17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

SEISMIC MICROZONING: METHODOLOGY AND APPLICATIONS AFTER THE 2016-2017 CENTRAL ITALY SEISMIC SEQUENCE

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Abstract

The Seismic Microzonation (SM) is nowadays a world-wide accepted tool for the mitigation of the seismic risk. The SM is a complex process involving different disciplines ranging from Engineering-Geology and Applied Seismology to Structural and Geotechnical Engineering. The outcome of a SM is presented on zoning maps in terms of selected ground shaking intensity parameters and susceptibility to main ground instability (soil liquefaction, settlements, landslides, fault ruptures). In an advanced SM study for a given area, 4 main interdisciplinary steps can be recognized: 1) definition of the reference input motions, 2) construction of the subsoil model, 3) performing of numerical analyses and computing of amplification factors, 4) identification of zones with different geotechnical hazard potential and drawing up of the SM map. After the earthquakes of 2016-2017 that struck a large area of Marche, Umbria, Abruzzo and Lazio Regions in Central Italy, intensive studies of SM were performed, aiming at supporting the reconstruction in these territories. Particularly, the amplification phenomena due to geological, geotechnical and geomorphological conditions have been considered in this context, and the adopted procedure for addressing the main 4 steps that characterize the SM study for soil amplification are here presented. In particular, for the definition of the reference input motions a set of 7 real unscaled accelerograms matching on average the reference spectrum (defined by the Italian building code NTC18 for outcropping rock conditions and the return period of 475 years) in the period range 0.1-1.1 s, was selected. For the construction of the subsoil model, a large number of non-invasive surface tests was performed. To obtain the characterization of nonlinear cyclic behavior of soils some laboratory tests were performed on undisturbed samples. Ground response was assessed using 1D or 2D numerical codes, depending on the complexity of the geological and geomorphological situation. The results were presented both in terms of amplification factors defined as the ratio between the integral of the acceleration elastic response spectrum of the output motion and the corresponding integral of the acceleration elastic response spectrum of the input motion in three selected ranges of periods (0.1-0.5s, 0.4-0.8s and 0.7-1.1s) and in terms of acceleration elastic response spectra. Some critical issues inferring to the abovementioned steps are discussed with reference to paradigmatic examples, as the case of valley characterized by lateral heterogeneities causing significant lateral contrasts in the Vs values. Finally, a synthesis of the results and a proposal to incorporate the output of SM results in seismic design codes for the reconstruction are presented: the SM maps were adopted in land use planning, the results in terms of acceleration response spectra were used in supporting the seismic design of new buildings.

Keywords: Seismic Microzoning; Amplification Factor; Ground Response Numerical Analysis; Elastic Response Spectrum; Microzoning Map

1. Introduction

Seismic Microzonation (SM) can be defined as the process aiming at identifying and mapping the subsoil local response in a given area (typically an urban area) in terms of selected ground shaking intensity parameters and susceptibility to ground instabilities. In this respect, SM plays an important role in earthquake risk reduction and management strategy, providing a valuable input for urban planning.

In Italy, in the spirit to define guidelines for hinge the SM on the planning system of Regions and Municipalities, guidelines and criteria to achieve SM have been standardized and published in Working Group ICMS [1,2] by the Conference of Italian Regions and Autonomous Provinces, and the Italian Civil Protection Department. In general terms, the Italian guidelines establish that the scale of implementation is 1:10,000 or greater and define 3 Levels of approach to zonation. Level 1 (SM1) is the preparatory level for SM studies; it relies on the collection of existing data, which are processed to divide the investigated area into qualitatively homogeneous zones from a seismic perspective. Level 2 (SM2) is based on quick sub-soil exploration aiming at integrating existing data and it introduces quantitative assessments of local seismic hazard via simplified methods: abacuses can be used to obtain the ground motion amplification factors. Level 3 (SM3) produces maps from the results of numerical analyses based on a detailed subsoil mechanical characterization; this is done for areas characterized by high seismic hazard, subsoil complexity and/or economic and social relevance.

The SM3 study is a complex process involving different disciplines ranging from Engineering-Geology and Applied Seismology to Structural and Geotechnical Engineering. In particular, focusing on ground motion amplification, 4 main interdisciplinary steps can be recognized in performing a SM3 study [3]: 1) definition of the input motion (reference earthquake), 2) construction of the subsoil model, 3) ground response numerical analyses and estimation of amplification factors, 4) compilation of SM3 maps. The results of SM3 studies can be applied in several areas: typically for urban and emergency planning, reconstruction after the earthquake, and in support of building and infrastructure design.

After the 2016-2017 Central Italy seismic sequence that struck a large area of Marche, Umbria, Abruzzo and Lazio Regions, intensive studies of SM3 were performed following the Ordinance of the Presidency of the Council of Ministers [4] in 137 municipalities, aiming at supporting the reconstruction in these territories. Particularly, the amplification phenomena due to geological, geotechnical and geomorphological conditions were considered in this context.

