Pergalani F., Pagliaroli A., Bourdeau C., Compagnoni M., Lenti L., Lualdi M., Madiai C., Martino S., Razzano R., Varone C., Verrubbi V. (2020). Seismic microzoning map: approaches, results and applications after the 2016–2017 Central Italy seismic sequence. Bulletin of Earthquake Engineering, 18: 5595–5629, doi: https://doi.org/10.1007/s10518-019-00640-1

Seismic microzoning map: approaches, results and applications after the 2016-2017 Central Italy seismic sequence

Pergalani F.[1], Pagliaroli A.[2], Bourdeau C.[3], Compagnoni M.[1], Lenti L.[3], Lualdi M.[1], Madiai C.[4], Martino S.[5], Razzano R.[6], Varone C.[7], Verrubbi V.[8]

[1] DICA - Politecnico di Milano
[2] Dipartimento di Ingegneria e Geologia - Università degli Studi G. d'Annunzio - Chieti - Pescara
[3]University Paris-Est LCPC/ The French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR) / Department GERS-14-20
[4]DICA – Università degli Studi di Firenze
[5]Department of Earth Sciences of the University of Rome «Sapienza» and Research Center for the Geological Risks (CERI).
[6] CNR-IGAG – Roma
[7]École Supérieure d'Ingénieurs des Travaux de la Construction (ESITC) de Paris
[8]Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile (ENEA), Rome, Italy.

Corresponding Author: floriana.pergalani@polimi.it

Key words: Seismic Microzonation; Amplification Factor; Numerical Analysis; Elastic Response Spectrum; Microzoning Map; Seismic Code

Abstract

The Seismic Microzonation of level 3 (SM3) is nowadays a world-wide accepted tool for the mitigation of seismic risk. The SM3 is a complex process involving different disciplines ranging from Geology and Applied Seismology to Structural and Geotechnical Engineering. The outcome of a SM3 is presented on a zoning map in terms of a selected ground shaking intensity parameter and susceptibility to main ground instability (soil liquefaction, settlements, landslides, fault ruptures). In an advanced SM3 study for a given area, four 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 SM3 map. After the 2016-2017 Central Italy seismic sequence, intensive studies have been performed to obtain SM3 maps in 137 municipalities most damaged by the earthquakes. The aim of these studies has been to obtain a clear background on site effects to perform a correct reconstruction of the municipalities. In the paper, main results and critical issues of the above-mentioned steps of SM3 procedure are discussed together with some remarks on the use of SM3 output in supporting seismic design for reconstruction.

1. Introduction

Seismic risk (R) in a given area can be defined as the symbolic product of three terms: R=H*V*E where H (Hazard) defines the expected seismic ground motion in the area within a given time period, V (Vulnerability) is the degree of propensity for damages of structures or infrastructures following the event, E (Exposure) refers to people, goods (buildings, structures, infrastructures, cultural heritage, etc.) and activities which can be damaged by the event. As the reduction of H in terms of ground motion is not possible, it is necessary to modify V and E in order to mitigate seismic risk and reduce it below an acceptable level. This can essentially be done: i) at the building scale adopting up-to-date building codes and seismic retrofitting programs, ii) at the urban scale performing appropriate studies (namely Microzonation Studies) and including their results in urban/territory planning tools.
When a site is subjected to seismic shaking, the earthquake effects consist of transient or permanent phenomena: the first display themselves in terms of modifications in amplitude, frequency content and duration of ground motion (local amplification or site effects), while the latter involve ground instabilities such as landslides, liquefactions and settlements. These phenomena defining the local seismic hazard, vary from place to place depending on the local geology and morphology (i.e. the local conditions). The Seismic Microzonation (SM) can be defined as the process aimed 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 (Ansal et al. 2009, 2010; Crespellani 2014; Celikbilek and Sapmaz 2016; Aversa and Crespellani 2016).

In Italy, in the spirit to define guidelines for hinge the Seismic Microzonation on the planning system of Regions and Municipalities, guidelines and criteria to achieve SM have been standardized and published in Working Group ICMS (2008, 2011) 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 three grades of approach to zonation. Level 1 is the preparatory level for the SM studies; it relies on the collection of existing data, which are processed to divide the investigated area into zones that are qualitatively homogeneous in a seismic perspective. Level 2 is based on quick sub-soil exploration aimed at integrating existing data and introduces quantitative assessments of local seismic hazard via simplified methods; in Level 2 zoning for ground motion amplification, simplified abacus can be used, and the results are expressed in terms of expected amplification factors. Level 3 of Seismic Microzonation (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 Geology and Applied Seismology to Structural and Geotechnical Engineering. In particular, focusing on ground motion amplification, four main interdisciplinary steps can be recognized in performing a SM3 study (Pagliaroli, 2018): 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.

One of the key aspects in SM3 studies is the selection of the input motion at the seismic outcropping bedrock based on deterministic or probabilistic studies or, more simply, starting from the expected response spectra specified by the seismic code. For dynamic numerical analyses the input motions are generally expressed in terms of acceleration time histories, i.e. recordings of earthquakes, synthetic traces generated from seismological source models and accounting also for path effects, artificial spectrum-compatible signals generated from nonstationary stochastic simulations.

