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GIS-BASED IDENTIFICATION OF TOPOGRAPHIC SITES IN ITALY WITH SIGNIFICANT GROUND MOTION AMPLIFICATION EFFECTS

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ABSTRACT

Surface topography can significantly affect earthquake ground motions, as suggested by many examples of unexpected damage suffered by buildings located on the top of hills, on ridges or along slopes. European and Italian seismic codes suggest topographic aggravation factors in the 1 – 1.4 range to be applied to seismic actions, depending not only on simple morphologic parameters (average slope angle, width and height of the relief) but also on the type of relief (isolated cliff or ridge) and on the location of the site relative to the relief. Furthermore, strongly irregular topographies should be dealt with by a specific study.
To provide a practical tool for the identification of critical topographic sites, analyses of high resolution digital elevation models (DEM), with the support of Geographic Information Systems (GIS), are presented in this paper. Simple GIS functions are used to classify critical ranges of inclination, while the identification of valleys and ridges requires more complex procedures. A comparison of different methods for their identification is presented in this work, aiming at finding the most suitable ones for seismic microzonation analyses.
Once the critical conditions are synthesized into GIS layers, their proximity to inhabited centres or strategic structures are checked. The resulting maps can be used for topography-related seismic risk assessment at large scale. We present two examples of application of this procedure, with particular attention to the small historical centres located on the Apennine mountains in Central and Southern Italy.

INTRODUCTION

Unexpected high levels of damage observed during past earthquakes close to the top of steep reliefs have proven the relevance of seismic waves amplification due to surface topographic irregularities. This problem is especially critical in Italy due to the presence of a the large number of towns and villages located on irregular topographic profile, especially in Central and Southern Italy where the most seismically active areas are concentrated. Furthermore the historical centers of these villages are the most seismically vulnerable part and are often located at the top of isolated steep cliffs or at the crest of ridges.

There are many observations in the recent Italian seismic history of the relevance of such topographic effects, mainly based on macroseismic data, but supported as well more recently by instrumental data. A summary of references to relevant case histories during the Friuli (1976), Irpinia (1980), Umbria-Marche (1997) earthquakes is reported by Paolucci (2002). It is also worth recalling the 1887 event in western Liguria documented by Faccioli et al., (2002) and the instrumental observations during the Molise 2002 earthquake (Cara et al, 2005).

The quantitative analysis of topographic seismic effects is made difficult by the relatively small number of instrumental strong motion data, and by the fact that the available case histories are often controversial, mainly for the difficulty of separating the stratigraphic and morphologic contributions (Paolucci et al., 1999). Several important advancements on this side are expected based on the careful investigation of the records of the Italian strong motion network (RAN), that is presently carried out in the framework of the upgrade of the Italian strong-motion database ITACA (http://itaca.mi.ingv.it). Within the same research activity, the investigation of records

from the April 2009 L'Aquila earthquake sequence is presently under way, with special reference to the Narni topography array located about 70 km away from the mainshock epicenter (http://esse4.mi.ingv.it).

To account for topographic effects, the building codes suggest the use of seismic site amplification factors, related to the terrain morphology. For this purpose, the most recent Italian Technical Norms (NTC, 2008) provide a simplified classification of landforms, reflecting the same prescriptions as in the Part 5 of the EC8 (CEN, 2004). The norms identify four categories of landforms:

1. T1: flat surfaces, isolated slopes or reliefs with average inclination $\boldsymbol{i} \leq 15°$
2. T2: Slopes with average inclination $\boldsymbol{i} > 15°$
3. T3: Reliefs with ridge top width much smaller than the base, and average inclination $15° \leq \boldsymbol{i} \leq 30°$
4. T4: Reliefs with ridge top width much smaller than the base, and average inclination $\boldsymbol{i} > 30°$

These categories refer to bidimensional configurations, such as elongated crests and ridges, and must be considered only when their height is greater than 30 m. For each category the topographic amplification factor (S_T) on the design spectrum is provided, with $1 \leq S_T \leq 1.4$, while for more complex morphologies the norms require that specific site effects analyses be carried out.

This is the relatively frequent case of isolated cliffs whose morphology cannot be reduced to a 2D model, and, as proven by 3D numerical simulations (Paolucci, 2002; Scandella et al., 2008), may exhibit an amplification factor even larger than 1.4, also related to resonance effects involving the whole relief.

