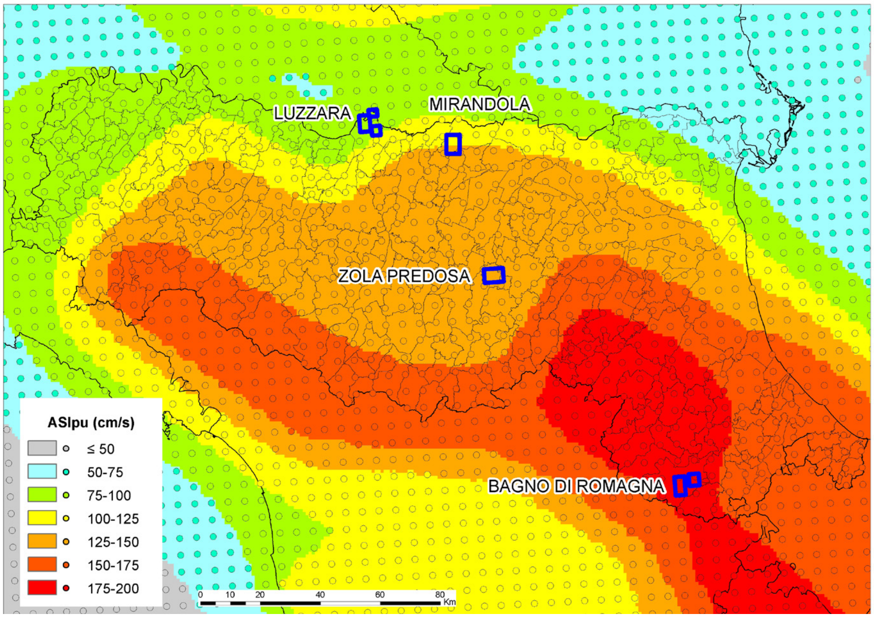

Fig. 4 - Map of ASI_{PU} values (T_R = 475 years, 50th percentile) for the Emilia-Romagna and surrounding areas, with location of the study areas.

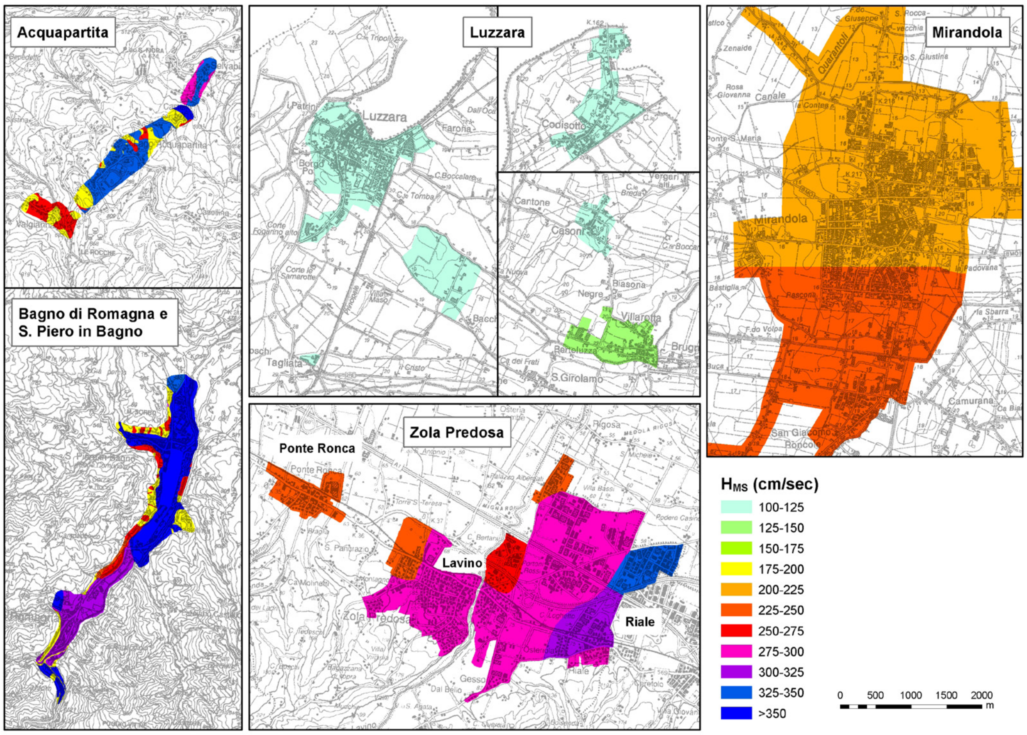

Fig. 5 - H_{MS} seismic microzonation maps for the study areas.