Another critical issue is the definition of the subsoil model resulting from geological, geophysical and geotechnical investigations. The first item is typically the geological model which defines the main lithotypes, the geometric relationships between them (i.e., the buried morphology). Then, the mechanical characterization of lithotypes, in terms of properties relevant for site response analyses, and the definition of the seismic bedrock lead to the subsoil model to be employed for the quantitative analysis of site effects or permanent deformations produced by the earthquake scenarios.

The spatial extension of the results obtained from numerical analyses (typically 1D and 2D), taking into account, if available, recordings or documented damage patterns available for previous earthquakes, finally leads to SM3 maps.

The results of SM3 studies can be applied in several areas: typically for urban and emergency planning, the reconstruction after the earthquake, and to support the structural design of buildings and infrastructures.

After the earthquakes of 2016-2017 that struck a large area of the Marche, Umbria, Abruzzo and Lazio Regions, intensive studies of SM3 were performed following the Ordinance of the Presidency of the Council of Ministers No. 24 of 12/05/2017 (ODPCM 24/2017), aimed to support the reconstruction in these territories. Particularly, the amplification phenomena due to geological, geotechnical and geomorphological conditions have been considered in this contest. In the paper, the adopted procedure for addressing the main four steps that characterize the SM3 study for soil amplification are presented being the study of ground instabilities out of the scope of the paper. Some critical issues pertaining to the abovementioned steps are discussed with reference to paradigmatic examples. Finally, a synthesis of the results and a proposal to incorporate the output of SM3 results in seismic design for the reconstruction are presented.

2. Definition of input motion

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 due to the ground condition. Therefore, the selection of the most suitable input motion is a key point in carrying out a SM3 study. A first aspect regards 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 reference ground motion (usually an acceleration response spectrum) at seismic bedrock, to carry out a site response analysis 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.

Both probabilistic (PSHA) and deterministic (DSHA) approaches can be employed to define the seismic hazard (McGuire 2001; Bommer 2002; Marcellini et al. 2001). The probabilistic approach considers the probability of exceedance of the ground motion in a given period of time providing an equiprobable spectrum combining a series of earthquakes that can affect, to different degrees, the site under study. In this respect, it is certainly more suitable than deterministic approach because SM3 is essentially a planning tool focused on preventing damage that could occur due to future earthquakes having different magnitudes and distances from the site (Ansal et al., 2009). PSHA reference spectra characterized by a “standard” 475 years return period (corresponding to a 10% probability of exceedance in 50 years) have been used for several SM3 studies (Pergalani et al. 1999; Lo Presti et al. 2002; Madiai et al. 2015, Eurocode 8 1998).

Regarding acceleration time-histories to be used as input motion for site response analyses, real accelerograms are nowadays emerging as the most attractive input for dynamic analyses mainly because they genuinely reflect the main factors (source, path and site) influencing the nature of ground motion (Bommer and Acevedo 2004; Pagliaroli and Lanzo 2008). Their increasing availability due to the growing development of online databases (the Italian ITACA, http://itaca.mi.ingv.it/, the European ESM http://esm.mi.ingv.it and the worldwide PEER http://ngawest2.berkeley.edu among others) is another valuable advantage.

In this study, for each of the 137 municipalities, a specific acceleration response spectrum, as prescribed by the Italian building code NTC18 (Ministero delle infrastrutture e dei Trasporti, 2018) for outcropping rock conditions (subsoil class A) and 475 years return period was assumed as reference. The NTC18 spectra are based on the PSHA study carried out by INGV for the whole Italian territory (INGV, 2007).

A set of 7 real unscaled accelerograms matching on average the reference spectrum in the period range 0.1-1.1 s was selected. The time-histories were extracted from the Italian ITACA database by constraining the selection based on: i) magnitude and distance reference windows, ii) fault mechanism, iii) soil and topography category at recording station. Regarding the first aspect, the reference for defining the search windows was the disaggregation study carried out in the framework of PSHA study (INGV, 2007). Normal fault recordings were included in the search being this mechanism largely predominant in the study area (Central Italy). Only recording at outcropping and flat rock conditions (i.e., subsoil class A and topography category T1 according to Italian technical code NTC18) were considered. The matching criterion with reference spectrum has been the following: the average 5% damped elastic response spectrum of selected time-histories should have no value lower than 90% and higher than 130% of the corresponding value of the target spectrum; this criterion must be satisfied in the period range of interest (0.1-1.1s). More details on the procedure for the selection of input motion time-histories can be found in Luzi et al. 2019 (present issue).

3. Definition of 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 (Sanchez-Sesma and Crouse 2015).

As the model should 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. These sites were selected in representative sites, where most lithotypes were encountered, or, in widespread territories, 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. More details on these investigations can be found in Caielli et al., 2019, this issue.

