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Maps for land management: from geology to seismic hazard

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ABSTRACT Seismic microzonation maps usually represent local seismic hazard through amplification factors, i.e. relative values, and reference seismic hazard maps do not consider the local effects that may derive from local geological and morphological conditions. For the implementation of policies to reduce the seismic risk, authorities responsible for territorial management need realistic seismic hazard maps comparable on a national scale. Thanks to the available data on geology and seismic hazard and to the procedures indicated by the Regional and national guidelines, it is possible to produce, quickly and cost-effectively, site seismic hazard maps at any scale. The use of the H_{SM} parameter for this mapping makes it possible to consider both the reference seismic hazard and the local effects and makes the final results comparable on a national scale; therefore, it allows a realistic classification of the seismic hazard applicable to all scales. The results of tests conducted on local and regional scales, according to national and Regional guidelines, are shown and discussed.

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

1. Introduction

For the correct and effective implementation of risk prevention and mitigation policies, the authorities responsible for territorial management need documents and maps representative of the real hazard conditions of their territory. The most used map on a regional and national scale concerning seismic hazard is the MPS04 (2006) by INGV (OPCM 3519/2006, available on line at www.mi.ingv.it/pericolosita-sismica/), while on a local scale the reference is undoubtedly the seismic microzonation mapping.

The MPS04 (Fig. 1) is the current reference for seismic hazard studies in Italy and it shows the distribution on the national territory of the reference peak ground acceleration (PGA or a_g) on type A ground [i.e. flat rock, see Eurocode 8 (EN-1, 1998) and national rule (NTC, 2008)], with a 10% probability of exceedance in 50 years (or reference return period T_R = 475 years). Therefore, the MPS04 (2006) does not take into account the effects that may derive from local geological and morphological conditions ("local effects"), above all the amplification of seismic motion.

The main topic of seismic microzonation studies is the analysis of local effects influence on the seismic response on the surface. The final maps of these studies, according to national and

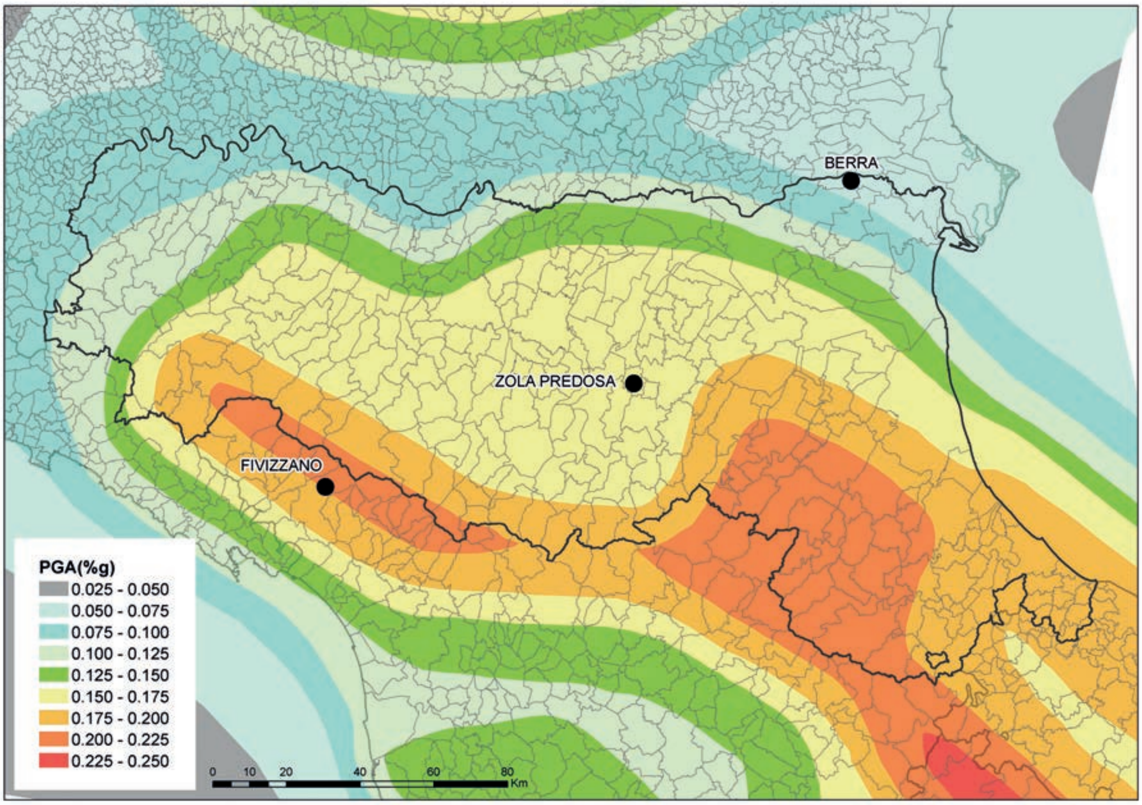

Fig. 1 - Map of the reference seismic hazard [*PGA* on type A ground (EN-1, 1998; NTC, 2008)] for $T_R = 475$ years [from MPS04 (2006), INGV: <zonesismiche.mi.ingv.it>], with location of the study areas.

Regional guidelines (RER, 2007; RT, 2015; SM Working Group, 2015; CTMS, 2017c), point out the distribution on the territory of the amplification factors (*AF*), defined as:

$$AF = \frac{\int_{T1}^{T2} Sa\, dT}{\int_{T1}^{T2} Sb\, dT} \tag{1}$$

where *Sa* is the elastic response spectrum at the study site (usually at the surface), *Sb* is the 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[1]. Therefore, AF is a pure

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[1] The amplification factors usually applied in the seismic microzonation in Italy (see SM Working Group, 2015; CTMS, 2017c; 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 reference site and *PGA* is the peak ground horizontal acceleration at the study site, at the same period $T = 0$ s;
- *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 high period);
- $FH = SI/SI_0$, where SI_0 is the Housner Intensity at the reference site and *SI* is the Housner Intensity at the surface of the study site for the interval of periods $0.1 \leq T \leq 2.5$ s or other fixed intervals of *T* (usually FH_{0105} for $0.1 \leq T \leq 0.5$ s; FH_{0510} for $0.5 \leq T \leq 1.0$ s and FH_{0515} for $0.5 \leq T \leq 1.5$ s);
- FA_{0105}, acceleration amplification factor for the interval of periods $0.1 \leq T \leq 0.5$ s. Recently, the use of amplification factors referred to intervals of higher periods *T* has also been proposed: FA_{0408} for $0.4 \leq T \leq 0.8$ s and FA_{0711} for $0.7 \leq T \leq 1.1$ s (CTMS, 2017c).

number and this kind of map provides a representation of the local seismic hazard in terms of relative but not absolute values (see an example in Fig. 2). Consequently, most of the seismic microzonation maps allow the comparison among the seismic hazard of adjacent zones and are very important for urban planning and land management on a local scale (town, municipality) but do not allow a classification, and consequently the comparison, among the seismic hazard of zones far from each other (towns in different regions, for instance).

