Seismic risk reduction: a local effects map for territorial and urban planning. The example of the Rimini Territorial Plan

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ABSTRACT Studies on local seismic response and seismic zonation constitute one of the most valuable tools for an effective seismic risk reduction strategy. They allow us to map the areas of greatest seismic hazard and then to identify low-risk areas suitable for urbanization and permissible interventions. These maps are, therefore, particularly effective when utilized starting from the very earliest planning stages. Consequently, it is important to gather information on seismic hazard on a territorial scale through studies to be carried out as quickly, and as cost-effectively, as possible. The proposed method allows us to quickly produce maps of areas potentially susceptible to local effects, thanks to GIS-assisted processing of existing data.These documents can also prove useful for a more realistic definition of damage forecasts for emergency planning (Civil Protection plans).

1. Introduction

The Italian law L. 741 (1981) establishes that Local Authorities are responsible for promoting studies and formulating plans of action aimed at reducing seismic risk, for implementation during territorial and urban planning.

The Emilia-Romagna Regional Authority embraced this regulation in the regional law L.R. 35 (1984).

Land zonation, based on local seismic response, is one of the most effective tools for the definition and reduction of seismic risk, since it provides precious help in the identification of areas of greatest seismic hazard; this, in turn facilitates the identification of low-risk areas suitable for urbanization and the outlining of permissible interventions.

Accordingly, since the circular 1288/1983 “Methodological indications on geological surveys to be produced as attachments to municipal urban planning documents”, confirmed by regional law L.R. 31 (2002), the Emilia-Romagna Regional Authority has instructed that all seismic-prone municipalities should identify the territorial elements that might determine local effects and that planning choices should take this seismic zonation into account.

In 2003, the new Italian seismic legislation n. 3274 (OPCM 3274, 2003) declared all Italian municipalities seismic, dividing the territory into four classes, based on seismic hazard (class 1 = high seismicity, class 4 = very low seismicity). The more recent Italian ministerial decree D.M. LL.PP. 14/9/2005 urges Local Authorities to promote analyses of local seismic response and seismic microzonation. On this matter, Deliberation n. 1677/2005 of the Emilia-Romagna Authority, which provides an implementation framework for OPCM 3274 (2003) and D.M. LL.PP. 14/9/2005, confirms (paragraph 6) that territorial and urban planning must identify areas subject to local effects in accordance with the indications set out in the regional circular 1288/1983 and L.R. 31 (2002).

These maps are particularly effective when they can give information about the choice of areas from the earliest territorial and urban planning stages, i.e. constitute part of the knowledge framework of the Provincial Territorial Coordination Plans and of the Municipal Structural Plans, as provided in regional law L.R. 20 (2000), indicating authorities and professionals which further studies and surveys one and permissible interventions.

We must, therefore, have detailed information on local seismic hazard scenarios which enable territorial zonation with time-scale and costs that are proportionate to the level of information of the knowledge framework. To produce these documents quickly and cost-effectively is in stark contrast with the importance of the information required; we must therefore identify a method which allows us to map local seismic hazard scenarios using time-saving methods based on reliable data.

2. The proposed method

The knowledge of the territory we possess today (geological maps and databases, topographical maps and digital terrain models) allows us to quickly identify those geological and morphological elements that can promote local effects.

The main territorial elements that contribute to seismic hazard in Emilia-Romagna are listed in Table 1.

The majority of data required to identify these territorial elements is generally available; in particular, from the various Local Authorities (Regional, Provincial and Municipal Authorities, Basin Authorities, Mountain Community), from local consortiums and utility companies and from the major companies responsible for the planning and realization of large-scale works (Autostrade per l'Italia, Italferr, ANAS, ENEL, ENI).

Today, armed with the necessary data, we can avail of GIS technology to quickly and cost-effectively compile maps of areas subject to local effects, according to the shown diagram Fig. 1.