Regarding the characterization of nonlinear cyclic behaviour of soils, the nonlinearity of stiffness and damping properties of soils is usually assessed by cyclic and dynamic laboratory tests which generally provide the variation of secant shear modulus (G) and damping ratio (D) with the shear strain amplitude. The shear modulus at low strain levels, G_0, is typically determined assessing in-situ shear wave velocity Vs by means of geophysical tests and applying the relationship $G_0=\rho*Vs^2$ where ρ is the soil density. Stiffness from laboratory tests on specimens reconsolidated coherently with the in-situ stress state, is recognized to be lower than those estimated by in situ measurements. This is because geophysical tests measure the stiffness of the soil in the natural state, involving larger volumes, without the problems associated with soil sampling and consequent disturbance effects. For this reason, the stiffness adopted in site response analyses is currently obtained from the laboratory normalized modulus reduction curve G/G_0-γ scaled using the G_0 value estimated by in situ geophysical tests. The implicit assumption is obviously that the shape of G/G_0 decay curve is not substantially affected by disturbance, reconsolidation and representativeness of the soil samples. On the contrary, since material damping ratio cannot presently be estimated accurately in-situ, the “field” damping curve is assumed to be identical to the laboratory material damping curve.

Laboratory testing is always strongly recommended for nonlinear characterization, at least for fine grained soils for which undisturbed samples can be cheaply retrieved. However, the large 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. Consequently, a key aspect was the choice of literature curves for normalized shear modulus and damping ratio capable to describe the behaviour of soils and soft rock at the site of interest. In addition to the “standard” literature curves available for the different lithotypes (Vucetic and Dobry 1991, Darendeli 2001, Rollins et al. 1998, Seed and Idriss 1970 among others), a “local” database of the nonlinear curves was built on the basis of the large amount of cyclic/dynamic laboratory tests carried out in all 137 municipalities (Ciancimino et al. 2019, this issue). These curves properly associated to the main controlling factors, i.e. confining pressure, state and index properties, allowed a more refined and representative choice of the nonlinear properties for the site response analysis. See also Pagliaroli et al. 2019, this issue, for the application to some selected case histories of site response modelling.

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 of the complexity of bedrock morphology, soil layering and topography (Bilotta et al. 2011). In particular, the typology of the numerical modelling (1D vs 2D) and the resolution of the seismo-stratigraphic models strongly influence 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 in presence of valleys or ridge where the seismic response is strongly controlled by several variables defining their geological settings and 2D numerical modelling is needed (Bard and Bouchon 1985; Martino et al. 2015; Madiai et al. 2017).

To date, the 3D analysis is not a feasible approach in SM3 for several reasons: i) geological, geo-physical and geotechnical data are generally insufficient to build a suitable subsoil model, ii) high skills are required to manage 3D codes, iii) a great computational effort is needed. Regard this last point, in order to achieve sustainable computational times, the size of 3D elements can be enlarged; however, in this way important lithostratigraphic details cannot be modelled and, even in complex 3D subsoil conditions, sometimes 2D analyses better reproduce observed seismic response with respect to 3D modelling, at least in the medium-to-high frequency range (Puglia et al. 2009). All above considered, site response analyses for SM3 studies are therefore usually 1D and/or 2D as attested by SM studied carried out in Italy in the last decades (Pagliaroli, 2018).

Another issue is the selection of the method of analysis and the related constitutive relationships for soil behaviour under cyclic loading conditions. Two methods of analysis can essentially be chosen to take into account soil nonlinearity: equivalent linear, based on a series of iterative analyses assuming a viscoelastic soil behaviour, or a true nonlinear approach, this latter involving other issues such as the model for the skeleton curve, criteria for loading-unloading-reloading behaviour, total stress or effective stress analysis approach, pore water pressure generation/dissipation models.

In SM3 studies, the limited data generally available on cyclic behaviour as well as the large number of numerical simulations to be carried out generally force to adopt the “standard” equivalent linear approach, both for 1D and 2D analyses. For the SM3 project described here (see some examples in Pagliaroli et al. 2019 this issue), the 1D numerical analyses have generally been performed using STRATA (Kottke and Rathje, 2008) operating in frequency domain and using the equivalent-linear visco-elastic approach to model cyclic soil behaviour, like SHAKE (Schnabel et al. 1972) or its derivative codes (Idriss and Sun 1992). The 2D analyses were carried out through the time domain 2D FEM codes LSR2D (Stacec 2017) and QUAD4M (Hudson et al. 1994) also based on an equivalent linear strategy. Only in very few cases a nonlinear approach was employed, using the finite difference FLAC code (Itasca, 2011); however, it should be pointed out that a very simple constitutive model (such as a cyclic nonlinear elastic model called “hysteretic damping model” in the FLAC library) in terms of total stresses was considered; the effect of pore water pressure generation and dissipation on seismic ground response was not addressed.

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). Different ground motion parameters have been assumed over the years in the definition of amplification factors for SM studies (Pagliaroli 2018). According to the latest revision of the Italian standardized guidelines for microzoning (Working Group ICMS 2008; 2011), in the present SM3 study the Amplification Factor (AF) has been defined with reference to the 5% damped pseudo-acceleration elastic response spectra. It is calculated as the ratio between the integral of the pseudo-acceleration elastic response spectrum of the output motion and the pseudo-acceleration elastic response spectrum of the input motion in a selected range of period:

$$AF_{Tn} = \frac{\int_{Ta}^{Tb} S_{,out}\, dT}{\int_{Ta}^{Tb} S_{,inp}\, dT} \qquad \text{with } n = 1, 2, 3 \qquad \text{(eq. 1)}$$

where $S_{,out}$ is the pseudo-acceleration elastic response spectrum of the output motion; $S_{,inp}$ is the pseudo-acceleration elastic response spectrum of the input motion (i.e. the reference site that is subsoil type A, outcropping); Ta and Tb represent the extremes of the evaluated interval of periods Tn.