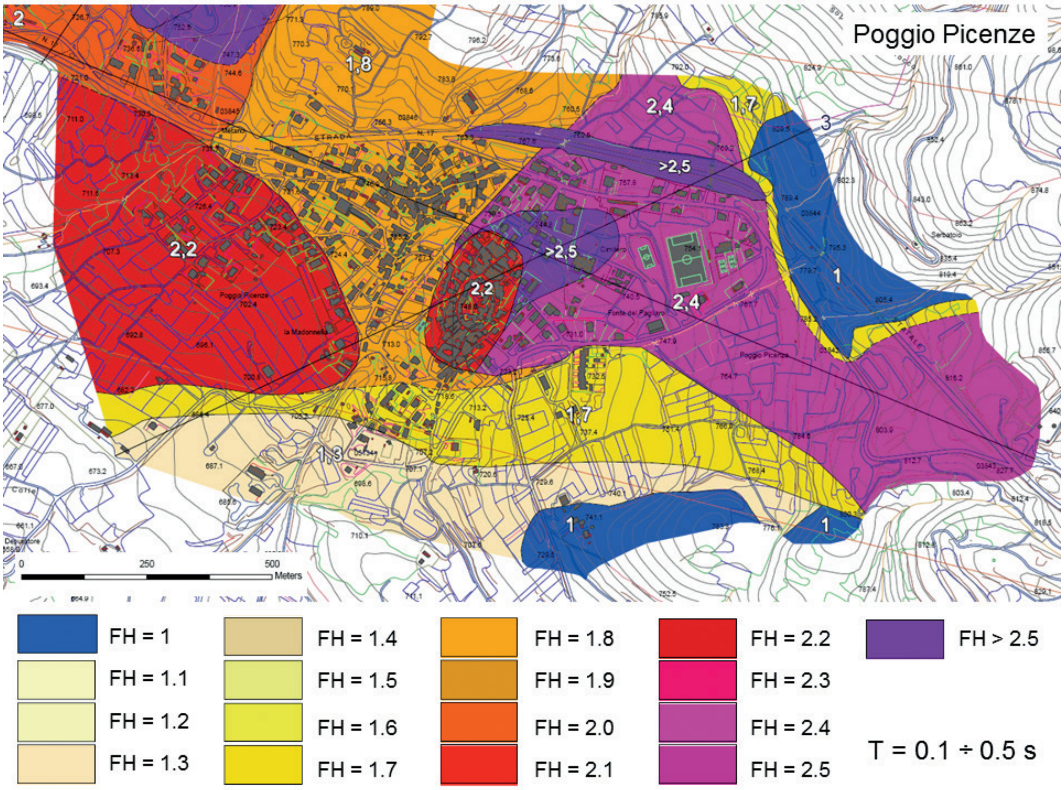

Fig. 2 - Example of seismic microzonation map according to national and Regional guidelines (from Lanzo *et al.*, 2011).

For a more correct choice and a more effective implementation of the seismic risk prevention and mitigation policies, it would be useful to have maps which provide absolute values of site seismic hazard, i.e. the reference seismic hazard increased by the local effects. This kind of map gives more realistic information and shows a comparison and classification of the seismic hazard that can be applied to all scales (local, regional and national).

2. Procedure

The national and Regional guidelines for seismic microzonation (RER, 2007; RT, 2015; SM Working Group, 2015; CTMS, 2017c) provide a shared procedure to realise maps of local seismic hazard based on geological, geomorphological, geotechnical and geophysical data.

This procedure is summarised and schematised in Fig. 3.

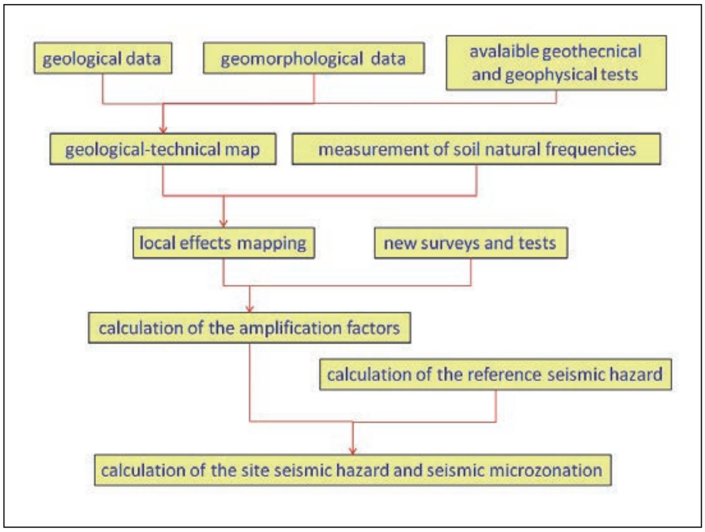

Fig. 3 - Scheme for site seismic hazard mapping according to Italian guidelines for seismic microzonation (SM Working Group, 2015; CTMS, 2017c).

Storing data in a GIS database grants quick and low-cost processing.

To demonstrate the applicability of this method, we have carried out tests on local and regional scale. On a local scale, the proposed procedure has been applied in territories characterised by very different seismicity and geomorphological environments: Fivizzano, town of the northern Apennines with a high seismicity, Zola Predosa, town of the Apennine - Po Plain margin with a medium seismicity, and finally Berra, town of the Po Plain with a low seismicity. On a regional scale, the procedure has been applied in Emilia-Romagna, which extends from the Apennine ridge to the Po River and Adriatic coast, thus including areas with very different seismicity and geology (Figs. 4 and 5). The outcome maps from these tests are shown and discussed below.

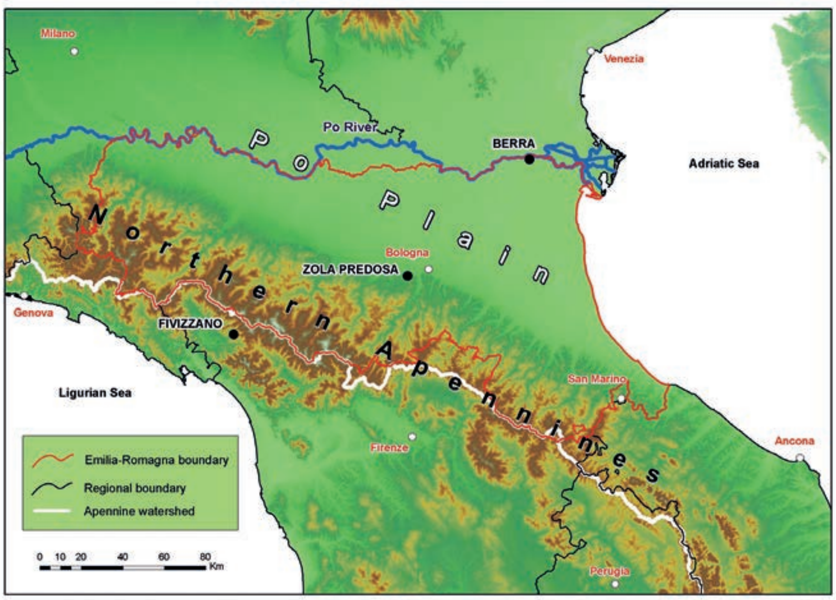

Fig. 4 - Geographical framework of the study areas.