A more detailed classification of topography sites has been recently introduced in the technical guidelines for seismic microzonation studies in Italy (Working Group "Indirizzi e criteri generali per la microzonazione sismica", 2008) where empirical graphs are introduced to support the calibration of amplification factors as a function of the geometrical parameters identifying the topographic relief.

The identification at a large (regional) scale of small towns, or of specific sites potentially affected by significant topographic effects is herein addressed through GIS support.

A method has been firstly developed to perform microzonation analyses at national or regional scale. This “Level 0” approach identifies the simultaneous presence of zones of potential amplification of seismic ground motion and of critical elements, such as small urban centers or critical sites. A more detailed approach (Level 1) is then introduced, to classify at local scale the potential areas of amplification according to the T1 ÷ T4 landforms defined by the Italian norms.

The GIS analysis has shown that the proper identification method depends on the resolution of the Digital Elevation Model (DEM) and on the morphological features of the terrain. For these reasons, the case-histories presented in this paper refer to the Marche region (Central Italy) and the Calabria region (Southern Italy), the first one characterized by mountains with relatively low height and gentle morphology, and the second by high mountains and sharp topographic features.

Statistical results are presented for the inhabited localities of the two test regions, using a 20x20m DEM and the official census (ISTAT) data on residential buildings, aiming at providing a common framework to be extended all over the national territory.

Analyses are finalized to give an answer on how many localities could be affected by topographic amplification effects, and subsequently to recognize which are the critical elements for each locality (steep slope, presence of ridge, hilltop position, etc.) (Level 0). Once the locality has been recognised as critical, and after classifying the type of topographic irregularity, the relative amplification factor is associated to the site (Level 1).

A further level of approach (Level 2) consists in the specific analysis, experimental and/or numerical, of the topographic amplification effects of seismic motion at a specific site. Although this Level is not specifically addressed in this paper, it is worth mentioning that common spectral ratio techniques, such as the Horizontal-to-Vertical Spectral Ratios (HVSR), are generally inadequate for topographic sites and a detailed numerical analysis of a complex topographic site often requires complex 3D computational tools, only available to few research groups.

GIS PROCEDURES

The flowchart of Fig. 1 outlines the procedures used to identify the inhabited areas which may undergo topographic amplification effects. Two procedures to extract the required morphological parameters from a DEM have been tested, and the resulting layers overlaid with the administrative data. The first procedure may be used to perform a preliminary screening of the inhabited centres over large areas, and is compatible with a Level 0 microzonation analysis, while the second is more suitable for a more detailed, Level 1 microzonation study.

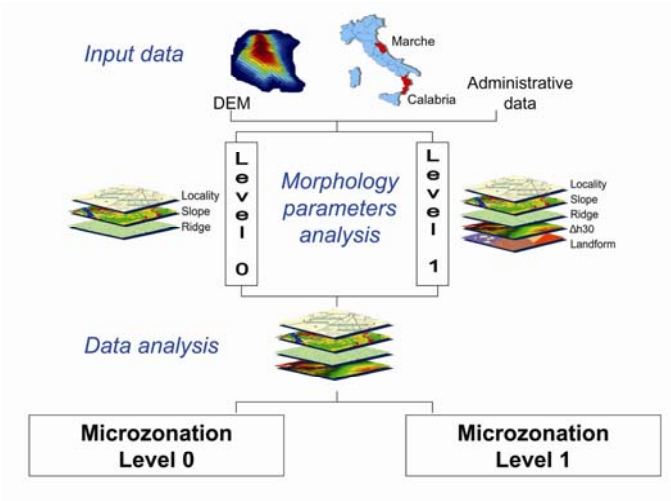


Fig.1. Flowchart of the proposed approach for identification of localities with amplification effects. The studied regions are the red polygons in the Italy map.

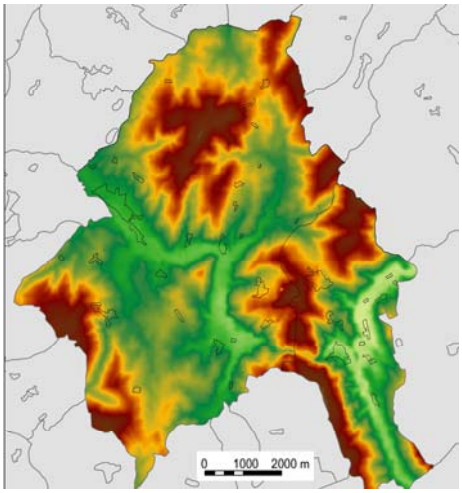


Fig. 2. The Genga municipality (in Marche region) is composed by 36 urbanized centres with different morphological features. Analysis has to be carried out at very local scale.