The three different range of period considered in this study in the eq.1 are the following: T_1=0.1-0.5s; T_2=0.4-0.8s and T_3=0.7-1.1s. This choice was made taking into account the typical fundamental periods of buildings in studied municipalities, which in turn can be generally related to some building characteristics (essentially the number of floors), considering that the most of the buildings are masonry, sometimes with poor quality design structure. 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 buildings heritage (https://www.istat.it/it/archivio/199364) have been firstly considered. In their studies (Working Group ISTAT 2016), it is shown that almost the 50% of residential buildings has a number of two floors, while the vast majority has a number of floors up to three (Figure 1). 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 one to four floors, which corresponds to fundamental period of vibration roughly estimated in the range 0.1-0.5 s (the first selected range of integration for AF) has been selected.

As an alternative approach, if an average structural inter-story height of 3.3 m is supposed, and the rule of thumb T = Ct H with H= total height of the structure and Ct= 0.02 (Michel and Gueguen 2013) is considered, two corresponding fundamental periods of 0.07 and 0.26s (as indicated in Table 1) are obtained for one- and four-storey buildings respectively. With the aim of taking into account the elongation of the period of the structure, also including the dynamic soil-structure interaction effects, a second following rule of thumb is used: elongated period of the structure Tel is twice the no–elongated period of the structure Tnel (Calvi et al. 2006; Mucciarelli et al. 2004). 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.

It is useful to remind that this interval is also the one historically chosen in most SM3 studies in literature (i.e. MS-AQ Working Group 2010; Pagliaroli 2018).

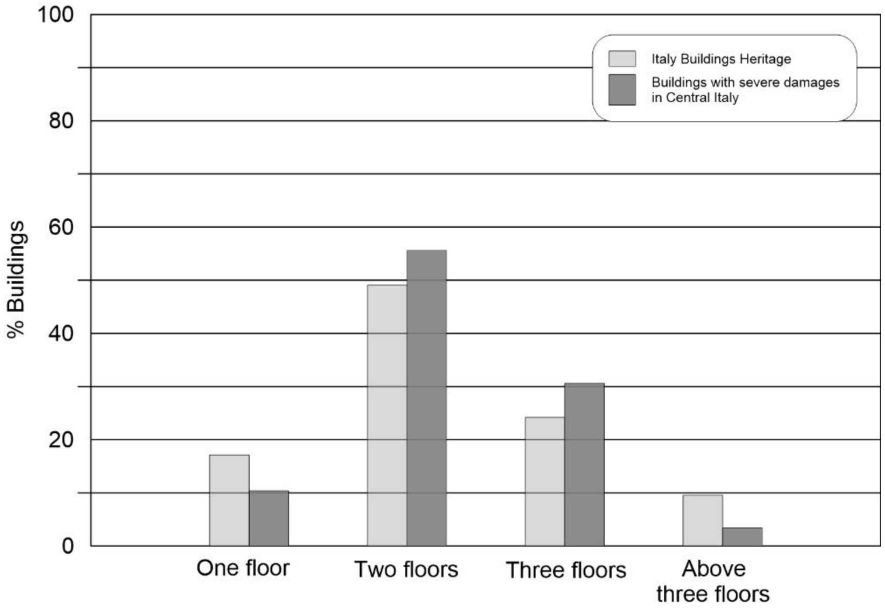

Figure 1
Percentages of buildings for number of floors in Italy (light grey bar chart) and in Central Italy (dark grey)

With the aim of taking into account in the seismic risk mitigation policies derived from SM3 studies, also soil amplification phenomena that may influence higher buildings, two other intervals were assumed: 0.4-0.8s and 0.7-1.1s. They roughly correspond to buildings with a number of floors from 3 to 6 and from 5 to 8 (Table 1).

Table 1
Criteria for choosing period ranges based on the characteristics of buildings

No. of floors	**Inter – storey height**	**Minimum corresponding Resonance Period (s)**	**Maximum corresponding Resonance Period (s)**	**Elongated Minimum Resonance Period (s)**	**Elongated Maximum Resonance Period (s)**	**Selected Period Range**
From 1 to 4	From 3.3 m to 13.2m	0.07	0.26	0.1	0.5	T1 (0.1-0.5 s)
From 3 to 6	From 9.9 m to 19.8 m	0.2	0.4	0.4	0.8	T2 (0.4-0.8 s)
From 5 to 8	From 16.5 m to 26.4 m	0.33	0.53	0.7	1.1	T3 (0.7-1.1 s)

5. Influence of subsoil model: an example

As an example of the influence on the results of the subsoil model, a case of valley characterized by lateral heterogeneity in the alluvial deposits causing lateral contrasts of the Vs values is here presented. Focusing on 2D numerical modelling in which the influence of 2D effects due to the shape of the valley are considered, the presence of the heterogeneities of the deposits plays an important role in assessing the site response. Neglecting these variables, a strong approximation affects the results and it might lead to an underestimation of the ground amplification prediction. The more the site is characterized by amplification, the more the underestimation is relevant.