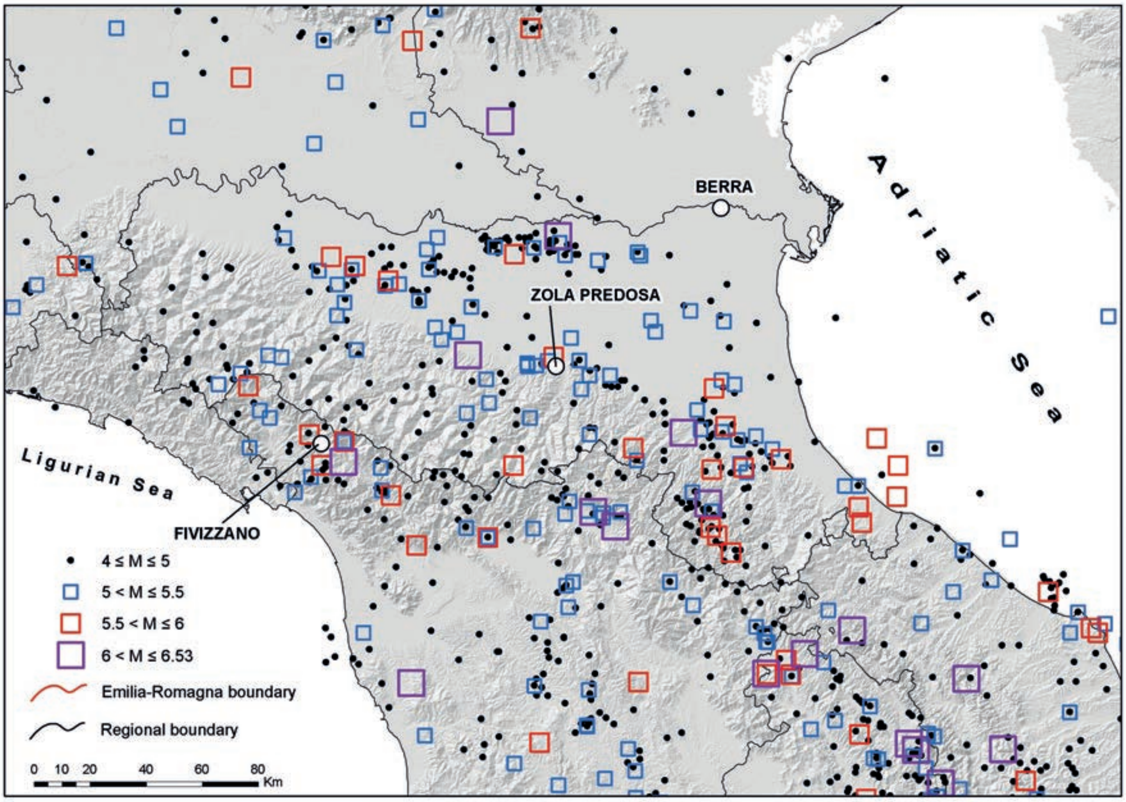

Fig. 5 - Epicentres of major earthquakes ($M_W \geq 4.0$) occurred in Emilia-Romagna from 1000 to 2014 (ISIDe Working Group, 2015; Rovida *et al*., 2016); size and colour of the symbol are representative of the magnitude (see the legend).

3. Geological and seismological frameworks of the study areas

Fivizzano is a small town of the northern Apennines, between Lunigiana and Garfagnana (Fig. 4), characterised by Quaternary fluvial-lacustrine basins of tectonic origin (graben) and high seismicity (Figs. 1 and 5). The town has often been seriously damaged (maximum I = IX) by earthquakes of estimated magnitude up to 6.5 (Locati *et al*., 2016).

The local seismicity is originated by the activity of normal faults (Fig. 6) which delimit the intermontane basins (DISS Working Group, 2015; Martelli *et al*., 2017).

The study has been carried out in Fivizzano town; it is located on the ancient terraced alluvial deposits of the Rosaro River (Rainone *et al*., 2004) overlying a heterogeneous substratum consisting of mudstone, limestone and sandstone (Upper Cretaceous - Lower Miocene); the alluvial cover is made up of coarse deposits varying in thickness from a few metres to about 40÷50 m. Furthermore, some important active and dormant landslides are present in this area (D'Intinosante and Gruppo Lavoro Fivizzano 2014, 2015a, 2015b).

Zola Predosa is located along the Apennine - Po Plain margin, west of Bologna (Fig. 4). This area is characterised by a not very high seismicity (Figs. 1 and 4) but the town and Ponte Ronca Village have been seriously damaged by the 1505 earthquake, I = VII ($M_W = 5.62$), and by the 1929 seismic sequence, I = VI ÷ VII (main shock: $M_W = 5.36$) (Locati *et al*., 2016).

The local seismicity is originated by the activity of the pede-Apennine thrust system (Fig. 6) (DISS Working Group, 2015; Martelli *et al.*, 2017).

The study has been carried out in the 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, prevalent clays with sands (Argille Azzurre, Pliocene - Early Pleistocene, and Imola Sand, Middle Pleistocene) and terraced alluvial sediments (Middle and Late Pleistocene). The central and northern parts of the study area are in the plain and the soil foundation is made up of alluvial deposits on a bedrock (the clayey and sandy Pliocene - Pleistocene succession) dipping to the north; since the study area is located above the pede-Apennine thrust, the thickness of the alluvial deposits grows rapidly toward the north, from a few tens to several hundred metres.

Berra is a small town located along the right bank of the Po River, near its mouth, in the Ferrara Province (Fig. 4). This area is characterised by a low seismicity (Figs. 1 and 5). No important earthquake damage is known in this territory (Locati *et al.*, 2016).

In this area, no seismogenic faults responsible for strong earthquakes are known (Fig. 6); the seismicity is caused mostly by surrounding seismogenic zones, such as the buried thrust system of the Ferrara Folds present toward SW (DISS Working Group, 2015; Martelli *et al.*, 2017).

The study has been carried out in the town. The subsoil is made up of alluvial sand, silt and clay of the Middle-Upper Pleistocene and Holocene, several hundred metres thick; the bedrock,

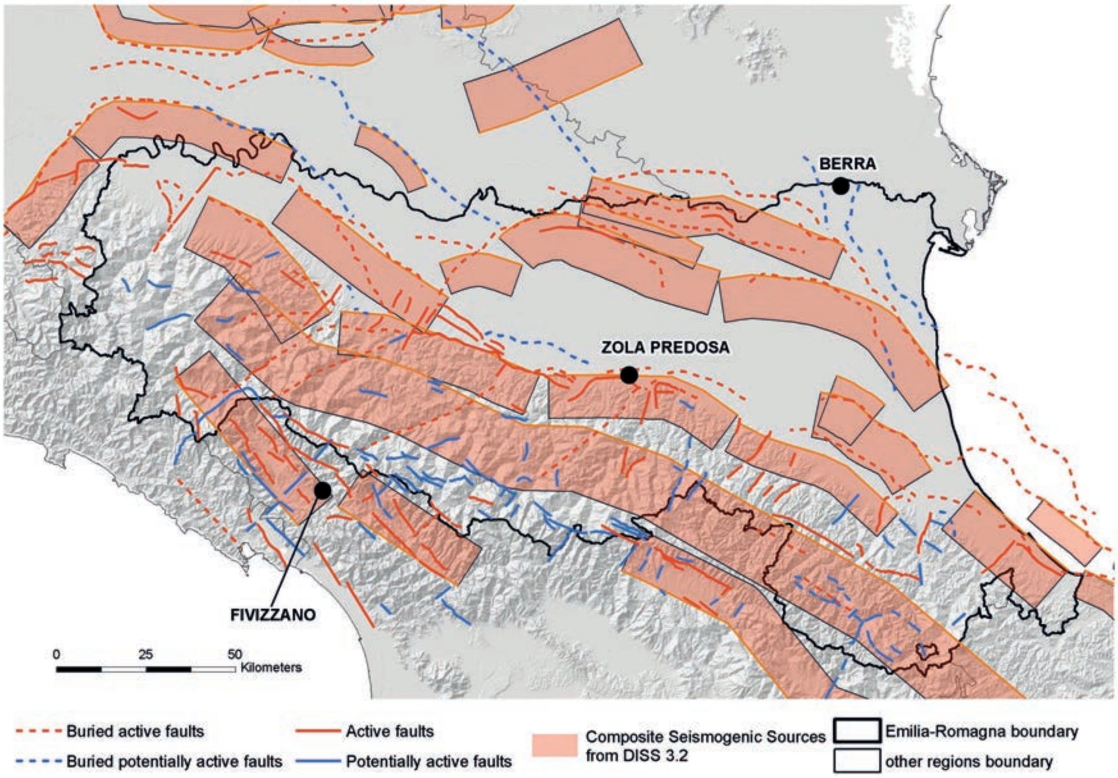

Fig. 6 - Seismogenic sources *of* earthquakes $M \geq 5.5$ (DISS Working Group, 2015) and recognised active faults (Martelli *et al.*, 2017), with location of study areas.

which is very deep, 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 Berra is in the syncline north of the buried Ferrara Folds.

The Emilia-Romagna region is located between the Apennine watershed, the Po River and the Adriatic Sea (Fig. 4). Fig. 5 shows that the strongest earthquakes ($M_W \geq 5.5$) are concentrated along the Apennine ridge, the Apennine - Po Plain margin, and in some sectors of the plain (Fig. 6), where buried active thrusts are present (DISS Working Group, 2015; Martelli *et al*., 2017); areas with rare and low magnitude earthquakes are the Po delta and the western sector of the region, in particular the plain around Piacenza (Locati *et al*., 2016; Rovida *et al*., 2016).