2. Input motion definition

For a given soil deposit, the amplification function, and therefore the ground motion amplification synthetized in SM3 maps, are strongly dependent on the characteristics of the input motion. Therefore, the selection of the most suitable input motion is a key point in carrying out a SM3 study. The first aspect concerns the methodology to define, at regional or national scale, the seismic hazard at rock site conditions, i.e. the reference input motion at outcropping bedrock which does not include modifications caused by local geological, morphological and geotechnical conditions. Once estimated the site reference ground motion, it is necessary to select a set of acceleration time histories matching the reference spectrum. In this respect, a significant issue concerns the choice of artificial, synthetic or real (natural) accelerograms. Real accelerograms are nowadays emerging as the most suitable input for dynamic analyses mainly because they genuinely reflect the main factors (source, path and site) influencing the nature of ground motion. Their increasing availability due to the growing development of online ITACA databases (http://itaca.mi.ingv.it/) is another valuable advantage.

In this study, for each of the 137 municipalities under study, a specific acceleration response spectrum, as prescribed by the Italian building code NTC18 [5] for outcropping rock conditions (subsoil class A) and 475 years return period, was assumed as reference. The NTC18 spectra are based on the study carried out by INGV for the whole Italian territory [6].

A set of 7 real unscaled accelerograms matching on average the reference spectrum in the period range 0.1-1.1s was selected. The time-histories were extracted from the Italian ITACA database by constraining the selection based on: i) earthquake size and location: ranges for reference magnitude and source-to-site distance were selected by referring to the disaggregation study carried out in the framework of INGV study [6]; ii) fault mechanism: recordings associated with normal fault movements were selected since this is the mechanism largely predominant in the study area; iii) soil and topography class at the recording station: only recordings at outcropping and flat rock conditions (subsoil class A and topography category T1 according to Italian technical code NTC18) were considered. The matching criterion with the reference spectrum was the following: the average elastic response spectrum of the selected time-histories should have no values lower than 90% and higher than 130% of the corresponding values of the target spectrum in the whole period range of interest (0.1-1.1s)[7].

3. Definition of the subsoil model

The definition of the subsoil model requires the identification of the seismic bedrock (depth and shape) and the characterization of the soil layers in terms of geometry, physical and mechanical properties of the materials, relevant for site response assessment, namely shear/compressional wave velocity, soil density and nonlinear shear modulus and damping ratio under cyclic and dynamic loading conditions [8].

As the model has be defined at urban scale, typical of SM3 studies, large volumes of subsoil need to be investigated. A critical issue is therefore the choice of the type and density of investigations necessary to achieve an appropriate knowledge of the subsoil conditions. Expensive in-hole geophysical tests cannot be used extensively and driven at great depths; they therefore must be integrated with cheap non-invasive surface tests. In the SM3 studies in Central Italy, no more than 2 down-hole (DH) tests were carried out for each municipality. They were performed at representative sites, where most lithotypes were encountered, or in the most important zone, i.e., the chief town, where strategic buildings and infrastructures were located. A large use of non-invasive surface tests was therefore made, including Multichannel Analysis of Surface Waves (MASW), and Horizontal to Vertical Spectral Ratios (HVSR) tests [9].

Regarding the characterization of nonlinear cyclic behaviour of soils, the nonlinearity of stiffness and damping properties is usually assessed by cyclic and dynamic laboratory tests. Laboratory testing is strongly recommended for nonlinear characterization. However, the large subsoil volumes involved in a microzonation study made impossible to carry out a large number of cyclic/dynamic laboratory tests. No more than two undisturbed samples for each municipality were available in the Central Italy SM3 project; for a rational use of the results, a “local” database of nonlinear stiffness and damping curves was built on the basis of the cyclic/dynamic laboratory tests carried out on the samples from all the 137 municipalities [10]. These curves, properly associated to the main controlling factors, i.e. confining pressure, state and index properties, allowed a refined and representative choice of the nonlinear properties for the site response analysis.

4. Selection of numerical approach and amplification factors

Nowadays a plethora of computer programs for site response analyses exists; they differ mainly for geometry, method of analysis and domain, constitutive models. The geometry scheme for modelling (1D or 2D/3D) should be first selected in reason based on the complexity of bedrock morphology, soil layering and topography. In particular, the typology of the numerical modelling (1D vs 2D) and the resolution of the seismo-stratigraphic models strongly influence the ground-motion predictions. It is worth noticing that the definition of a high resolution seismo-stratigraphic model is necessary for a thorough assessment of ground motion amplifications, particularly for valleys or ridge where the seismic response is strongly controlled by several variables defining their geological settings and 2D numerical modelling is needed [11,12,13]. For the SM3 project described in this paper, the 1D numerical analyses were generally performed using STRATA computer program [14] which operates in frequency domain, using the equivalent-linear visco-elastic approach to model the nonlinear cyclic soil behavior. The 2D analyses were carried out in the time domain using 2D FEM codes LSR2D [15] also based on the equivalent linear strategy. Only in very few cases a nonlinear approach was employed, using the finite difference program FLAC [16].