The case study of Fonte del Campo site in the Municipality of Accumoli (Rieti) highlights the underestimation of the local seismic response of a microzone when a homogeneous geological setting is considered for the valley.

The numerical modelling at Fonte del Campo (Geological cross section AA' in Figure 2) was performed with the 2D finite difference code FLAC 7.0 (Itasca 2011).

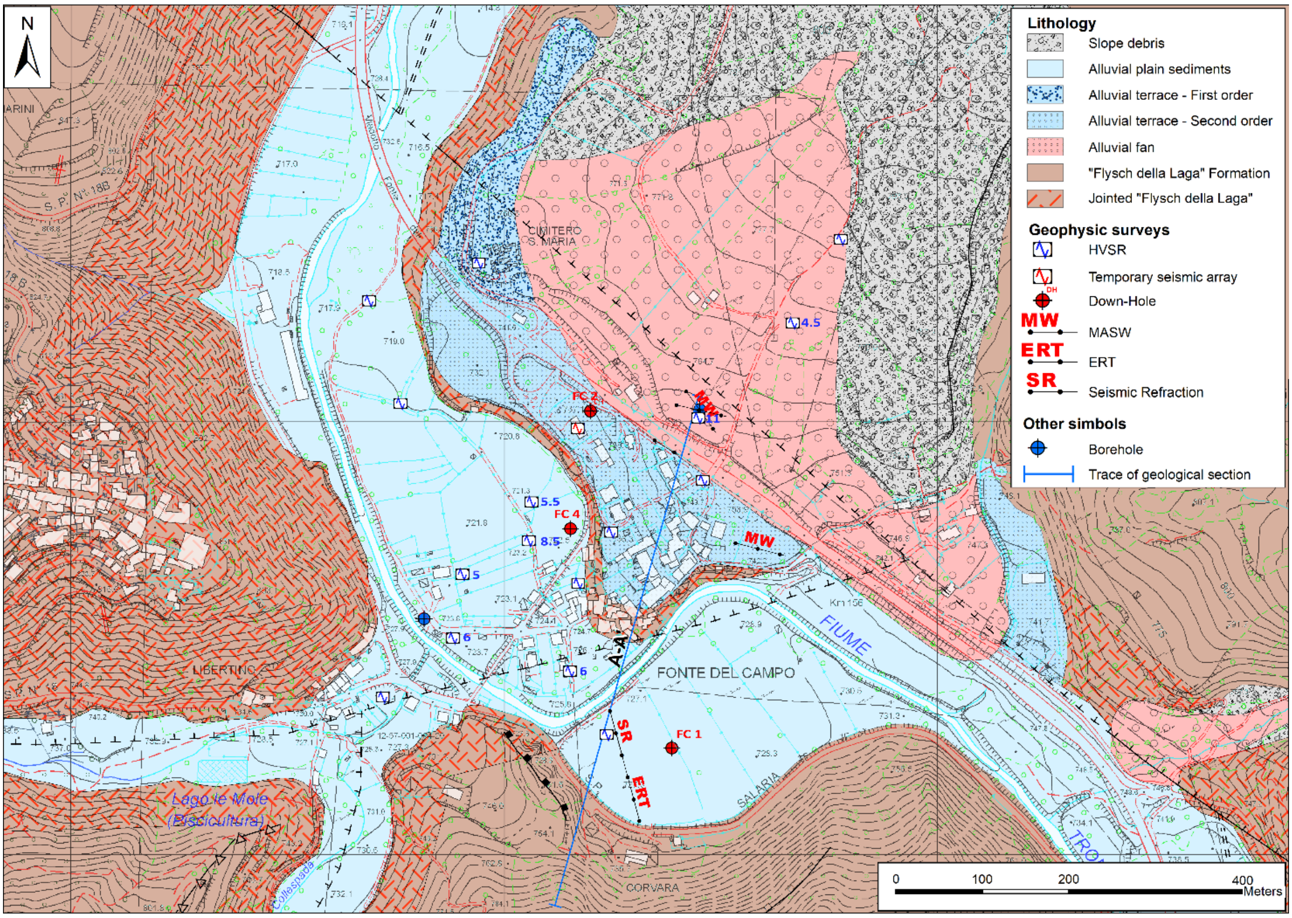

Figure 2

Lithotechnical map of Fonte del Campo (Accumoli Municipality) from Microzonation study. The location of AA' geological cross section is also reported.

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 (Figure 3), 4 MASW, 12 seismic noise measurements analysed through HVSR according to the Nakamura (Nakamura, 1989) technique, 1 section for geoelectric and seismic tomography.

Two different numerical models were then implemented as described in the following.

A "heterogeneous model" (HeM) representative of Fonte del Campo morphology and geological setting (Figure 4a) 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 4a 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 (First and Second order) 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 the study are reported in Table 2. The compressional wave velocities was defined according to 4 down-hole tests as a direct measurement of the velocity or as logarithmic average in case of several measurements of velocity within a given lithological unit. Three down-hole test was performed at Fonte del Campo (FC1 – FC2 and FC4 in Figures 2 - 3) while the fourth one (GR1 – Coordinates: 42°44'08.87''N – 13°15'51.44''E), refers to a borehole drilled at Griscano in the Tronto River valley (Figure 3). The unit weight was obtained from laboratory tests for units FC_TERR and FC_SOFT2, while for the other units, which cannot be sampled due to their grain size distribution, values were assumed from literature (Bozzano et al. 2008 and Caserta et al. 2012).