Processing of administrative data

Data about inhabited localities are from GeoBusiness Italy databank, elaborated by ESRI Italia S.p.A., on the base of the 1991 census data of the population (ISTAT, 2005), which store information about inhabited area at the resolution of census tract. These data have been processed by dissolving the polygons of inhabited centres and sparse buildings for each municipality, so that a new map of localities is created, to be overlaid to the grid information on slope, height difference and ridges. This processing has been made necessary since, especially in mountainous area, the municipalities embrace large territories with very different morphologic features and their characterization as a whole is meaningless. Instead, the new layers allow to carry out the analysis at the level of inhabited centre. For instance, Fig. 2 illustrates the Genga municipality (Marche region, Central Italy) that is predominantly mountainous and is constituted by 12 main centres (1.3% of the whole territory), mostly located on plain, and 24 small centres ("case sparse") made of few close houses, covering again the 1.3% of the municipal area. About 55.8% of the population lives in the main centres, while 35.4% inhabits the small ones. It is clear that a morphological classification at municipal scale would not provide useful indication for the management of the seismic risk.

Morphological parameters

The topographic features that need to be extracted from the DEM to identify possible sites of topographic amplifications are ridges and hilltops, together with morphological parameters such as slope and height difference.

Standard procedures exist nowadays in any GIS software for the production of slope maps that can subsequently be classified in three slope ranges according to the building code requirements ($\boldsymbol{i} < 15°$, $15° \leq \boldsymbol{i} < 30°$ and $\boldsymbol{i} \geq 30°$). The identification of crests and ridges, that, as shown in the introduction, is critical for a proper identification of the topography class, requires instead more complex procedures.

After testing different methods for the ridge identification, (for instance inversion of DEM and hydrology flow accumulation function or filtering process on the combination of curvature and slope maps) the following procedure has been proposed:

1. The DEM is smoothed with a low pass filter on a 3x3 pixel window, using the mean function, to reduce the DEM noise.

2. A flow accumulation and a curvature raster are created and compared, to select the areas with convex curvature and low flow accumulation.

3. The resulting map is filtered with a majority filter, first using a 3x3 pixel block then a 5x5 moving window, so that the main ridges are thickened and isolated pixel classified as ridge are removed.

4. A slope map is derived by the smoothed DEM and generalized for value ≤ 5°, using a Generalize – Region

group function, so that small topographic irregularities present in large flat areas are eliminated.

5. The slope map produced in step 4 and the first ridges map (step 3) are combined together by selecting only the ridges in steep zones (slope > 5°), so that local ridges in plain are removed.

The ridge areas of the resulting raster are then thinned and converted to vector features as shown in Fig.3.

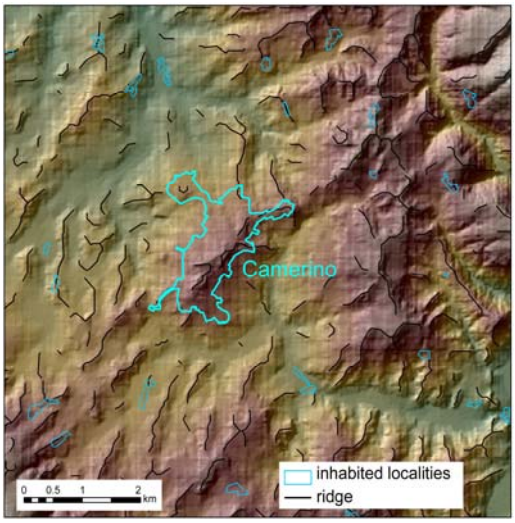


Fig. 3. Results of ridge detection (black lines) in the Appennine mountains.

The proposed method is relatively simple and fast to apply, and can be used for Level 0 analyses at the regional or national scales. At this phase it is possible to identify flat surfaces and isolated slopes or reliefs with average inclination $\boldsymbol{i} \leq 15°$, corresponding to the T1 class of the Italian building code, while the identification of the T2, T3 and T4 classes (isolated slopes and ridges with $\boldsymbol{i} > 15°$ and $\Delta h > 30$m) is still not immediate.

A more complex GIS procedure, implemented by Jenness (2006), has been tested to provide a more detailed landform classification. The procedure, originally developed for ArcView 3.x software, has been adapted in this work it for ArcMap 9.x.