4. Seismic hazard

As it is important to apply the cartography of seismic hazard since the early stages of territorial governance, i.e. before approving land use and urban plans, we have chosen to develop maps that take into account the seismic hazard for a range of T periods as significant as possible for most of existing and new buildings.

The elaborations carried out on the ISTAT data (2001 census), about the number of floors in residential buildings (Bramerini and Di Pasquale, 2002), show that over 95% of buildings in Italy do not exceed five floors (Fig. 7); therefore, most of the vibration periods (T) of the Italian buildings probably is included between 0.1 and 0.5 s.

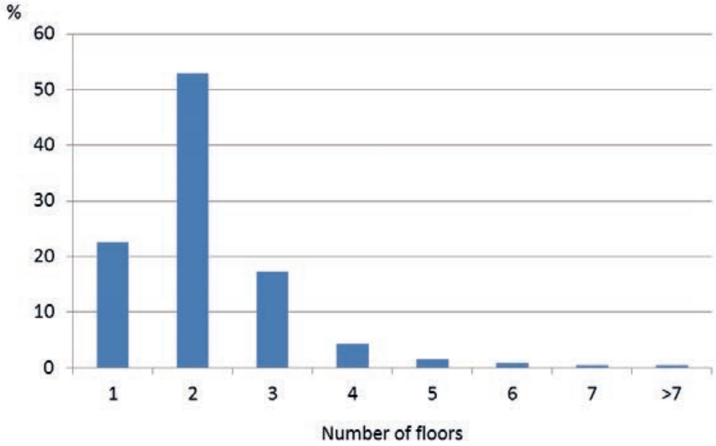

Fig. 7 - Percentage of Italian residential buildings by number of floors [ISTAT data from 2001 census, modified from Bramerini and Di Pasquale (2002)].

For this reason, we have decided to realise maps which refer to the range of T periods between 0.1 and 0.5 s, for $T_R = 475$ years. Therefore, as an indicator of the seismic hazard, we have picked the H_{SM} parameter (Fig. 8), proposed by Naso *et al*. (2016) and tested by Martelli and Ercolessi (2019), defined as the product of the acceleration spectrum intensity (ASI_{UHS}), i.e. the integral value of the spectrum calculated between 0.1 and 0.5 s (Von Thun *et al*., 1988) divided ΔT, multiplied by the acceleration AF calculated for the same interval $0.1 \leq T \leq 0.5$ s (AF_{0105}):

$$H_{SM} = ASI_{UHS} / \Delta T \times AF_{0105} \tag{2}$$

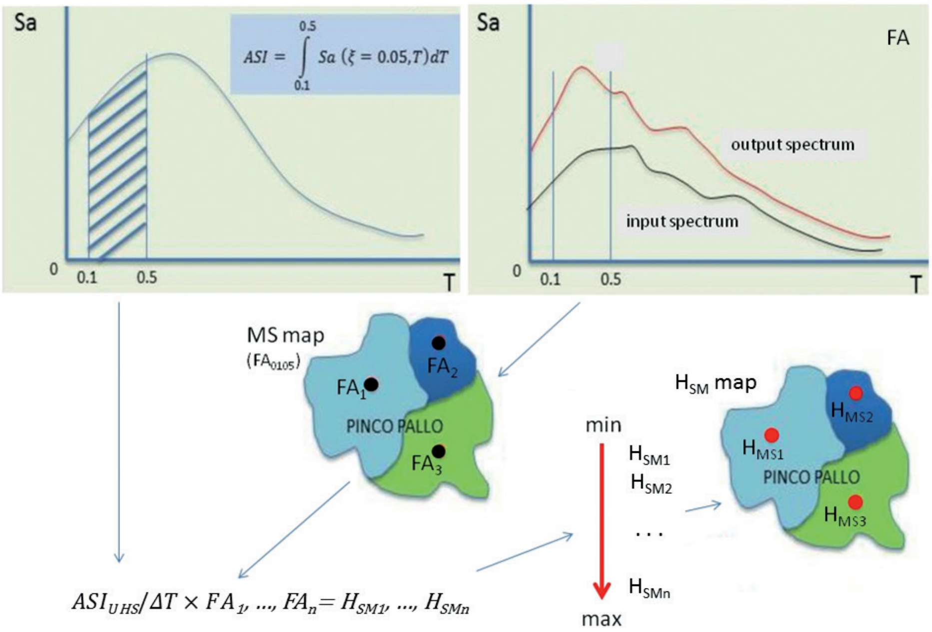

Fig. 8 - Scheme for calculation of H_{SM} parameter and H_{SM} mapping.

Anyway, it is possible to estimate H_{SM} also for other vibration periods, e.g. 0.5 - 1.5 s, 0.1 - 2.5 s.

The realisation of these maps, regardless of the scale, requires the preliminary evaluation and mapping of the reference seismic hazard, in this case the map of ASI_{UHS} values.

3.1. Reference seismic hazard

Data for the reference seismic hazard can be downloaded from the INGV web site [http://esse1.mi.ingv.it/d3.html (available in GIS format)].

For the calculation of ASI_{UHS} we have used data for $T_R = 475$ years, 50 percentiles.

ASI_{UHS} values have been calculated for each point of the INGV grid, spaced 5 km (Fig. 9a); the values of ASI_{UHS} calculated for each grid point have been interpolated to realise the reference seismic hazard maps, so that in each point of the territory it is possible to have an ASI_{UHS} value, regardless of the scale. ASI_{UHS} map for the Emilia-Romagna and surrounding areas is shown in Fig. 9b. The map in Fig. 9b represents the continuous variability of the ASI_{UHS} values in the Emilia-Romagna territory; for the following processing, this continuous distribution has been discretised into cells in which ASI_{UHS} value is homogeneous. The size of the cells will depend on the purpose, the scale of the study and the required detail.

3.2. Local effects

For the calculation and mapping of H_{SM}, in addition to the value of ASI_{UHS}, an AF (AF_{0105}) must also be attributed to each cell.

For the three local scale test areas, seismic microzonation studies carried out for urban planning by the municipal and Regional administrations were already available. Therefore, AF_{0105} values have been derived from these studies (Fig. 10).