A "homogeneous model" (HoM) characterized by the same morphology as HeM but where the valley is filled only with gravels (FC_GA) overlying the softened layers of bedrock (FC_SOFT1 and FC_SOFT2) (Figure 4b).

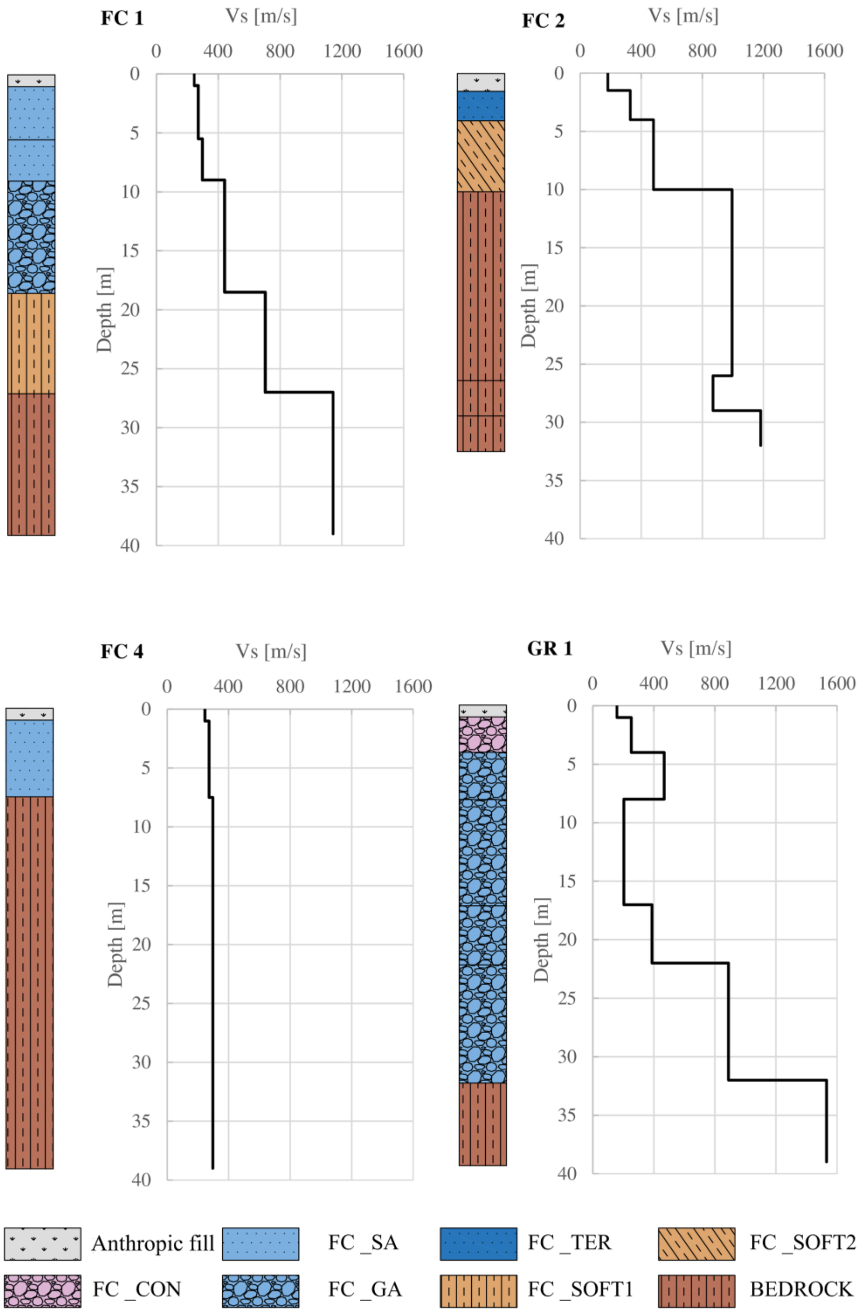

Figure 3
Lithological units and related Vs obtained from down-hole tests (see Figure 2 for location)