Once numerical ground response analyses have been performed, another key aspect in a SM3 study is the selection of the most suitable amplification factor to adopt in synthetizing and mapping the results. Generally speaking, an Amplification Factor (AF) is defined as the ratio between the value of a given motion parameter at the study site (usually at the ground surface) and the value of the corresponding parameter at the reference site (usually on outcropping bedrock). According to the latest revision of the Italian standardized guidelines for microzoning [1,2], in the present SM3 study the Amplification Factor (AF) has been defined with reference to the 5% damped acceleration elastic response spectra. It is calculated as the ratio between the integral of the acceleration elastic response spectrum of the output motion and the acceleration elastic response spectrum of the input motion in a selected range of periods:

$$AF_{Tn} = \frac{\int_{Ta}^{Tb} S{,}out\ dT}{\int_{Ta}^{Tb} S{,}inp\ dT} \qquad \text{with } n = 1, 2, 3 \tag{1}$$

where S,out is the acceleration elastic response spectrum of the output motion; S,inp is the acceleration elastic response spectrum of the input motion; Ta and Tb represent the extremes of the evaluated interval of periods Tn. Three different ranges of periods were considered in this study: T1=0.1-0.5s; T2=0.4-0.8s and T3=0.7-1.1s.

This choice takes into account the typical fundamental periods of buildings in the studied municipalities, which in turn can be generally related to some building characteristics (essentially the number of floors or the overall height). In order to define the number of floors of buildings and therefore roughly estimate their fundamental period of vibration, the National Institute of statistics (ISTAT) distribution percentages of the building heritage were considered. In these studies [17] it is shown that almost 50% of residential buildings have 2 floors, while the vast majority have up to 3 floors. This is true in general for the whole Italy and, in particular, for the most heavily damaged municipalities of Central Italy after the 2016-2017 earthquakes. Considering all the uncertainties involved in these estimates, a first range including buildings from 1 to 4 floors, which corresponds to fundamental periods of vibration roughly estimated in the range 0.1-0.5s (the first selected range of integration for AF) was selected. As an alternative approach, if an average structural inter-story height of 3.3m is supposed, and the rule of thumb T = Ct H with H= total height of the structure and Ct= 0.02 [18] is considered, two corresponding fundamental periods of 0.07 and 0.26s are obtained for 1 and 4-storey buildings respectively. With the aim of taking into account the elongation of the structure, also including the dynamic soil-structure interaction effects, a second rule of thumb was used: elongated period of the structure Tel is twice the non–elongated period of the structure Tnel [19]. It is therefore possible to confirm the values 0.1 and 0.5s, respectively used as lower and upper limits of the first range of integration.

In order to take into account also soil amplification phenomena that may influence higher buildings in the seismic risk mitigation policies derived from SM3 studies, 2 other intervals were assumed: 0.4-0.8s and 0.7-1.1s. They roughly correspond to buildings with 3 to 6 floors and 5 to 8 floors.

5. Influence of the subsoil model: an example

As an example of the influence on the results of the subsoil model, the case of a valley characterized by lateral heterogeneities in the alluvial deposits causing strong lateral contrasts in Vs values is presented. Focusing on 2D numerical modelling, in which the influence of 2D effects due to the shape of the valley are considered, it is known from literature that the heterogeneities of the deposits play an important role in the site response. Therefore, neglecting these variables, a strong approximation may affect the results and it might lead to an underestimation of the ground amplification prediction factor. The case study of Fonte del Campo site in the Municipality of Accumoli (Rieti) highlights the underestimation of the local seismic response in each microzone when a homogeneous geological setting is considered for the valley.

The numerical modelling at Fonte del Campo (Geological cross section AA' in Fig. 1) was performed with the 2D finite difference code FLAC 7.0 [16]. The subsoil model was built using data from the geophysical surveys performed during the SM3 study. These investigations included: 4 boreholes drilled up to 40 m b.g.l. including down-hole test, 4 MASW, 12 seismic noise measurements analyzed through HVSR technique, 1 section for geoelectric and seismic tomography.