Since Italian geological maps are mostly compiled using the criteria of lithostratigraphy (Salvador, 1994), deriving lithological maps of the bedrock and debris covers is virtually instant. The elaboration of these maps is made easier by databases containing information on the stratigraphy, geotechnical and geophysical characteristics of the lithological units in the subsoil.

Geological data, widely available from local authorities, coupled with stratigraphic logs from penetrometric tests and boreholes generally provide us with a detailed lithostratigraphical picture of up to a depth of approximately 30 m, and locally, up to several hundred metres when we can avail of deep-well stratigraphy for water supplies. The availability of seismic profiles and boreholes for hydrocarbon exploration enables us to make on interpretation that goes to far greater depths, also allowing us to identify the bedrock of alluvial deposits, sometimes hundreds of metres deep in the Po Plain (Regione Emilia-Romagna and ENI-AGIP, 1998; Boccaletti *et al.*, 2004).

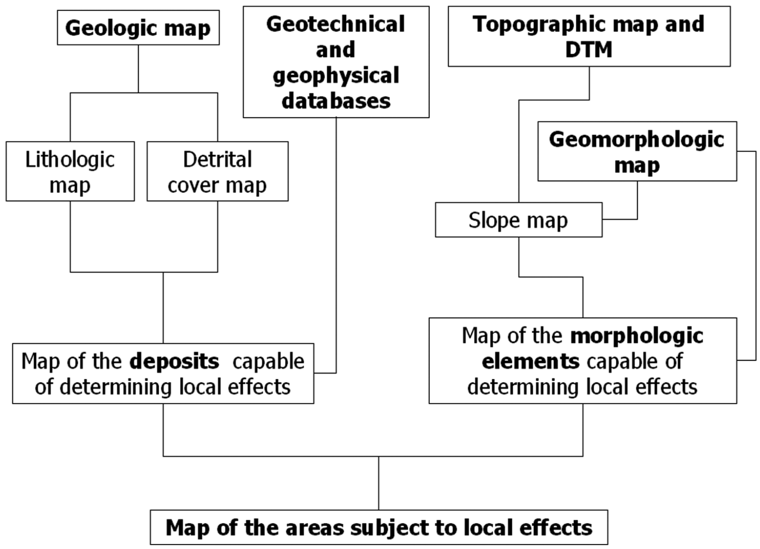


Fig. 1 - Flowchart of the proposed method for the compilation of local effects maps.

We can obtain a map of deposits susceptible to local effects from the lithological maps of the bedrock and of the detrital cover.

Morphological elements can be identified using detailed topographic maps (for example the regional technical map to scale 1:5,000 or 1:10,000). Selecting land forms is undoubtedly quicker when availing of a digital terrain model (DTM) to a suitable scale; based on the digital terrain model, GIS can be used to produce a slope map.

Naturally, we prefer to rely on geomorphological maps but, regrettably, this type of cartography is not yet widely available.

Given the scant number of studies on the behaviour of morphological elements during earthquakes, there are a few indications available on land forms that can potentially alter the seismic movement on the surface. In absence of more specific information, in mapping morphological elements, we may adopt Eurocode 8 as a reference (EN 1998-5, 2003).

From the maps of deposits and topographic elements capable of determining local effects, we obtain a map of the areas susceptible to local effects. This map, containing only qualitative information, cannot be considered a seismic zonation map; nonetheless, it allows us to identify areas with various local seismic hazard scenario potentials.

Since it is based exclusively on existing data, without additional information from new surveys, the map obtained with the proposed method is considered useful for planning at a territorial scale, i.e. sovra-municipal level (1:25,000). On a municipal or urbanistic scale (1:10,000 or 1:5,000) the quantity and distribution of data may not allow the automatic elaboration of a fully documented, reliable map: in this case further surveys may be necessary. At an urban planning level, more in-depth surveys must verify the effective presence and extent of elements with the potential of determining local effects.

In particular, since the phenomenon of amplification due to the presence of incoherent

Table 1 - Geological and topographic elements that can cause local effects in Emilia-Romagna.