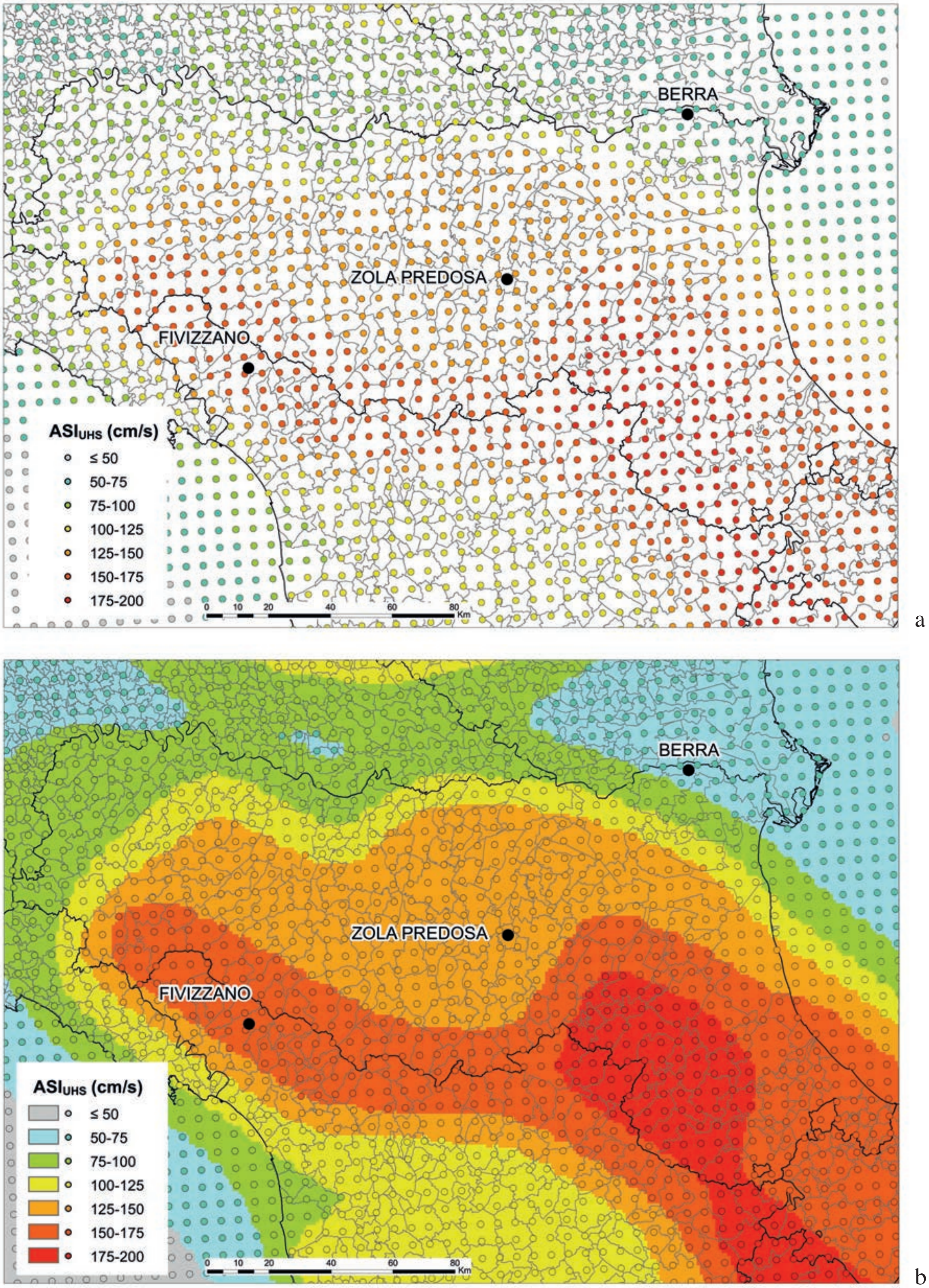

Fig. 9 - Map of ASI_{UHS} values ($T_R = 475$ years, 50 percentile) for the Emilia-Romagna region and surrounding areas with location of study areas; a) map of ASI_{UHS} values for grid points, b) interpolated map.

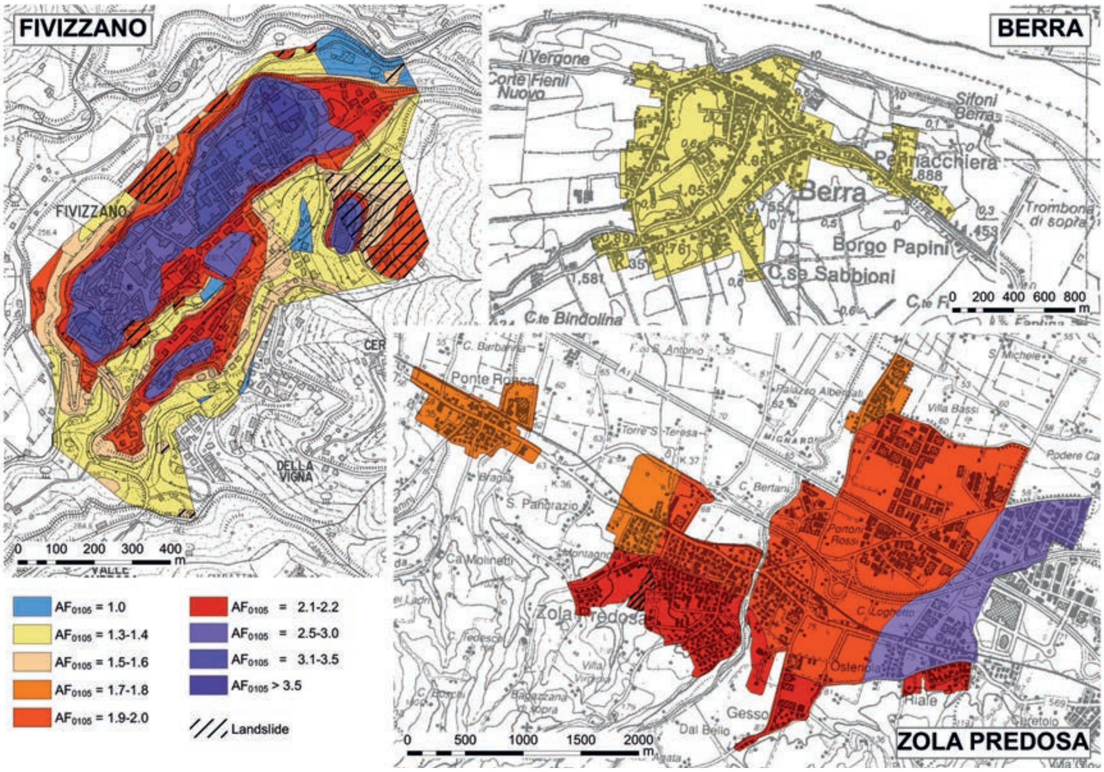

Fig. 10 - Seismic microzonation maps of the local scale test areas.

For the test on a regional scale, since the seismic microzonation is not yet available in all the municipalities of the region, the starting data have been obtained, as suggested by the procedure schematized in Fig. 3, from the available geological maps (Emilia-Romagna Geological Map 1:10,000 and Geological Map of Italy 1:50,000) and regional geological data base. The mapped geological units have been reconsidered in order to subdivide the territory into macrozones for seismic studies: each macrozone is characterised by lithostratigraphic homogeneity.

So, the regional territory has been subdivided as follows (v. Annexes A1 e A2, DGR 2193/2015) (Fig. 11):

a) outcropping solid rock (debris thickness < 3 m);
b) outcropping soft rock (debris thickness < 3 m);
c) slope debris and valley floor alluvial sediments (thickness ≥ 3 m);
d) succession made up mostly of alluvial fan gravel (up to 100 m thick) resting on Pliocene - Pleistocene marine clay and sand (type A alluvial succession of the Apennine - Po Plain margin);
e) succession of alluvial gravel, sand and silt (up to 100 m thick) resting on Pliocene - Pleistocene marine clay and sand (type B alluvial succession of the Apennine - Po Plain margin);
f) succession of alluvial sand, silt and clay; bedrock at 100 ± 30 m depth (type 1 plain deposit);
g) succession of alluvial sand, silt and clay; bedrock at 130 ÷ 300 m depth (type 2 plain deposit);