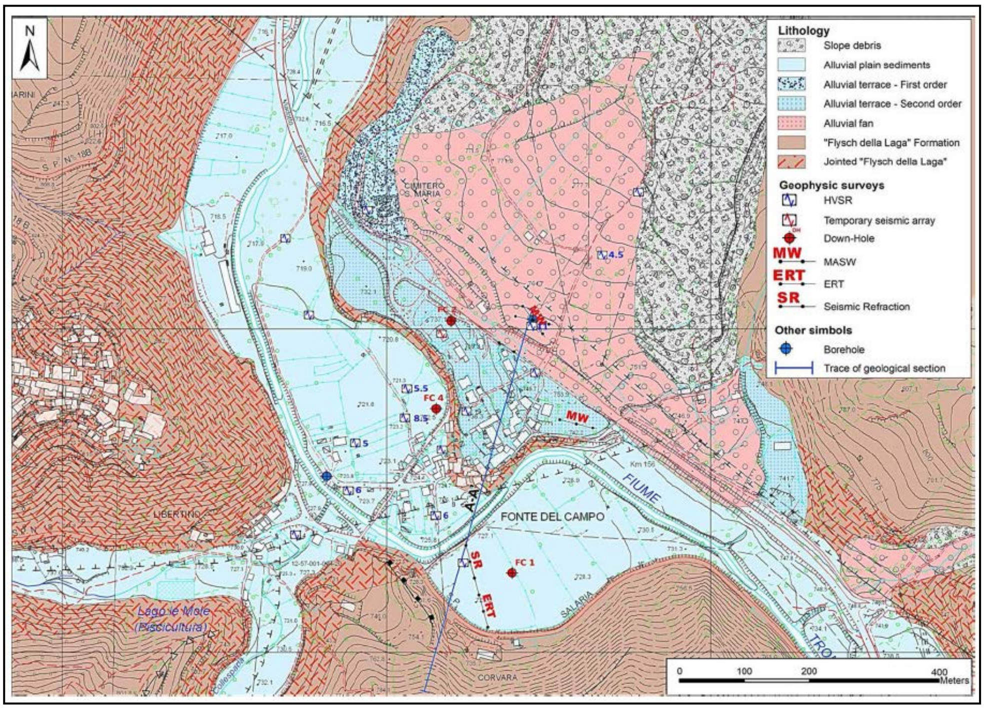

Fig. 1 - Lithotechnical map of Fonte del Campo (Accumoli). The trace of the AA' geological cross section of Fig. 2 is also reported

Two different numerical models (called "heterogeneous model" and "homogeneous model", respectively) were then implemented. The "heterogeneous model" can be considered representative of Fonte del Campo morphology and geological setting (Fig. 2a) which is characterized by a roughly sharp topography on the left side with a slope angle of 26° approximately. The geological cross section shown in Figure 2a is a transversal representation of the Tronto River valley (SW-NE): the alluvial valley is shown in the middle of the cross section and it has a relatively smooth topography on the right side of the cross section (towards East). The bedrock is composed of the arenaceous member of the Flysch della Laga Formation, while the valley consists of alluvial plan deposits composed of sands (FC_SA) and gravels (FC_GA); on the right side of the section model there are mainly alluvial terrace deposits composed of sandy silts (FC_TERR) and gravels (FC_CON). The arenaceous member of the Flysch della Laga Formation underwent a softening process during deposition of alluvial and fluvial deposits that determines the presence of two softened layers of bedrock defined by FC_SOFT1 and FC_SOFT2 respectively. The unit weight and the shear and compressional wave velocities of the deposits used in this study are reported in Table 1. The "homogeneous model" (HoM) is characterized by the same morphology as HeM but the valley is filled only with gravels (FC_GA) overlying the softened layers of bedrock (FC_SOFT1 and FC_SOFT2) (Fig. 2b).

A non-linear behavior was assumed for all lithological units characterizing the cross section with the exception of FC_BED. The decay curves associated to each lithological unit were available in the database compiled for the SM3 studies [10]. They were introduced in the numerical models using built-in functions (FLAC library) representing the variation of shear modulus reduction factor and damping ratio with cyclic strain. This hysteretic damping formulation used in FLAC provides almost no energy dissipation at very low cyclic strain levels, which may be unrealistic. To avoid low-level oscillations at very low cyclic strain levels, a small amount of Rayleigh damping (between 0.5 and 1%) approximately frequency-independent over a restricted range of frequencies (1 – 8Hz) was added for all lithological units with the exception of FC_BED.