Expected effect: AMPLIFICATION
- Deposits (thickness ≥5 m): a) slope debris (landslides, colluvium, moraines, …) b) alluvial fans c) alluvial sediments d) piedmont debris and talus cones e) fluvial-lacustrine sediments f) landfills g) hard fractured or altered bedrock h) substratum (marine clays, silts or sands) with Vs < 800 m/s
- Topographic elements: a) scarp (slope angle ≥45°) with height ≥10 m b) isolated cliffs, crest or elongated ridge with height ≥30 m and slope angle ≥30° c) slopes with angle ≥15° and height ≥30 m
Expected effects: AMPLIFICATION, LIQUEFACTION, SUBSIDENCE
- Loose sandy soils < 20 m deep, with water table close to the surface (< 15 m) (potentially liquefiable soils)
- Deposits (thickness ≥5 m) of loose-to-medium cohesionless soil (with or without some soft cohesive layers) or of predominantly soft-to-firm cohesive soil, characterized by N_{SPT} < 15 o c_u < 70 kPa o Vs_{30} < 180 m/sec
Expected effects: DIFFERENTIAL EFFECTS (AMPLIFICATION, SUBSIDENCE)
- boundary zones between lithologic units characterized by different geotechnical properties;
- underground cavities
Expected effect: SLOPE INSTABILITY
- active landslides and surrounding areas;
- potential unstable areas: dormant landslides; detrital slopes or clayey slopes or hard fractured slopes with angle>15°; slopes made by alternation of shales and sandstones, with beds parallel to the slope or with angle of dip < slope angle.

deposits interacts only with constructions in the presence of thicknesses > 5 m, so for municipal scale planning, primary importance must be given to the thickness of the detrital cover and the depth of the bedrock in order to exclude the areas not affected by the phenomenon.

3. An example of the proposed method: the local effects map of the Rimini Province

To better illustrate the proposed methodology, we will describe the various stages (Fig. 1) that go into the creation of the local seismic hazard map for the knowledge framework of the Rimini Provincial Territorial Coordination Plan (PTCP).

With reference to national seismic classification, all municipalities of the Rimini Province are in class 2, i.e. medium-high seismicity, with historical earthquakes of magnitude up to 6 on the

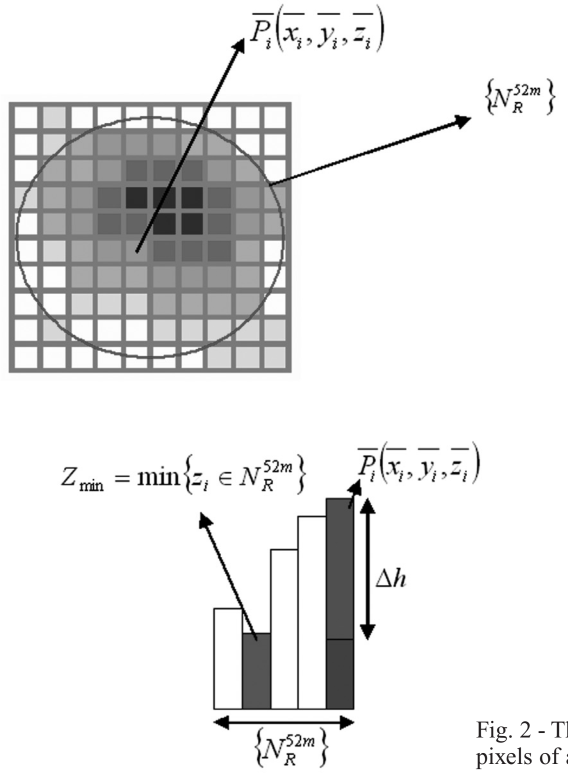


Fig. 2 - The figure describes the approach used to identify the pixels of area 1 (for explanation see the text).

Richter scale and intensity IX-X on the MCS scale.

Hence, in 2004, the Provincial Authority, in conjunction with the Regional Authority, decided to carry out a study on local seismic hazard and include a map of expected local effects in the knowledge framework of the new PTCP.