Jennes algorithm calculates a Topographic Position Index (TPI) from a DEM, which allows to classify the landscape into slope position and landform category. Of the 10 landform classes proposed by Jennes some can be useful for the identification of ridges and hill tops. The calculation of the landforms is very time consuming, therefore the method is more easily applied to small regions rather than large areas and can be used to improve the Level 0 results. Fig. 4 shows the comparison between the landform classification and the ridge identification obtained by the Level 0 analysis described above.

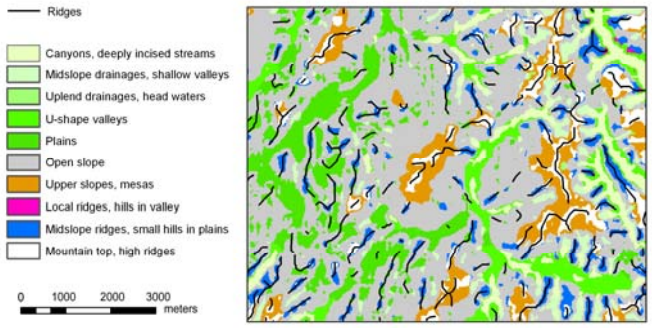


Fig. 4. Ridge identification (black line) and Jeness landform classification for the same area of Fig.3.

The landform procedure has been profitably used to introduce the height difference parameter ($\Delta h > 30$m) prescribed by the building code, that could not be taken into account with the Level 0 procedures. To this aim, a new method is implemented (see Fig. 5):

- Classes# 9 and #10 of the landform map refer to "midslope ridges, hills in valley" and "mountain top, high ridges" respectively. They are grouped together and transformed into uniform polygons representing the presence of a relief.

- *Table Statistic Analysis* is performed between these polygons and the DEM. Within each polygon the software read the elevation values and save the range of heights in a table, together with different statistic values (minimum and maximum value, mean, median and sum of the elevation data).

- The extraction of elevation data with range values > 30 m within every new polygons assures the presence of a sufficiently high relief.

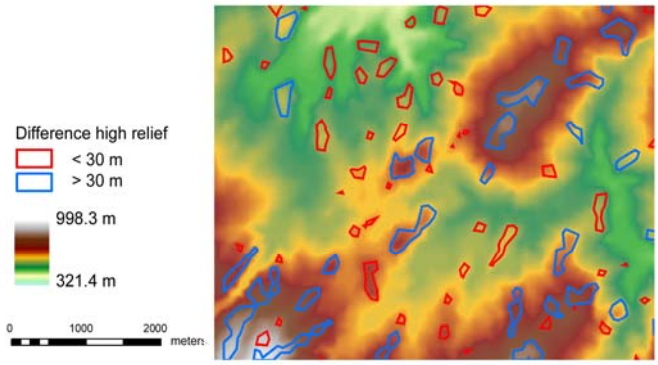


Fig. 5. Identification of areas with height difference larger than 30 m (blue polygons) (Detail of Fig.4).

THE CASE STUDY

Microzonation analysis – Level 0

The Level 0 microzonation of the inhabited areas is obtained through a *Table Statistic Analysis* between the administrative layer and the Level 0 morphological parameters. The slope map is reclassified into three classes with values ranging between 0 and 3 ($\boldsymbol{i} \leq 15$, $15° \leq \boldsymbol{i} \leq 30°$ and $\boldsymbol{i} > 30°$ respectively), while values of 0 (no ridge) and 1 (presence of ridge) are assigned to the ridge map. Within the polygon of each inhabited area the software calculates various statistics of the reclassified slope and ridge maps, such as minimum and maximum value, mean, median or sum. By combining the different values it is possible to identify the localities that can be affected by topographic amplification effects.

We consider

i) localities without amplification effects, with average slope $\boldsymbol{i} \leq 15°$, corresponding to the T1 class of the NTC

ii) localities with possible amplification effects, with $\boldsymbol{i} > 15°$, with or without presence of ridges

ii_a) localities with $\boldsymbol{i} \geq 30°$ and presence of ridges

As regard to ridge classification, a locality is selected if at least 1% of the inhabited area is occupied by a ridge. With regard to the slope class to which the village is assigned, this depends either on the maximum slope value present within the polygon, or on the median value. The first case is more conservative, while the second is useful to apply a more selective screening. The criteria used to define the three groups are shown in Table 1 below.