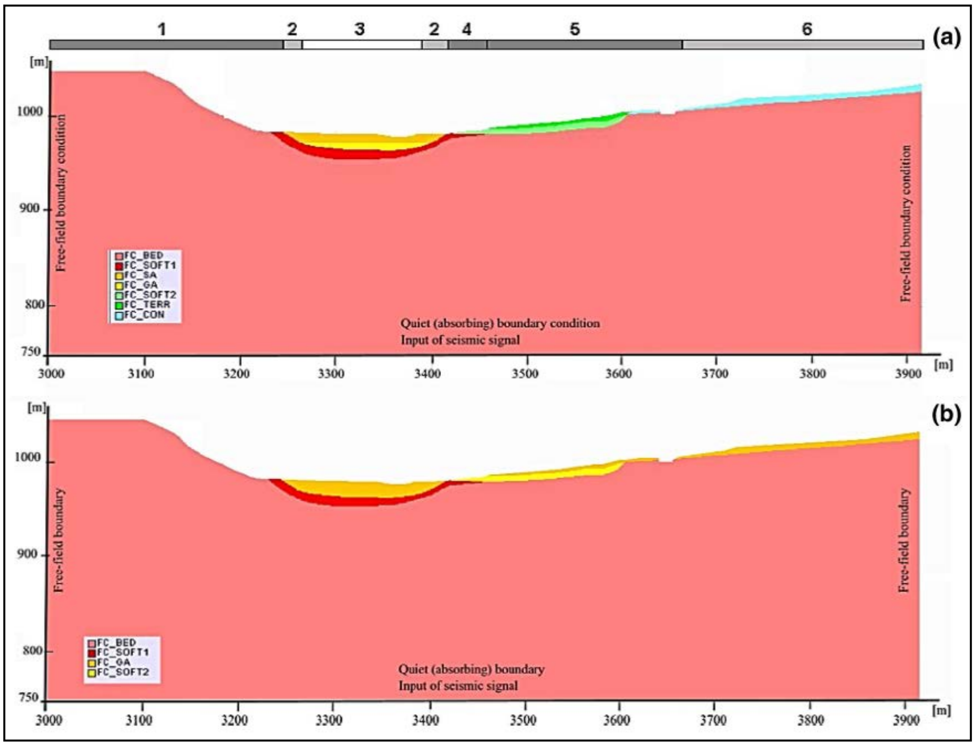

Fig. 2 - Seismo-stratigraphic layering (see Table 2) of HeM (a) and HoM (b) models; for HeM the positions of the defined microzones (from 1 to 6) are also indicated in the upper bar

Table 2 - Values of the properties attributed to the different lithotechnical units

	Unit weight γ (kN/m^3)	Shear-wave velocity Vs (m/s)	Compressional-wave velocity Vp (m/s)
Sands (FC_SA)	19.2	285	533
Gravels (FC_GA)	21.0	441	825
Soft material (FC_SOFT1)	21.0	705	1319
Soft material (FC_SOFT2)	21.0	480	898
Sandy silts (FC_TERR)	16.5	327	612
Gravels (FC_CON)	21.0	252	471
Bedrock (FC_BED)	21.0	1170	2188

The models shown in Fig. 2a and Figure 2b were discretized by using quadrangular elements. To capture appropriately the propagation of seismic waves inside the model up to a frequency of 20 Hz, a constant element size Δl=1m was assumed [20]. Free field boundaries were defined along the lateral edges of the considered domain. Seven real accelerograms were applied as a vertically up-coming shear stress time-history at the lower boundary of the models [7].

For the post-processing of the numerical modelling, time histories of acceleration were collected every 1m along the ground surface of the domain to assess elastic response spectra and amplification factors AF. Six microzones were defined considering as threshold value a difference in terms of amplification factor equal or greater than 0.2 (Fig. 2).

The comparison between HeM and HoM results in terms of AF (Table 3) highlights that neglecting the presence of lateral heterogeneities in the alluvial deposits the amplification factor is underestimated up to 20% (Microzones 2,3,6 in Table 3) in case of microzone affected by amplification phenomena.

Table 3 - Synthesis of the amplification factors AF obtained by considering HeM and HoM respectively

Microzone	AF HeM			AF HoM		
	0.1 -0.5 s	0.4 -0.8 s	0.7 -1.1 s	0.1 -0.5 s	0.4 -0.8 s	0.7 -1.1 s
1	0.8	0.6	0.6	0.8	0.6	0.6
2	1.2	0.6	0.5	0.9	0.5	0.5
3	1.5	0.6	0.5	1.2	0.6	0.5
4	0.8	0.5	0.5	0.8	0.5	0.5
5	0.9	0.6	0.6	0.9	0.6	0.6
6	1.2	0.7	0.7	0.9	0.7	0.7

6. Global analysis of the SM3 results

During the project here described, SM3 studies on 137 municipalities were performed. The amount of the available data allows to point out some general aspects. Particularly, analysing the obtained values of the Amplification Factor AF, as defined in Eq. (1), the following considerations can be drawn.

To explore the results derived from SM3 studies in terms of ground motion amplification, statistical distribution of the AFs was computed with reference to the 137 municipalities (for a total of 4209 homogeneous microzones), in the 3 period ranges Tn (with n = 1, 2, 3): $0.1 \leq T1 \leq 0.5$s, $0.4 \leq T2 \leq 0.8$s and $0.7 \leq T3 \leq 1.1$s. Median values of AF decrease from the T1 interval (where AF median values are equal to 1.5) to the T3 interval (where AF median values are equal to 1.2).

For comparison, AF values obtained as the ratio between the integral of the acceleration response spectra recommended by the Italian building code (NTC18) for the 4 soil classes B, C, D and E, and for the soil class A, with reference to the 3 selected intervals of periods, were also computed. A 475 years return period was selected, in accordance with the choice adopted for the input motion selection in SM3 studies. The results show that the AF median values calculated for all 4 soil classes with reference to the NTC18 spectra, are greater than the AF median values from SM3 studies in the second and third intervals of periods (medium-to-long periods). On the contrary, in the 0.1-0.5s period range: for soil class B, AFs from NTC18 are generally slightly underestimated compared to AFs from SM3, while the opposite can be noticed for class D; for C and E classes, AFs from both NTC18 and SM3 are almost the same.