Based on the geological map to scale 1:10,000 of the Emilia-Romagna Apennines a lithological map of the bedrock was produced, grouping lithostratigraphic units into the following classes:

1. massive stones; stratified sandstones, limestones and marls; alternation of sandstone and mudstone with sandstone/mudstone ratio ≥ 1/5; shales;
2. alternation of mudstones and sandstones with sandstone/mudstone ratio < 1/5; clays; poorly cemented sandstone or sand; deeply fractured rocks.

The subdivision of the substratum lithological units into these two classes is based on considerations regarding the geomechanical characteristics of outcropping Apenninic formations in the Rimini Province and on the analysis of Vs measurements available. Down-hole, cross-hole tests and refraction microtremor tests, carried out for other projects in various areas of the region, indicate that the lithologic units of class 1 are characterized by Vs ≈ 750÷800 m/s or more (value considered indicative of seismic bedrock) while the lithologic units of class 2 are often characterised by Vs varying between 350 and 600 m/s, lasting also for several metres, comparable to that of detrital cover. Consequently, despite the fact that they belong to the Apenninic marine successions, the lithologic units of class 2 cannot be considered seismic bedrock and they must be treated as deposits which can cause amplification. On the contrary, in gravels of buried alluvial fans, at a depth of 30÷40 m, we have even measured Vs>700 m/s. So, seismic bedrock does not always coincide with outcropping pre-Quaternary marine lithologies or with the base of alluvial sediments.

For this reason, in the plain and coastal sectors, we have compiled maps of outcropping and buried deposits.

The map of outcropping deposits is based on surveys carried out for the new Geological Map of Italy (for example, see Martelli *et al.*, 2005). Deposits of the plains and coast have been grouped into two broad lithologic-environmental classes:

1. alluvial deposits, consisting of gravel, sandy silt and silty sand;
2. coastal deposits, consisting mainly of fine and medium sand, generally 6÷10 m thick, with the water table close to the surface.

These deposits are both susceptible to amplification; distinction between the two classes was necessary because the terrains in class 2 present characteristics that predispose them to liquefaction. The propensity to liquefaction of the terrain in several areas along the Romagna coast is confirmed by the preliminary study of Cipriani *et al.* (2000) and by historical reports (Serpieri, 1889; Postpischl, 1985; Galli and Meloni, 1993).

The map of the subsoil, created using the subsoil geological database available for the entire Emilia-Romagna plain, gathers together numerous stratigraphic logs from continuous core drillings, water wells, hydrocarbon exploration bore holes and cone penetration tests. It represents buried lithological bodies which might potentially constitute the seismic bedrock. The map therefore details the upper surfaces (isobaths refer to average sea level) of main gravel bodies with thickness > 5 m. These bodies belong to the alluvial fans of the Marecchia and Conca Rivers.

The geological map to 1:10,000 of the Emilia-Romagna Apennines was also used to develop the map of the detrital cover of the Apenninic sector. This elaboration was facilitated by the organization of the geological map database into different data layers, allowing separate data management.

Quaternary continental deposits are grouped into the following 3 classes:

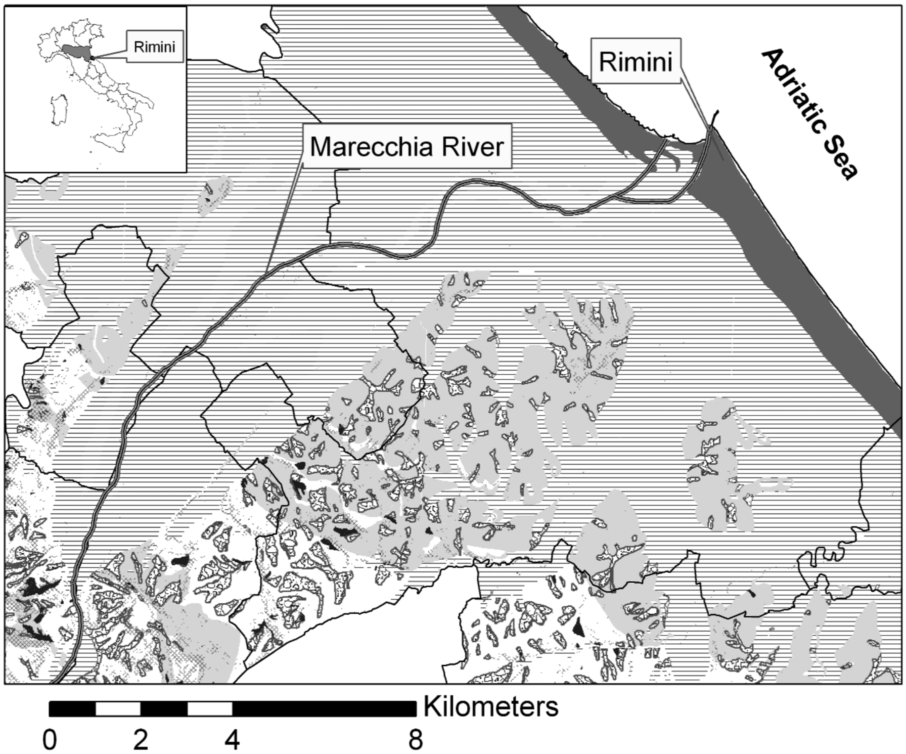
1. active landslides;
2. slope deposits, including quiescent landslides;
3. alluvial deposits.

The distinction between active landslides and slope deposits, although both are susceptible to amplification and slope instability, has been maintained in view of the significantly greater propensity of the deposits in class 1 to slide down, and also because interventions in those areas affected by active landslides are generally restricted by specific regulations, aport from the seismic risk.

To identify and represent morphological elements capable of determining amplification, a special DTM (with 5 m x 5 m grid cells) was developed for the entire territory of the Rimini Province. The DTM in question was obtained by interpolating point elevations and level curves surveyed on site using the ANUDEM algorithm.

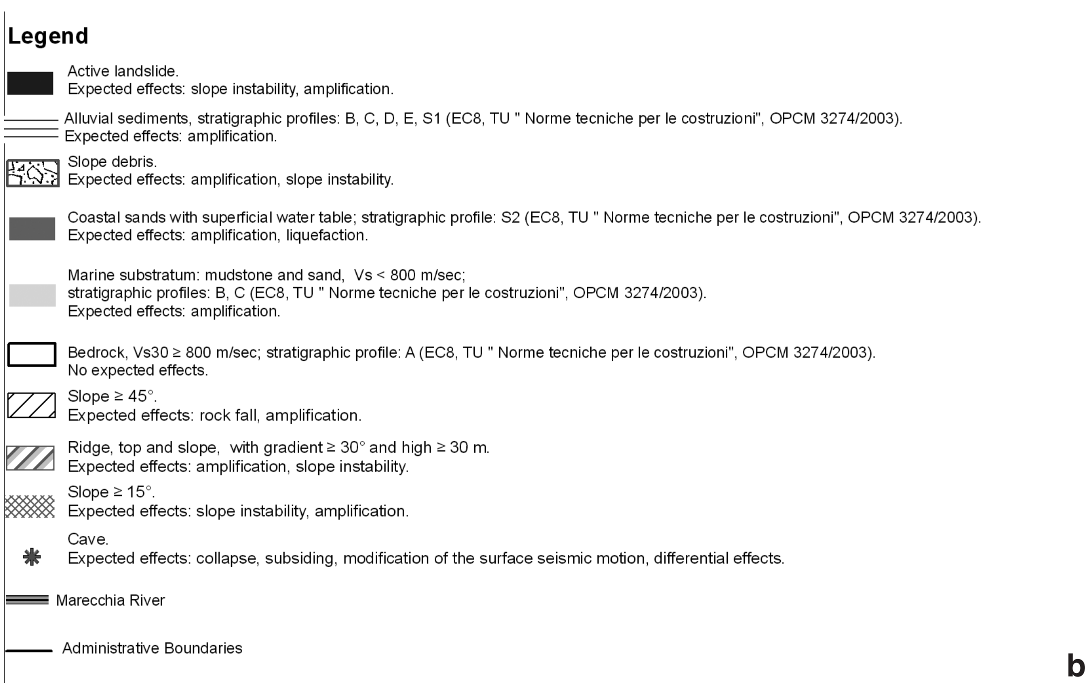
The identification of topographic elements (EN 1998-5, 2003), such as