Table 1. Criteria used to define the Level 0 classification

Class	Percent_ridge	Slope_class
i	--	0
ii	--	≥ 1
ii_a	>1%	2

Table 2 shows the results of the analysis for the Marche and Calabria region, expressed in terms of percent of inhabited areas falling within the three amplification classes defined above, using the maximum slope value in the selection process.

Table 2. Level 0 classification results

Localities	Marche	Calabria
(i) without amplification effects	37.9%	25.8%
(ii) with possible amplification effects	62.1%	74.1%
(ii_a) with critical conditions	10%	27.3%

The statistical results reflect the different morphology present in the two regions, with a larger number of villages possibly affected by amplification effects in the Calabria region, which is characterised by steeper reliefs than Marche, as it was pointed out previously.

Fig. 6 shows the difference in the results obtained for the Level 0 microzonation by using the maximum and the median slope value in the Calabria region. By using the maximum slope value a larger number of polygons is selected, but many of them have only a small portion falling on a ridge or on a steep area. On the other hand, the inhabited area assigned to ii) using the median slope value fall nicely on ridge tops or steep slopes, but some villages on flat hilltops and ridges are missed out.

The application of either of the two methods depends on the purpose of the microzonation map. The more conservative choice could be selected to produce national or regional maps highlighting the zones which deserve a more detailed analysis by the local councils. A more selective screening could be used instead by a regional authority whishing to prioritise its resources to perform a survey on a limited number of critical villages. For the Calabria study area the difference in using the two method is relevant (see Table 3).

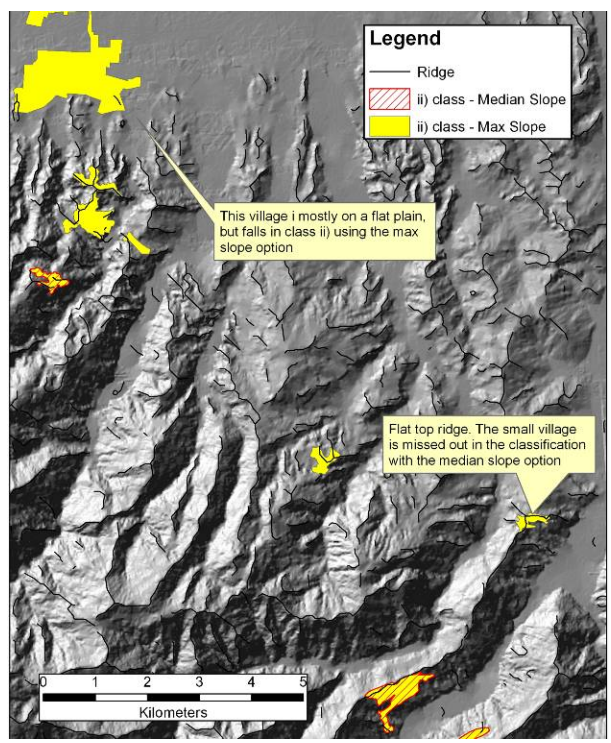


Fig. 6. *Inhabited areas with possible amplification effect (class ii). In yellow the polygons identified using the maximum slope option, in red dash the polygons identified with the median slope option.*

Table 3. Level 0 results for Calabria region – Difference obtained by using the median and the maximum slope value in the selection criteria

Localities	Median slope	Max slope
(i) without amplification effects	78.83%	25.85%
(ii) with possible amplif. effects	21.17%	74.15%
(ii_a) with very critical conditions	0.09%	27.31%

Microzonation analysis – Level 1

The classes proposed for the Level 0 analysis are only indicative for administrative purposes and do not coincide with the classes proposed by the technical norms, which are site-specific. In fact the NTC 2008 define topographic amplification factors for slope and ridges with a height difference Δh greater than 30 m.

The Level microzonation is therefore obtained by performing the *Table Statistic Analysis* between the administrative layer and the Level 1 morphological parameters. In this case, while the slope and ridge maps remain the same, a new raster obtained by the landform procedure is added. The new raster has values of 1 where ridges with Δh > 30 m are present, otherwise 0. The combination between the presence of ridges, slope class and Δh30 class allows one to assign the inhabited areas to the T1 to T4 topographic classes of the norms, according to the criteria displayed in Table 4.