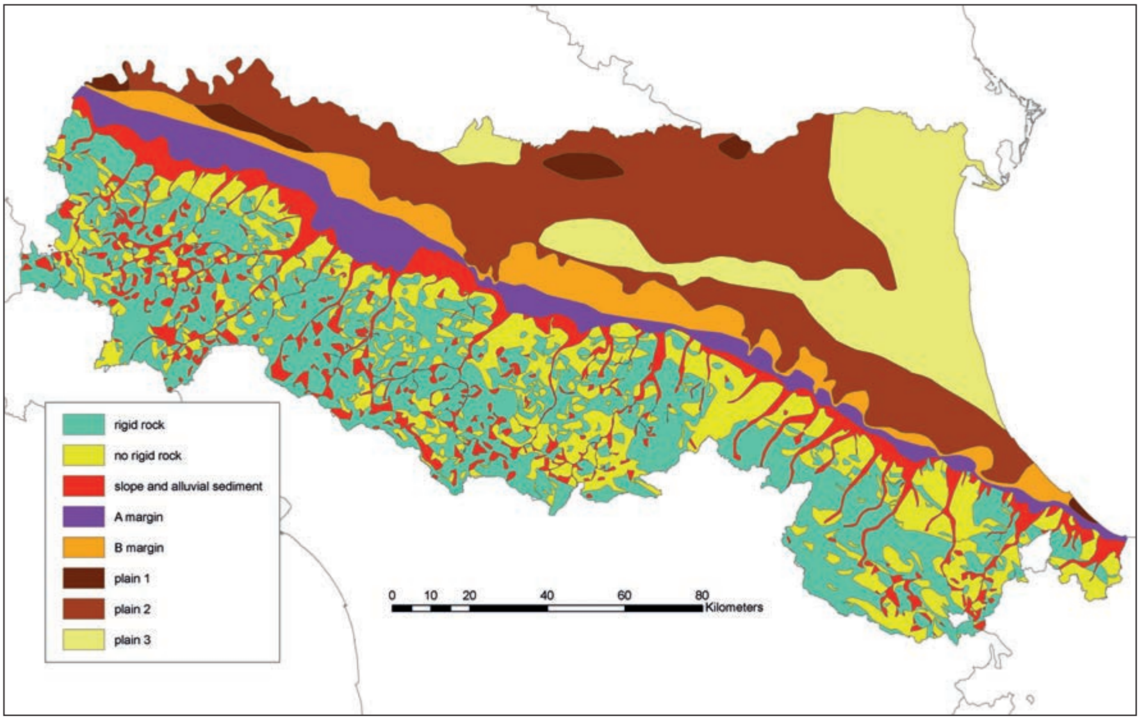

Fig. 11 - Emilia-Romagna map of the geologic macrozones for seismic studies.

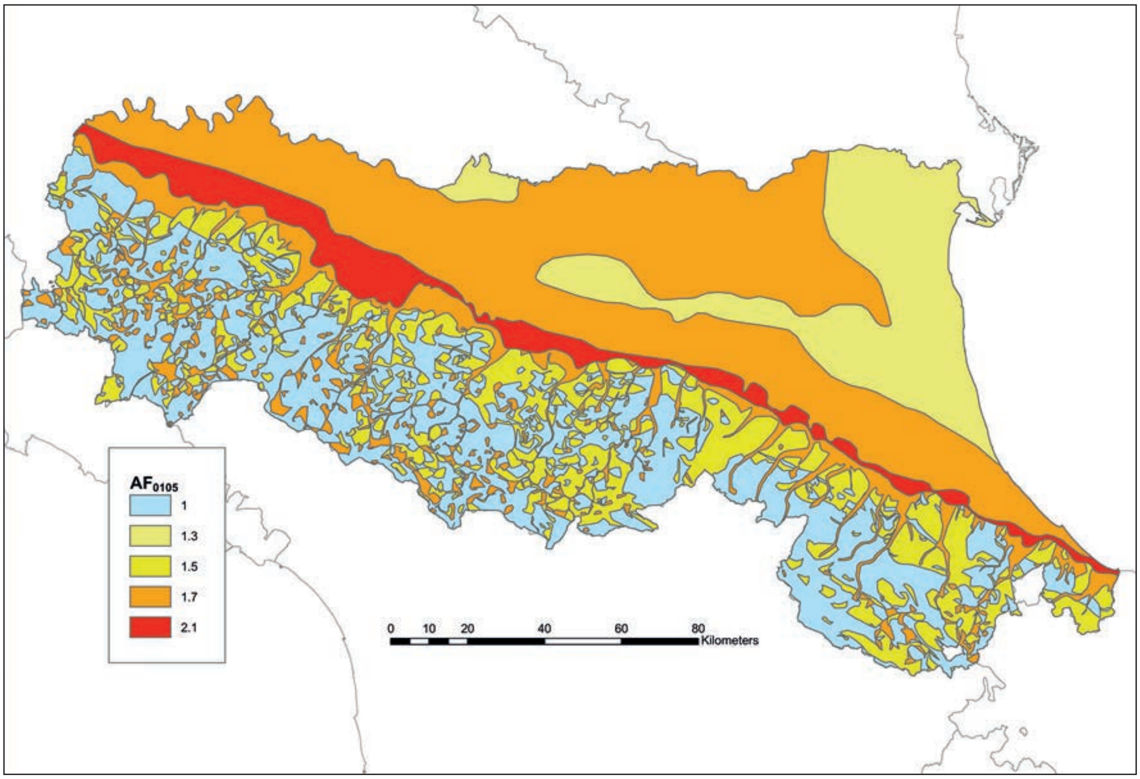

Fig. 12 - AF_{0105} Emilia-Romagna map, T_R = 475 years.

h) succession of alluvial sand, silt and clay; sometimes peaty, bedrock at depth greater than 300 m (type 3 plain deposit).

Thanks to many studies of local seismic response and seismic microzonation (75% of the Emilia-Romagna municipalities have seismic microzonation studies according to national and Regional standards), each of these macrozones has been attributed a mean acceleration AF for $0.1 \leq T \leq 0.5$ s (AF_{0105}) and $T_R = 475$ years (Fig. 12):

a) outcropping solid rock (bedrock): $AF_{0105} = 1.0$;
b) outcropping soft rock: $AF_{0105} = 1.5$;
c) slope debris and valley floor alluvial sediments: $AF_{0105} = 1.7$;
d) type A margin alluvial succession: $AF_{0105} = 2.1$;
e) type B margin alluvial succession: $AF_{0105} = 1.7$;
f) type 1 plain deposit: $AF_{0105} = 1.7$;
g) type 2 plain deposit: $AF_{0105} = 1.7$;
h) type 3 plain deposit: $AF_{0105} = 1.3$.

3.3. Site seismic hazard maps

By multiplying ASI_{UHS} values for the AF_{0105} of each microzone, in the case of local scale studies (seismic microzonation), or for each cell, in the case of regional scale studies, we obtain the H_{SM} value for the microzone or the cell and it is therefore possible to realise a site seismic hazard map ($0.1 \leq T \leq 0.5$ s, $T_R = 475$ years) with absolute values which considers both the reference seismic hazard and the local effects and shows a comparison and classification both applicable to local and regional scale. Figs. 13 and 14 show, respectively, the H_{SM} seismic microzonation maps of the local test areas and the H_{SM} site seismic hazard map for the Emilia-Romagna territory.

4. Discussion of the results

Maps in Figs. 13 and 14 show a realistic representation of site seismic hazard because they consider both the reference seismic hazard and the amplification caused by the local geological conditions.

By comparing the maps in Fig. 13 we observe the highest site seismic hazard values in Fivizzano ($H_{SM} > 1000$ cm/s^2), where the reference seismic hazard is high ($ASI_{UHS} > 150$ cm/s) and local geological conditions determine important local effects ($AF_{0105} > 2.5$), while the lowest values are in Berra ($H_{SM} < 300$ cm/s^2), where both the reference seismic hazard ($65 < ASI_{UHS} < 68$ cm/s) and AFs are low ($AF_{0105} \leq 1.3$), because of the presence of very thick loose sediments. In Zola Predosa, where the reference seismic hazard is medium ($0.125 < ASI_{UHS} < 150$ cm/s) and the AFs vary from medium to high ($1.7 \leq AF_{0105} \leq 2.4$), we have obtained intermediate site seismic hazard values ($500 < H_{SM} < 900$ cm/s^2). This comparison shows that the zonation of the territory through the H_{SM} parameter allows a true classification of local seismic hazard that is also valid between zones far from each other, i.e. belonging to different seismogenic areas, and with very different geomorphological environment.