The overestimation of AFs in the medium-to-high period range (0.4-1.1s) by the Italian technical code could be ascribed to the inadequacy of soil factors Ss, controlling the amount of stratigraphic amplification and/or Cc value controlling the shape of the spectra by enlarging the plateau at higher periods with respect to rock outcrop conditions. Moreover, it has to be considered that, where AFs are derived from 2D site response modelling, higher estimates may be expected compared to the ones from NCT18 spectra in all the 3 period ranges. This can be essentially referred to the fact that provisions consider only 1D soil conditions.

On the basis of the results obtained in this study, the simplified procedure proposed by the Italian building code (NTC18) seems to be conservative at medium-to-long periods, while it can lead to significative underestimation of amplification factors (and therefore of spectral accelerations) in lower period range (0.1-0.5s).

The statistical distributions of SM3-NTC18 amplification factors shows an important outcome: about 90% of the buildings in Italy (and even more in the study area) have resonance periods which fall within the range 0.1-0.5s, i.e. in the period range where NTC18 leads to amplifications comparable or lower than those computed by microzonation studies. These results highlight the need to provide general and objective recommendations on the most appropriate method for the evaluation of the seismic action (i.e. simplified approach based on subsoil categories or ad hoc site response numerical analyses), as also stressed in the last section.

7. From site response analysis to SM3 mapping

The final step of a SM3 study is the representation of results in a map showing the contours of zones (microzones) characterized by different ranges of a selected amplification parameter. This is a complex task, affected by a high level of uncertainty.

However, it should be noted that the accuracy of a SM3 map is always mainly influenced by the quantity and quality of the ground response analyses performed for the area under study. The reliability of such analyses depends in turn on the reliability of the defined geotechnical model and on the adopted seismic input that could affect dramatically the predicted ground motion.

For a given reference seismic input, ground motion at each point in the area under study depends on the dynamic behavior of the soil profile (stratigraphic effects), on the ground surface morphology (topographic effects) or on the presence of strong lateral discontinuities such as the edges of sedimentary basins (valley or basin effects) of the whole physical context where the area is located.

If both topographic and basin effects can be considered negligible in the area, the uncertainty in the identification of microzones with homogeneous seismic behaviour and the attribution of (one or more) selected amplification parameters to derive SM3 maps is due only to the horizontal and vertical stratigraphic variability. In such conditions, to draft a SM3 map it is convenient to start from the identification of the microzones with homogeneous seismic behaviour based on existing information and instrumental data (deriving from the results of a SM1). In order to quantify the selected amplification parameter with a predetermined confidence level, 1D numerical analyses for a set of reference input motions should then be performed at one or more vertical locations in each microzone with homogeneous seismic behaviour.

If topographic and subsurface irregularities are significant for the area under study, one-dimensional analyses are unsuitable to predict the specific site response and the ground motion distribution in the area. In this case, taking into account the distribution of surficial and buried morphology effects on the area is one of the main critical aspects to extrapolate the data under 3D conditions and therefore to draw the SM3 map. Since topographic and basin effects are typically 3D, their evaluation requires, strictly speaking, three-dimensional analyses. However the implementation of 3D numerical analyses is unfeasible in practice since they are generally complex and very time consuming in modelling and computation. As a result, at present, few applications of 3D numerical models have been carried out in practice. Once the values of amplification parameters have been calculated at selected surface nodes of the 3D numerical model, it is possible to draw a map of isolines of these amplification parameters by means of appropriate spatial prediction techniques commonly available on GIS platforms. The most suitable methods for drawing up SM3 maps are the local interpolation methods (Local models). According to the amount of statistical analyses, they can be classified as Mechanical/Empirical and Statistical prediction models [21].

Because of difficulties related to the implementation of 3D numerical models, SM3 studies usually refer to 1D and/or 2D numerical ground response analyses and the procedure to obtain a SM3 map is divided into the following steps:

- selection of a number of vertical soil profiles and cross sections representative of the different local soil conditions of the area;
- performing of 1D and 2D local seismic response analyses on the selected vertical soil profiles and cross sections;
- calculation of the values of the chosen amplification parameter at the ground surface of each vertical soil profiles and in a number of ground surface points of the two-dimensional models of the cross sections;

- representation of the results obtained in terms of the chosen amplification parameter on the geological map or on MS1 map. For 1D analyses, the value obtained for the chosen amplification parameter at the ground surface for each analysed vertical soil profile is unique. For 2D analyses, the chosen amplification parameter will vary from point to point along the ground surface of each cross section. In this case, it is necessary to define a certain number of classes for the chosen amplification parameter and to draw segments showing the extension of those classes in each cross section;
- drawing of the contours of the seismic microzones on the SM3, taking into account both the single values of the chosen amplification parameter obtained from 1D analyses and the classes identified along the cross sections analysed by means of 2D models. To carry out this final step it is necessary to make use of an expert judgment to identify, on the existing map, similar geological, lithostratigraphic, superficial and buried morphology conditions, in zones where no ground response analyses have been performed. In this case, noise and microtremor measurement results can also be a useful tool in defining the boundaries of each microzone.