1. isolated cliffs, crests and elongated ridges with height ≥ 30 m and slope angle ≥ 30°;



a)

Fig. 3 - From the “Local effects map of the Rimini Province”: a) simplified example; b) legend of the map.



2. slopes with angle ≥ 15° and height ≥ 30° ,

was carried out using a GIS-based algorithm.

For the areas at point 1 the GIS procedure identifies P_i pixels of the provincial DTM belonging to the ridge area when the difference in elevation between their height and the minimum elevation value of all pixels within a 52 m radius exceeds 30 m, the chosen 52 m radius ensuring that the average slope of the area is above 30 degrees.

The GIS based procedure for evaluating if a generic Pixel $\bar{P}_i\ (\bar{x}_i, \bar{y}_i, \bar{z}_i)$ of the DTM can be classified as an element belonging to class 1 consists in the following steps:

1) definition of set pixels N_R^{52m} that are included in a neighbourhood defined by a circle with a 52 m radius and centre at the Pixel $\bar{P}_i\ (\bar{x}_i, \bar{y}_i, \bar{z}_i)$ (Fig. 2);
2) evaluation of the minimum elevation $Z_{\min} = \min\left\{z_i \in N_R^{52m}\right\}$ of the pixels belonging to the set N_R^{52m} (Fig. 2);
3) evaluation of the difference Δh between the elevation $\bar{z}_i$ of the pixel $\bar{P}_i\ (\bar{x}_i, \bar{y}_i, \bar{z}_i)$ and the minimum elevation $Z_{\min}$ (Fig. 2);
4) the pixel $\bar{P}_i\ (\bar{x}_i, \bar{y}_i, \bar{z}_i)$ is classified as belonging to class 1 only if the Δh is greater than 30 m.

To identify these points, a GIS-based procedure was developed using the spatial functions of ArcGIS software (ArcToolBox), particularly the Neighbourhood and slope functions.

The above-described analytical maps form the basis for the final cartography, to scale 1:25,000, of areas susceptible to local effects (Fig. 3).

In addition to a brief description of distinct elements, the legend also indicates the local effects expected and the possible soil categories, in accordance with the classification outlined by Eurocode 8 (EN 1998-1, 2003), OPCM 3274 (2003) and D.M. LL.PP. 14/9/2005. The correlation between mapped areas and soil categories specified in current regulations was possible not only thanks to lithological considerations, but also on the basis of a number of geophysical and geotechnical surveys.

More specifically, the characteristics of the mapped elements are as follows.

- Slope-debris: detrital slope deposits, including landslide accumulations without sign of recent movement. These areas are susceptible to amplification (possible soil categories B, C, D and S_1) and strong earthquakes may even lead to slope instability phenomena. In these zones, therefore, it is necessary to evaluate the potential for amplification and the slope stability, taking into account possible seismic stress.
- Active landslide: landslide accumulations with signs of recent or ongoing movement. As mentioned above, the distinction between active landslide accumulations and other slope deposits is necessary in view of the former’s greater susceptibility to slide down, a critical condition that can be further aggravated by seismic activity. These areas are generally subject to specific regulations aimed at reducing landslide hazard and usually no new building or infrastructure is permissible; in the event of any consolidation and safety improvement measures on existing buildings, again in this case, surveys and studies must assess not only the risk of amplification, but slope stability conditions, taking into account seismic stress.
- Alluvial sediments: fluvial deposits including those on the valley floor and terraced fans in the Apenninic sector and those on the plain. All these areas are potentially susceptible to