The analysis of the site seismic hazard regional map (Fig. 14) and the comparison with reference seismic hazard (Figs. 1 and 9) allow us to even better appreciate the effectiveness of the H_{SM} parameter. According to the maps shown in Figs. 1 and 9, the reference seismic hazard in

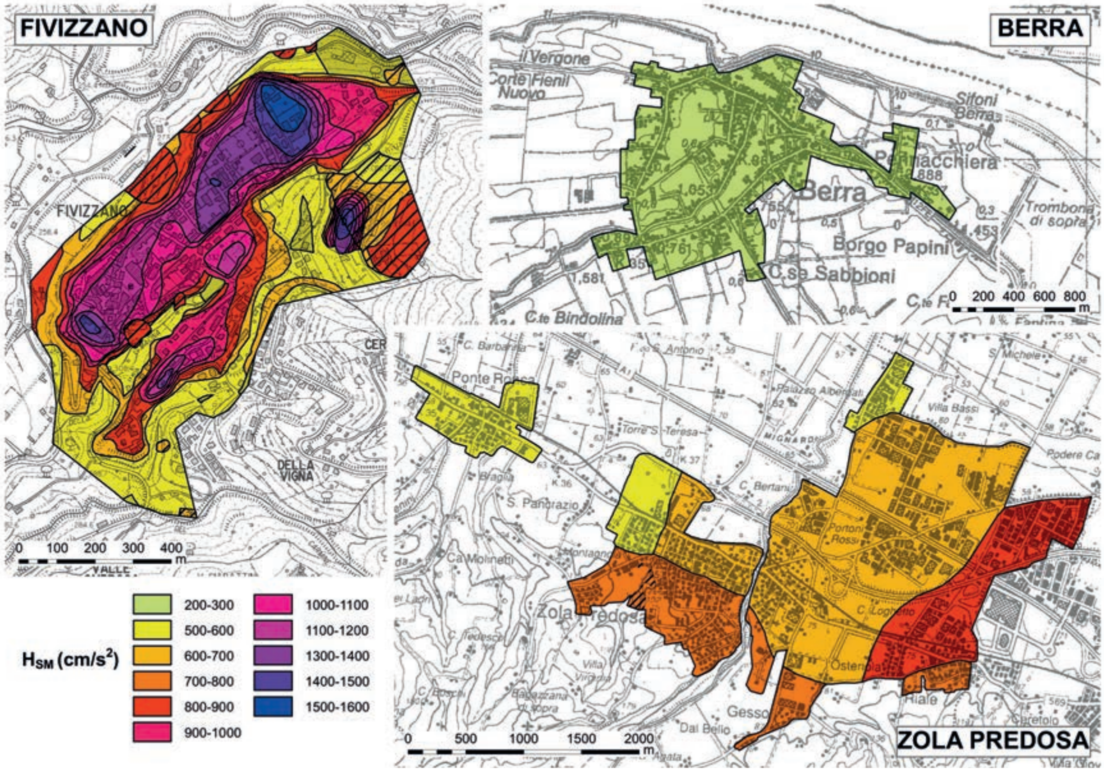

Fig. 13 - H_{SM} seismic microzonation maps of the local test areas.

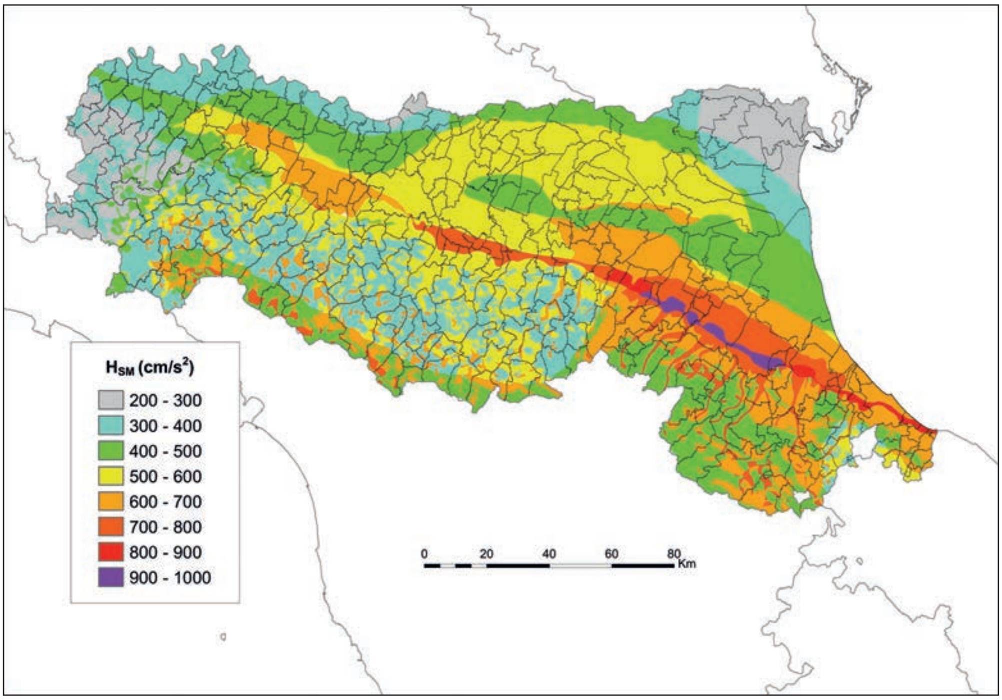

Fig. 14 - H_{SM} Emilia-Romagna map (regional site seismic hazard for $0.1 \le T \le 0.5$ s, $T_R = 475$ years).

Emilia-Romagna decreases gradually from the Apennine watershed to the Po River whereas the site seismic hazard (Fig. 14), which also takes into account the local effects (Fig. 12), shows a very different distribution of the values. In fact, the highest values ($H_{SM} > 700$ cm/s^2) are not expected in the Romagna Apennines, where the reference seismic hazard is the highest (Figs. 1 and 5), but rather along the Apennine - Po Plain margin, where the reference seismic hazard is intermediate ($ASI_{UHS} > 150$ cm/s) but the mean AF is higher ($AF_{0105} = 2.1$). The influence of the local hazard conditions in the plain is also important: high H_{SM} values ($H_{SM} > 500$ cm/s^2) are expected in areas with buried ridges (pede-Apennine thrust system; Emilia, Ferrara, Romagna and Adriatic Folds), where a high mean AF has been evaluated ($AF_{0105} = 1.7$), whereas in the syncline areas, where the loose sediments are hundreds of metres thick (type 3 plain deposit in Fig. 2a), low amplification ($AF_{0105} \leq 1.3$) and low H_{SM} values ($H_{SM} < 300$ cm/s^2) are expected.

In the Apennines, high values ($H_{SM} > 500$ cm/s^2) are expected in valley floors and where soft or deformed rocks are present (Pliocene - Pleistocene clay, fractured clay complex, etc.). The lowest values ($H_{SM} < 500$ cm/s^2) are expected, in addition, where solid rock outcrops ($AF_{0105} = 1.0$), in the westernmost sector of the region (western Piacenza Province) and in Po River delta where the reference seismic hazard is low ($ASI_{UHS} < 100$ cm/s).

The H_{SM} parameter can be discretised into classes in a semi-quantitative way, relating to the level of shaking, the potential damage to buildings and the instrumental intensity. Possible classes thresholds for the H_{SM} values (Table 1) can vary from "low-very low", "moderate-low", "moderate", "high", to "very high" seismic hazard.

Table 1 - Possible thresholds for H_{SM} and others physical parameters.

seismic hazard	low-very low	moderate-low	moderate	high	very high
H_{SM} (cm/s^2)	≤ 180	$180 < H_{SM} \leq 340$	$340 < H_{SM} \leq 650$	$650 < H_{SM} \leq 1240$	> 1240
potential damage	none - very light	very light - moderate	moderate - heavy	heavy	very heavy
instrumental intensity	≤ VI	VII	VIII	IX	≥ X

The threshold values of the classes in Table 1 have been defined empirically by establishing a relationship between H_{SM} and PGA.

$$H_{SM} = 0.8678 \times PGA_{SM} + 0.0044 \tag{3}$$

where PGA_{SM} is PGA at the surface, considering the amplification due to the soft deposits, and linking the PGA to the potential damage (macroseismic intensity) through the relation of Gomez Capera *et al*. (2007)

$$\text{Log}\ PGA_{SM} = -1.85 + 0.29 \times I_{MCS}. \tag{4}$$

The thresholds shown in Table 1 are congruous with the values found by Gomez Capera *et al*. (2007, 2015), as well as with those reported in Faenza and Michelini (2010) for the INGV Shake Maps and with the values of Bramerini and Di Pasquale (2002) for the proposal of seismic reclassification of the Italian national territory.