The procedures described above show that the drafting of an SM3 map is based on a multidisciplinary approach that requires skills in geology, geotechnics and geophysics. Knowledge on the use of spatial prediction procedures and GIS platforms is also necessary [22].

As an example, the data used to obtain the SM3 map of the Municipality of Scheggino, for an investigated area of approximately 250.000 m^2 are reported in the following. Particularly, in Fig. 3 the lithotechnical map and the location of geophysical and geotechnical investigations are shown (3 boreholes, 7 HVSR and 2 MASW and Seismic Refraction). In Table 4 and Fig. 4 the main selected parameters of the sismo-stratigraphic model and the corresponding normalized shear modulus $G(\gamma)/G_0$ and damping ratio $D(\gamma)$ curves are presented. The SM3 map (Fig. 5) was achieved from the results of the 2D numerical analyses performed by LSR_2D computer program [15] at the Section 1 (Fig. 5). They were extended to the different areas taking into account the geological condition. The acceleration response spectra at ground surface, for each microzone of SM3 map, calculated as the average obtained for the 7 applied input signals, are shown in Fig. 6.

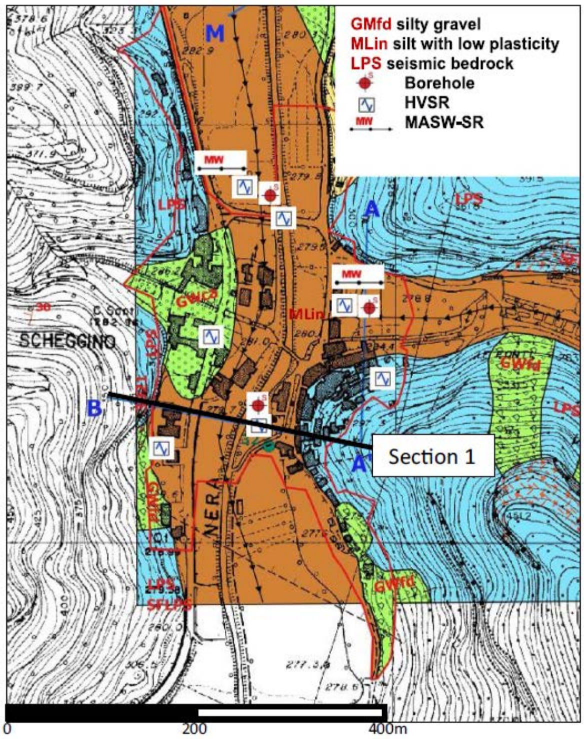

Fig. 3 - Lithotechnical map and location of geophysical and geotechnical investigations

Table 4 - Main parameters of the subsoil model

	Unit weight γ (kN/m^3)	Shear-wave velocity Vs (m/s)	Compressional-wave velocity Vp (m/s)
MLin1	18	200	800
MLin2	19	350	1300
MLin3	20	450	1800
GMfd	20	550	2300
LPS	24	800	3000

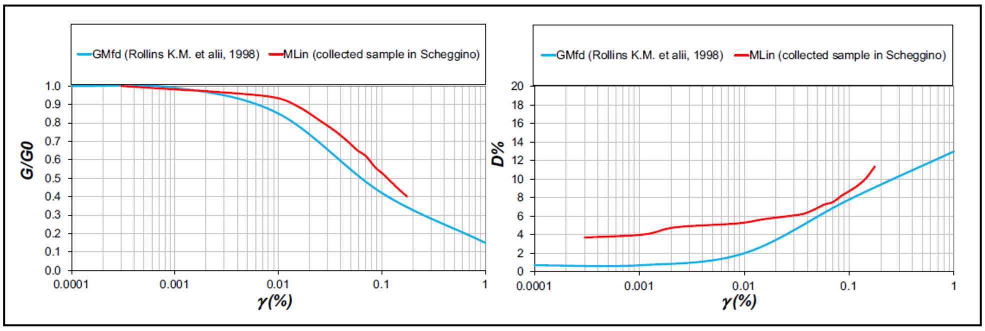

Fig. 4 - Normalized shear modulus G/G0 and damping ratio D versus shear strain γ curves for the main lithotechnical units