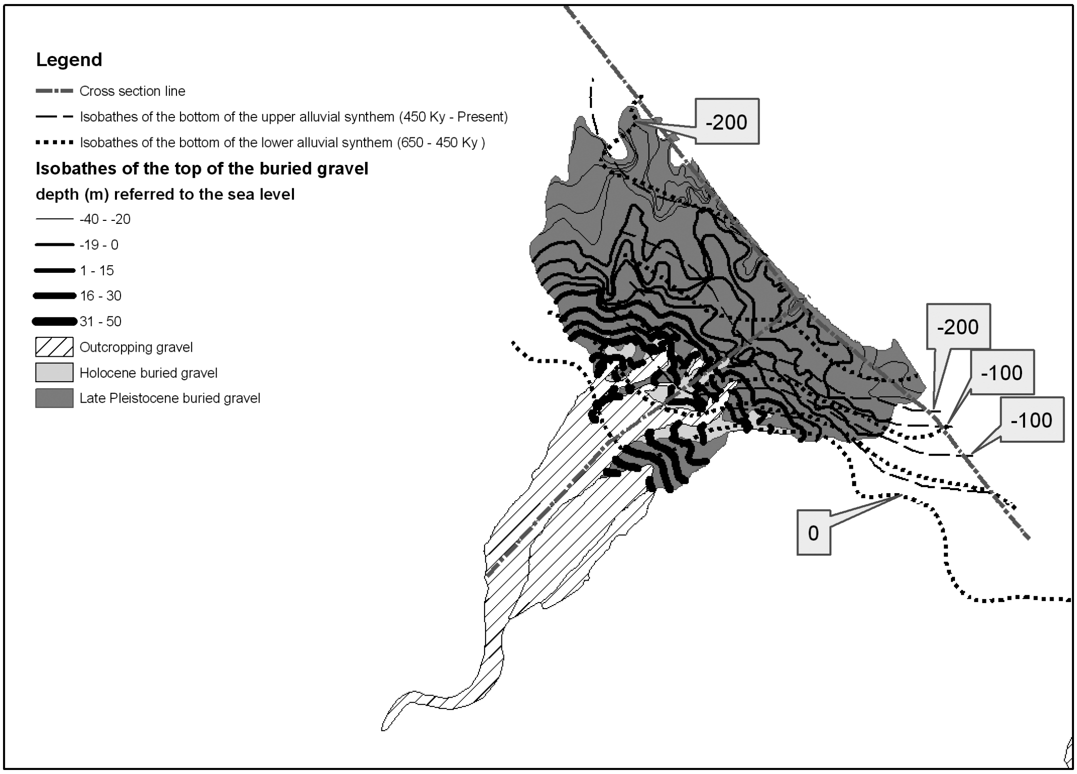


Fig. 4 - Example of the subsoil map.

amplification (possible soil categories B, C, D, E and S_1).

- Coastal sands: areas where, in the first 10 m from the surface, we find coastal deposits, mostly sandy, generally incoherent and well classed, with the water table near the surface. The combination of incoherent, well classed sand in the first 20 m from the surface and the presence of groundwater at a depth < 15 m constitutes a situation of predisposition to liquefaction and densification in the event of strong earthquakes (M>5). These areas therefore present the characteristics of a stratigraphic profile corresponding to soil category S_2; in these areas, therefore, we must assess not only the risk of amplification, but also the potential for liquefaction.
- Marine formations with low shear wave velocity: areas where the foundation soil consists of terrain ascribable to pre-middle Pleistocene marine lithologies with mechanical characteristics such that lead us to hypothesize Vs<800 m/s even at depths of several tens of metres (clays, poorly cemented sand), and hence potentially subject to amplification. These areas can be characterised by stratigraphic profiles corresponding to soil categories B and C. As a result, in these areas, surveys must be carried out as part of municipal urban planning to assess Vs and, in the event of Vs<800 m/s, further studies must be commissioned to evaluate local seismic response.