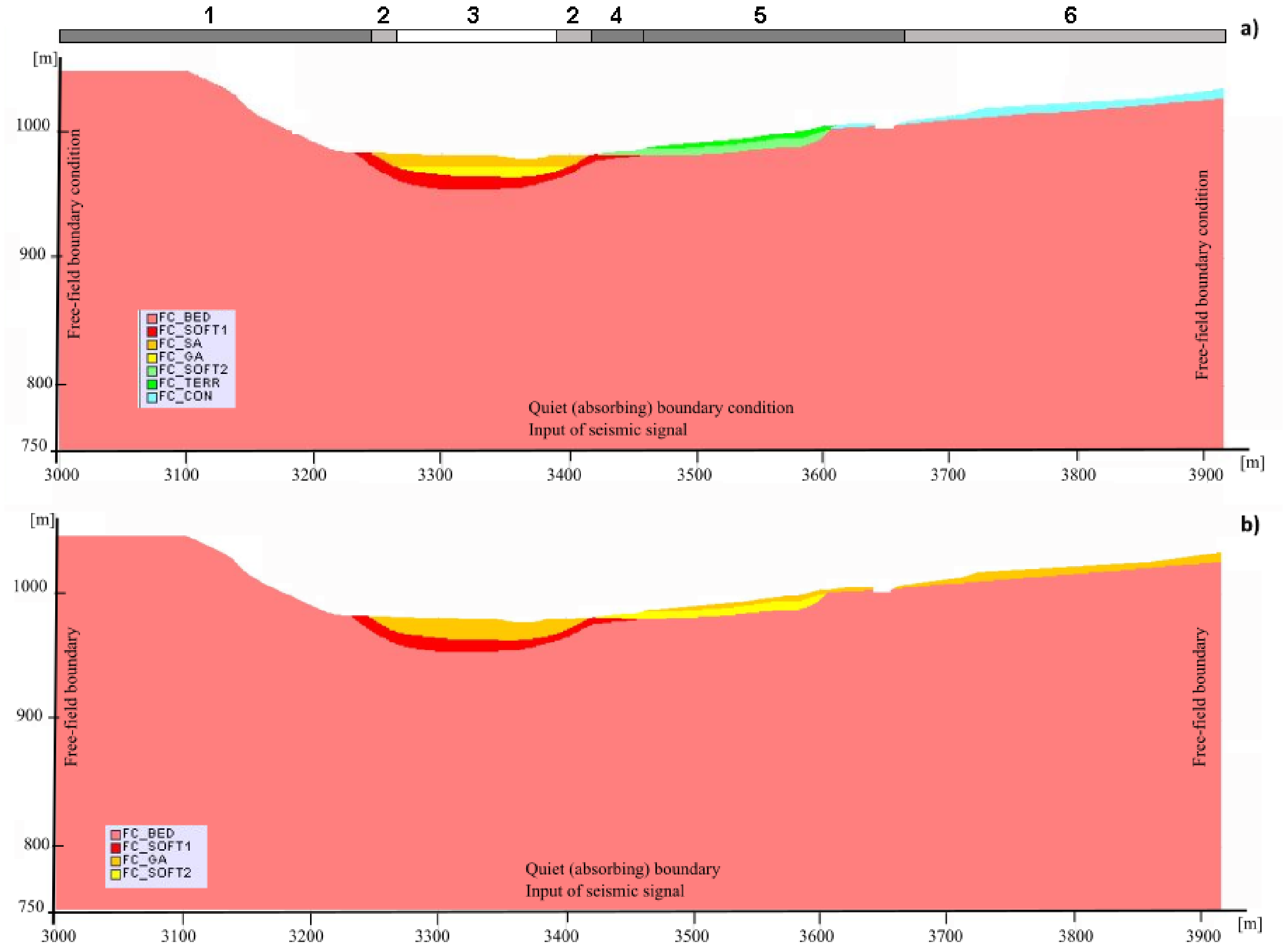

Figure 4
Seismo-stratigraphic layering (see Table 2) of HeM (a) and HoM (b) models; for HeM the positions of the defined microzones (from 1 to 6) are also indicated in the upper bar; boundary conditions used in the numerical modelling are indicated for both models.

A non-linear behaviour was assumed for all lithological units characterizing the cross section of Fonte del Campo with the exception of FC_BED. The decay curves associated to each lithological unit were available in the database compiled for the seismic microzonation studies (Ciancimino et al. 2018 present issue). 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.

The here presented results were obtained applying a fully non-linear approach while for the SM3 studies a more precautionary linear equivalent approach was considered, using FLAC code.

The results and maps obtained in the framework of the SM3 studies are also reported in Table 4 and Figure6.

Table 2
Values of the properties attributed to the different units for the numerical modelling at Fonte del Campo

	Unit weight γ (kN/m3)	**Shear-wave velocity Vs (m/s)**	**Compressional-wave velocity Vp (m/s)**
Sands (FC_SA)	19.2	285	533
Gravels (FC_GA)	21	441	825
Soft material (FC_SOFT1)	21	705	1319
Soft material (FC_SOFT2)	21	480	898
Sandy silts (FC_TERR)	16.5	327	612
Gravels (FC_CON)	21	252	471
Bedrock (FC_BED)	21	1170	2188

The strong motions used for the numerical modelling (Table 3 and Figure 5) were provided by Luzi et al. 2019, this issue. The dynamic input was applied as a vertically up-coming shear stress time-history at the lower boundary of the model.

Table 3
Characteristics of natural accelerograms selected as seismic inputs for the numerical modelling at Fonte del Campo (A = subsoil category A attributed based on available geological information at recording station).*

Acc.	**Event**	**Date**	**Mw**	**Epic. Distance (km)**	**Station (code-name)**	**Comp.**	**Site class. EC8**
#1	Central Italy	30.10.2016	6.5	22.6	MZ19-Pasciano Cimitero	NS	A*
#2	Central Italy	30.10.2016	6.5	22.6	MZ19-Pasciano Cimitero	EW	A*
#3	Central Italy	30.10.2016	6.5	18.6	ACC-Accumuli	EW	A*
#4	Central Italy	26.10.2016	5.9	10.8	CLO-Castelluccio di Norcia	EW	A*
#5	Central Italy	26.10.2016	5.9	10.8	CLO-Castelluccio di Norcia	NS	A*
#6	Central Italy	30.10.2016	6.5	19.2	MMO-Montemonaco	NS	A*
#7	Central Italy	30.10.2016	6.5	10.5	T1212-Avendita PG	NS	A*