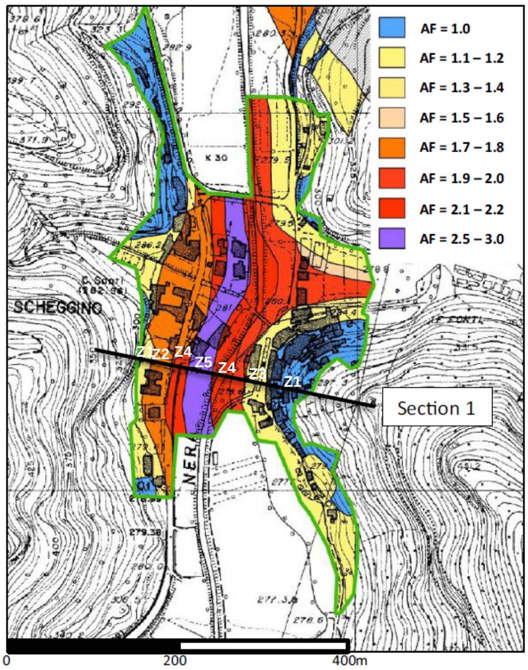

Fig. 5 - Seismic Microzonation map (SM3) map

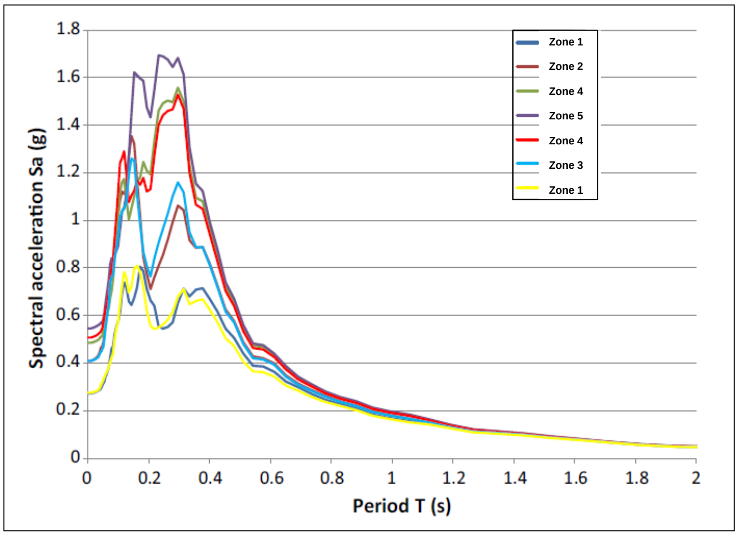

Fig. 6 - Ground acceleration response spectra for each zone (Z1-Z2-Z4-Z5-Z4-Z3-Z1) defined in SM3 map

8. Applications of SM3 studies: some remarks on their possible use in supporting seismic design

Appropriate measures and actions are generally considered in order to mitigate seismic risk and reduce it below an acceptable level. These actions can be undertaken at two different scales: i) adopting effective earthquake-resistant techniques in building construction; ii) introducing the results of appropriate Microzonation Studies in urban/territory planning tools.

On the first point, the recent Italian building code NTC18 [5] included very important novelties concerning the seismic aspect. In particular, the role of ground site effects is explicitly considered to modify seismic action on buildings. These modifications can be taken into account with specific site response analyses, only for regular and simple geo-morphological and geological situations, the use of simplified approach based on standard spectra, depending on subsoil and topography categories, is possible.

Regarding the second point, the SM3, as defined by the guidelines standardized and published in [1,2], is essentially a tool of basic knowledge in urban and territory planning : giving elements on the fundamental vibration periods of soil deposits in the new residential areas, a SM3 map provides guidance on the design of new buildings avoiding phenomena of double resonance; by indicating the most critical scenarios it enables to locate green areas in the most dangerous zones; by detecting hazard hierarchies it helps to choose the safest zones for strategic buildings, to set intervention priorities in the existing inhabited areas and to identify the critical points of infrastructures and lifelines. SM3 is also a valuable support in emergency planning and management (e.g., settling of temporary facilities, organization of emergency road networks) as well as in post-earthquake reconstruction [23,24].

Following the SM3 studies in the municipalities of Central Italy, general criteria for the use of the results of these studies for reconstruction projects, were delineated in the “Ordinanza n. 55/2018” [25]. In particular, to define design spectra, the designer has to preliminary compare spectra deriving from the SM3 studies with NTC18 simplified approach spectra. If the SM3 spectrum exceeds punctually 30% of the NTC18 spectra or the integral of the SM3 spectrum exceeds 20% of the NTC18 spectra in the period range of interest, the simplified NTC18 approach can be regarded as non-conservative. In this case, the designer should perform additional investigations and he is strongly encouraged to perform ad hoc site response analyses to define appropriate seismic actions. Moreover, in case of complex surficial or buried morphologies, he has to consider using the response spectra from 2D analyses carried out in SM3 study if they may be more accurate and conservative than standard 1D response analyses performed only at the building site.

9. Acknowledgments

The project was carried out with the funding from the National Authorities in the contest of "*Interventi urgenti in favore delle popolazioni colpite dagli eventi sismici del 2016* (Urgent interventions for the populations affected by the 2016 earthquakes)".

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