- Bedrock: white areas indicate those zones where bedrock is cropping out, or the detrital cover thickness < 5 m, and $Vs_{30} \geq 800$ m/s. These areas can therefore be considered as outcropping seismic bedrock; moreover, no topographic elements that might determine amplification are present. These terrains are therefore characterised by a stratigraphic profile corresponding to soil category A and in these zones, therefore, no local effects are expected.

As regards the areas subject to local effects due to topographic elements, in accordance with Eurocode 8 and as described above, the following scenarios have been highlighted:

- slopes with angle > 15°;
- isolated cliffs, crests and elongated ridges with slope angle ≥ 30° and height ≥ 30 m;
- scarps (slopes with angle ≥ 45°) with height ≥ 10 m.

Areas with underground cavities, both of anthropic and natural origin, are also marked, since they may alter seismic movement on the surface and generate collapses or subsidence and/or differential effects.

The map of the subsoil of the plain and coastal area (Fig. 4) was compiled thanks especially to the maps of the "Underground water reserves of the Emilia-Romagna Region" (Regione Emilia-Romagna and ENI-Agip, 1998) and the recent cartography for the Geological Map of Italy (see, for example, Martelli *et al.*, 2005). In this map, the basal unconformities (isobaths refer to average sea level) of the main alluvial cycles of the Po Plain subsoil, the Upper Emilia-Romagna Synthem (450 ky÷Present) and the Lower Emilia-Romagna Synthem (650÷450 ky) are mapped. The basal unconformity of the Lower Emilia-Romagna Synthem corresponds to the top of the marine succession.

In order to best represent the geometry, thickness and stratigraphy of the buried lithologies in the Po Plain-Adriatic subsoil, geological cross-sections can be attached.

After completion of this map, new geophysical surveys were carried out for other projects, providing additional Vs data.

This new data confirms the correlation between mapped areas and the soil categories indicated in the legend.

In the foothill areas and in the upper plain, mostly characterized by gravel of alluvial fans and terraces of the Marecchia and Conca Rivers, Vs_{30} is between 360 and 800 m/s, and so the stratigraphic profiles of the terrain correspond to soil category B.

Along the coast, below the horizon of coastal sands, fine alluvial deposits prevail, mostly consisting of clayey silt and sandy silt intercalated with sand. Available tests indicate Vs_{30} between 160 and 200 m/s, indicative of soil category C (180 m/s$<Vs_{30}<$360 m/s), D ($Vs_{30}<$180 m/s), and confirm the presence of potentially liquefiable soils (soil category S_2).

Some drillings perforated the marine substratum by several metres, allowing us to also obtain Vs profiles from down-hole tests. The late Messinian-Middle Pleistocene marine deposits, predominantly consisting of clays and poorly cemented sandstone, are characterised by Vs generally between 360 m/s and 800 m/s even for several tens of metres. This data confirms that the terrains belonging to the marine succession of the Apenninic margin can be classified as belonging to soil category B and therefore potentially subject to amplification. Moreover, this means that the geological survey is not sufficient to characterize the seismic bedrock and therefore geophysical tests are required.

4. Conclusions

Knowledge of the geological and geomorphological characteristics of the territory allows us to map areas of greatest seismic hazard, i.e. those zones characterized by territorial elements capable of determining local effects.

The organization and elaboration of basic geological and morphological data using GIS technology allows us to produce these territorial-scale maps quickly and cost effectively.

This zonation, although not quantitative and on a territorial scale, is fundamental for an effective seismic risk reduction strategy, above all when implemented right from the earliest stages of territorial and urban planning, so is one of the survey documents for the PTCP and Municipal Structural Plans.

The map of areas susceptible to local effects at a provincial scale can, in our opinion, improve the elaboration of damage scenarios for emergency planning (Civil Protection plans), since it allows us to consider the distribution of the effects taking into account the physical characteristics of a territory at a suitable scale.

Given the quick data analysis and elaboration techniques and the scale of this type of cartography, more detailed surveys, to verify the information and indications supplied, are necessary at the urban scale.

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