Table 4. Criteria used to define the Level 1 classification

NTC class	Percent_ridge	Slope_class	Δh30
T1	--	0	
T2	< 1%	≥ 1	1
T3	> 1%	1	1
T4	> 1%	2	1

Table 5 shows the distribution, in percentage, of the localities in the Marche region according to the classes prescribed by the norms. It must be noted that some combinations do not fall in any of the T1 to T4 classes of the NTC 2008, and are therefore classified (NC) in Table 5: these cases correspond to slopes and ridges with average inclination ***i*** > 15° but height smaller than 30 m, thereby not belonging neither to the T1 class (***i*** < 15°) nor to the T2 to T4 classes (height > 30 m).

Table 5. Level 1 classification results for the Marche region.

	Marche
T1	37.9%
T2	3.3%
T3	16.7%
T4	8.15%
NC	33.9%

Some important limits of the procedure have to be enlightened. First, the presence of a ridge is calculated, for each locality, as the % of ridge-pixel with respect of the total area of the locality, while the characterization of Δh30 is constrained only by the presence or absence of the considered parameter. That is, when considering the Δh30 value, even though only one pixel within a polygon has high difference greater than 30 m, all the locality is characterized by Δh30 = 1.

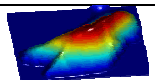
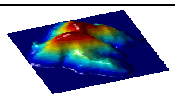
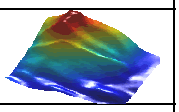
Sensitivity analyses have been carried out on the slope parameter to evaluate how the final classification depends on the choice of extreme or median values.

Further tests have also been done considering the slope parameter directly derived from the original DEM or from the smoothed version: localities with a decrease of their slope class are in the order of 8%, while the localities that increase their slope classes are 2.5%. Anyway, these variations are in the order of the uncertainties of the method.

Another important limitation is the reliability of the source data: ISTAT data are a very detailed and precise source of information, but some localities, even if identified by a polygon, miss the identity label and cannot be automatically used in the analysis, which results in increased time resources needed to manually solve the problem. We estimated that the missing localities in the Marche region are in the order of 8-10%, equally distributed in the whole area.

Three localities in the Marche region have been investigated in more detail. All of them are located on a typical 2D morphology (ridges with crest width significantly less than the base width), and were studied by 3D numerical simulations (Scandella et al., 2008). Table 6 shows the values of the parameters calibrated according to the present work, compared with the amplification factors suggested by the norms or derived by 3D analysis: the automatic detection method, based on the proposed criteria, permits to identify the critical zones and their classification into T1-T4 categories.

Table 6. Identification of topography parameters for three localities in the Marche region for which results of 3D numerical simulations are available

	Genga	**Arcevia**	**Belvedere**
			
Morphology	2D	2D	Larger ridge
Slope	$i > 15°$	$i > 15°$	$15° \leq i \leq 30°$
Δh30	(150) > 30 m	(225) >30m	(50) > 30m
Ridge (% of area)	4.8	2.7	8.9
Landform *	(9); (8); (6)	(10); (9); (7); (6)	(9); (6)
EC8 factor	1.4 (T4)	1.4 (T4)	1.2 (T2)
3D factor	1.55	1.38	1.12

* *(10) = Mountain top, high ridges; (9) = Midslope ridges, small hills in plains; (8) = Local ridges, hills in valley; (7) = Upper slopes, mesas; (6) = Open slope*

CONCLUSIONS

The proposed procedure for the identification of sites with potential significant topographic amplification effects is implemented for the Italian case, but can be profitably exported beyond the specific geographic area. The process can be replicated with data of different scale and resolution (DEM resolution, point or line features of critical sites). The procedure has been implemented at different levels of analysis: level 0 is proper for scale investigations at national or regional level, when large screening of critical locations is required; Level 1 is successively suggested for normative classification of smaller areas (provincial or local scale).

The selection of different statistical parameters to classify the topography, for example the extreme or the median value of the slope class, allows one to adopt a more or less conservative choice to identify all the critical situations deserving further inspections or to perform a more selective screening that can be used to give priority to the worst amplification cases.

The first results, even if the investigated area is less than 8% of the whole national territory, show that more than 50% of the inhabited localities may be affected by topography amplification effects, and that for 10% of localities in the Marche region and 27% in Calabria the inhabited areas encompass zones with very critical conditions which may be classified as T4 topography (S_T=1.4)..

Finally the microzonation maps produced through these automatic GIS procedures can find an important use by local authorities to plan the extension of new urban expansions and to allow permissions for new building construction.

ACKNOWLEDGEMENTS

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