where the reference seismic hazard is lower (0.091 g < PGA < 0.100 g; Fig. 2; 75 cm/s < ASI_{PU} < 100 cm/s; Fig. 4) and the high thickness of recent alluvial deposits determine low amplifications (FA_{0105} ≤ 1.3, Fig. 3).

The Zola Predosa map highlights the importance of local geological conditions: despite a medium reference seismic hazard (0.160 g < PGA < 0.164 g; Fig. 2; 125 cm/s < ASI_{PU} < 150 cm/s;

Fig. 4), the local seismic hazard is high ($H_{MS} > 225$ cm/s) because of rather high amplification factors ($1.7 < FA_{0105} < 2.4$). In fact, the local seismic hazard is greater than some microzones of Bagno di Romagna, where the reference seismic hazard is higher but the amplification factors are lower than 1.3 or equal to 1 and $H_{MS} < 200$ cm/s.

In Mirandola town the local seismic hazard is considerable, $H_{MS} > 200$ cm/s, in the southern sector, where the reference seismic hazard is higher ($PGA \geq 0.140$ g; Fig. 2; $ASI_{PU} \geq 125$ cm/s; Fig. 4).

From the above and from Fig. 5, it is clear that the H_{MS} parameter takes into account the reference seismic hazard and the local geological conditions. H_{MS} allows a clear and effective seismic microzonation and a comparison, and therefore classification, of the local seismic hazard, valid at local and regional scale.

For an easier and quick application of the results of this procedure, such as the classification of the territory according to the seismic hazard, thresholds could be established in order to group the H_{MS} values into classes (for example low, medium and high seismic hazard). However, a proposal of thresholds for such a classification is beyond the aims of this work, as it necessarily requires further studies in other parts of the Italian territory. Considerations on this theme and a first proposal can be found in Naso *et al.* (2019).

Lastly, it is important to note that the H_{MS} parameter can be used for both second and third level microzonation *sensu* regional and national guidelines (RER, 2015; SM Working Group, 2015).

At the moment, the analysis and representation of the local seismic hazard through H_{MS} appear to be the best seismic microzonation procedure, with a probabilistic approach, on a municipal or town scale (usually, in Italy, these studies are carried out by freelance geologists and engineers for local authorities). In fact, after ASI_{PU} has been determined with a specific seismic hazard study (for example the analysis of the seismic hazard of the national territory carried out by INGV for the MPS04; data available at http://zonesismiche.mi.ingv.it/), FA_{0105} can be determined with a site-specific ground response analysis based on geotechnical and geophysical data acquired through on-site and laboratory tests of the current type. This seismic microzonation procedure is part of the Level 2 approaches *sensu* Barani and Spallarossa (2017).

4. Conclusions

Thanks to seismic microzonation studies which have produced maps of acceleration amplification factors (FA_{0105}) and response spectra for the estimation of ASI_{PU} (see data for the national territory at http://esse1.mi.ingv.it/d3.html), the calculation of H_{MS} is simple and quick ($H_{MS} = ASI_{PU} \times FA_{0105}$).

The application of this procedure in some municipalities of Emilia-Romagna, characterised by different seismicity and geological conditions, showed that the H_{MS} parameter effectively takes into account the variability of reference seismic hazard and amplification factors due to geological differences. H_{MS} therefore allows a clear and effective seismic microzonation and a comparison, and therefore a classification, of the local seismic hazard that is valid at every scale.

Moreover, H_{MS}, being calculated for the interval of periods between 0.1 and 0.5 s, is of great interest for the management of the territory, in particular for urban planning; as a matter of fact, it is proved by various studies that the vibration periods of most of the existing buildings are included in this interval.

To sum up, the seismic microzonation through the H_{MS} parameter allows a comparison and a classification of the local seismic hazard that is valid at all scales and is therefore fundamental for a more realistic assessment of the seismic risk and for a more mindful implementation of risk mitigation policies.

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