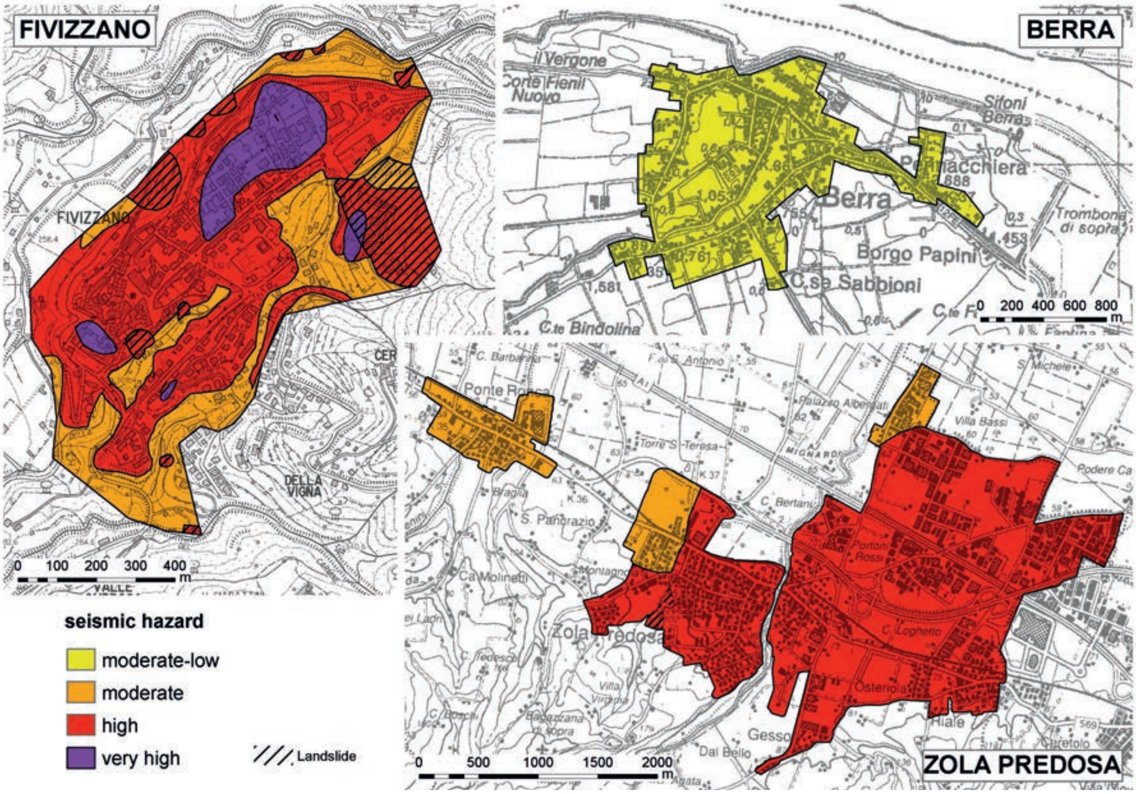

Fig. 15 - Seismic hazard maps of the local scale test areas according to Table 1.

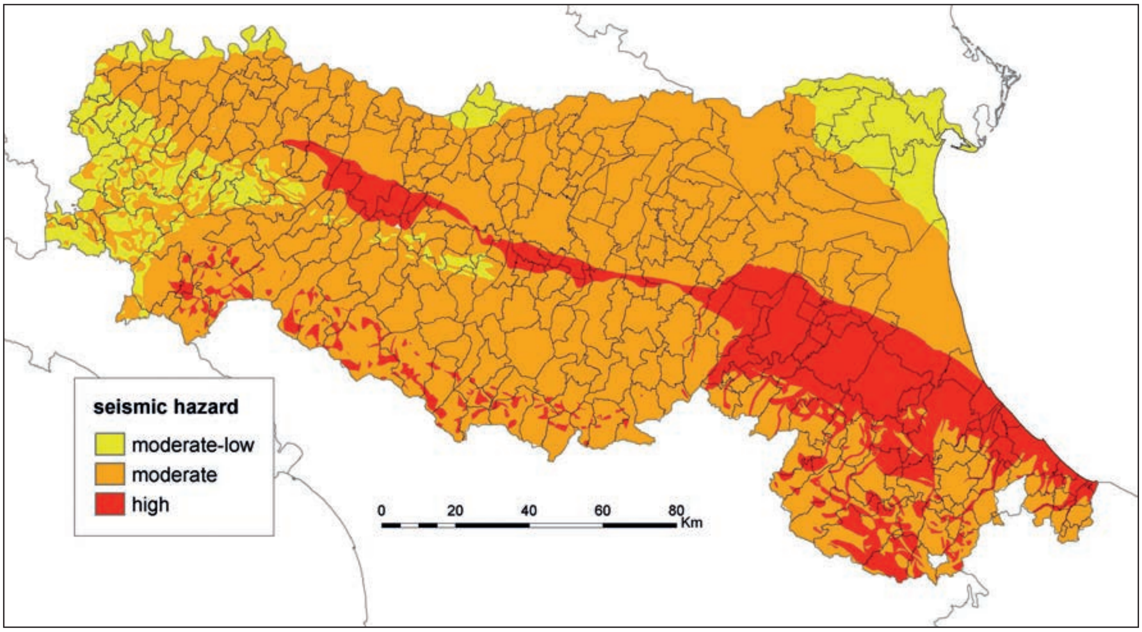

Fig. 16 - Seismic hazard maps of Emilia-Romagna (regional scale test area) according to Table 1.

A table of intensity descriptions with the corresponding PGA and peak ground velocity values and potential damage can be found in the Shake Maps background information [Earthquake Scenarios in Faenza and Michelini (2010)]. Earthquake Scenarios describe the expected ground motions and effects of specific hypothetical large earthquakes. In Table 1, the same values are faithfully reported. Figs. 15 and 16 show study areas maps according to classes of Table 1. This classification has an undoubted communicative power for non-experts (e.g. politicians, administrators) and can be better related to land use rules, as shown for the land use planning guidelines approved for zone prone instabilities (CTMS, 2015, 2017a, 2017b; TCSM, 2018).

5. Conclusive remarks

To implement policies for prevention and mitigation of natural risks in a correct and effective manner, the authorities responsible for territorial management need maps of hazard conditions of the territory as realistic as possible.

Tests carried out on local and regional scales show how it is possible to realise reliable site seismic hazard maps based on seismic microzonation studies or local seismic response analyses. Basic conditions consist of the knowledge on reference seismic hazard available throughout the country and storing data in GIS format. These low-cost maps can provide significantly different results compared to the seismic hazard maps used so far, usually referred to the reference seismic hazard and without considering local effects due to geological and morphological conditions, and can be quickly achieved. The tests demonstrate the simplicity of calculation and representation as well as the effectiveness of the H_{SM} parameter. The mapping of this parameter allows to create realistic maps and a classification of seismic hazard applicable to the various scales, from local to national territory.

It is worth underlining that the available data and procedures (see the reference seismic hazard data in http://esse1.mi.ingv.it/ and the Regional and national guidelines for seismic microzonation) make it possible to create seismic hazard maps even for other interval of T periods (e.g. PGA, $0.5 \leq T \leq 1.5$ s, etc.) and different return times, depending on needs and purposes.

The H_{SM} parameter can be discretised into classes characterised not only by a hazard in acceleration, but also by physical references that are easier to evaluate, such as the perceived shaking and potential damage; this classification has an undeniable communicative power and can be better related to land use rules.

This kind of maps allow the authorities responsible for territorial management to make more informed and effective choices for the reduction of seismic risk.

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