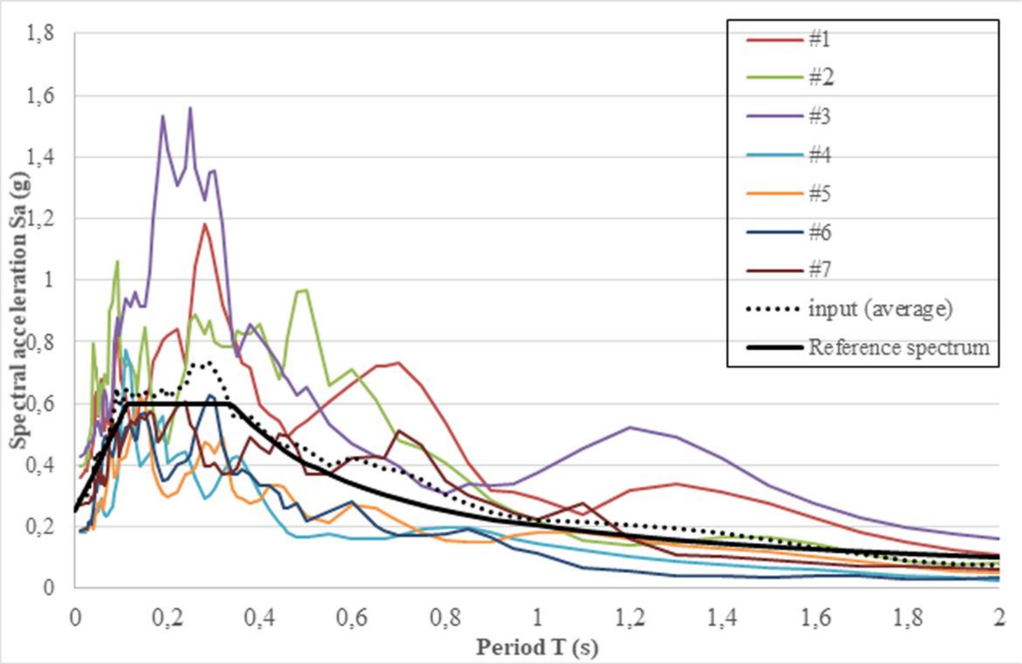

Figure 5
Response spectra of the 7 seismic inputs for the numerical modelling at Fonte del Campo (see Table 3 for the list of signals); the comparison between the average spectrum with the reference one is also reported

The models shown in Figure 4a and Figure 4b were discretized by 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 (Kuhlemeyer and Lysmer 1973). Free field boundaries (Cundall et al. 1980) were defined along the lateral edges of the considered domain (Figure 4). For the post processing of the numerical modelling, time histories of acceleration were collected at each 1 m grid node 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. For each microzone, a comparison among the response spectra obtained considering HeM, HoM was performed; moreover, the response spectra computed according to the Italian technical rules for constructions (NTC18) were compared to the obtained results (Figure 6). For assessing the response spectra according to NTC18, a soil category A for microzone 1 and soil category B from microzones from 2 to 6 and a 475-year return period for the ordinary building class were considered.

The comparison between HeM and HoM results in terms of AF (Table 4) highlights that the amplification factor is underestimated up to 20% (Microzones 2, 3 in Table 4) in case of microzone affected by amplification phenomena, if the presence of lateral heterogeneities in the alluvial deposits is neglected. This underestimation is more significant where compared with the more precautionary amplification factors obtained using a linear equivalent approach. It is worth to notice that, according to the amplification factors obtained when assuming an HoM, the microzone 6 (Table 4) is characterized by an AF equal to 1 in the period range 0.1–0.5 s (not amplificative microzone) while, according to the HeM it is characterized by an AF equal to 1.2 (amplificative microzone).

Table 4

Synthesis of the amplification factors AF obtained by considering HeM and HoM respectively. The amplification factors obtained using the linear-equivalent approach adopted in the SM3 study are also reported.

Microzone	AF HeM (this study)			AF HoM (this study)			AF HeM (SM3 study)		
	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	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	1.1	1.1	1.1
2	1.2	0.6	0.5	0.9	0.5	0.5	1.8	1.2	1.1
3	1.5	0.6	0.5	1.2	0.6	0.5	2.4	1.2	1.0
4	0.8	0.5	0.5	0.8	0.5	0.5	1.1	1.1	1.0
5	0.9	0.6	0.6	0.9	0.6	0.6	1.2	1.0	1.0
6	1.2	0.7	0.7	0.9	0.7	0.7	2.4	1.2	1.1

Moreover, neglecting the heterogeneity of the alluvia in case of amplificative microzones causes an underestimation of the predicted PSeudo-Acceleration (PSA) within the period range 0.0-0.6 s. The decreasing of the PSA ranges from 0.005g (i.e. microzone 1 in Figure 6) up to 0.4g (i.e. microzone 3 in Figure 6). As a further consideration, the comparison among numerical response spectra derived by NTC18 highlighted that this latter underestimates the ground motion prediction mainly in the range of periods 0.0-0.4s.

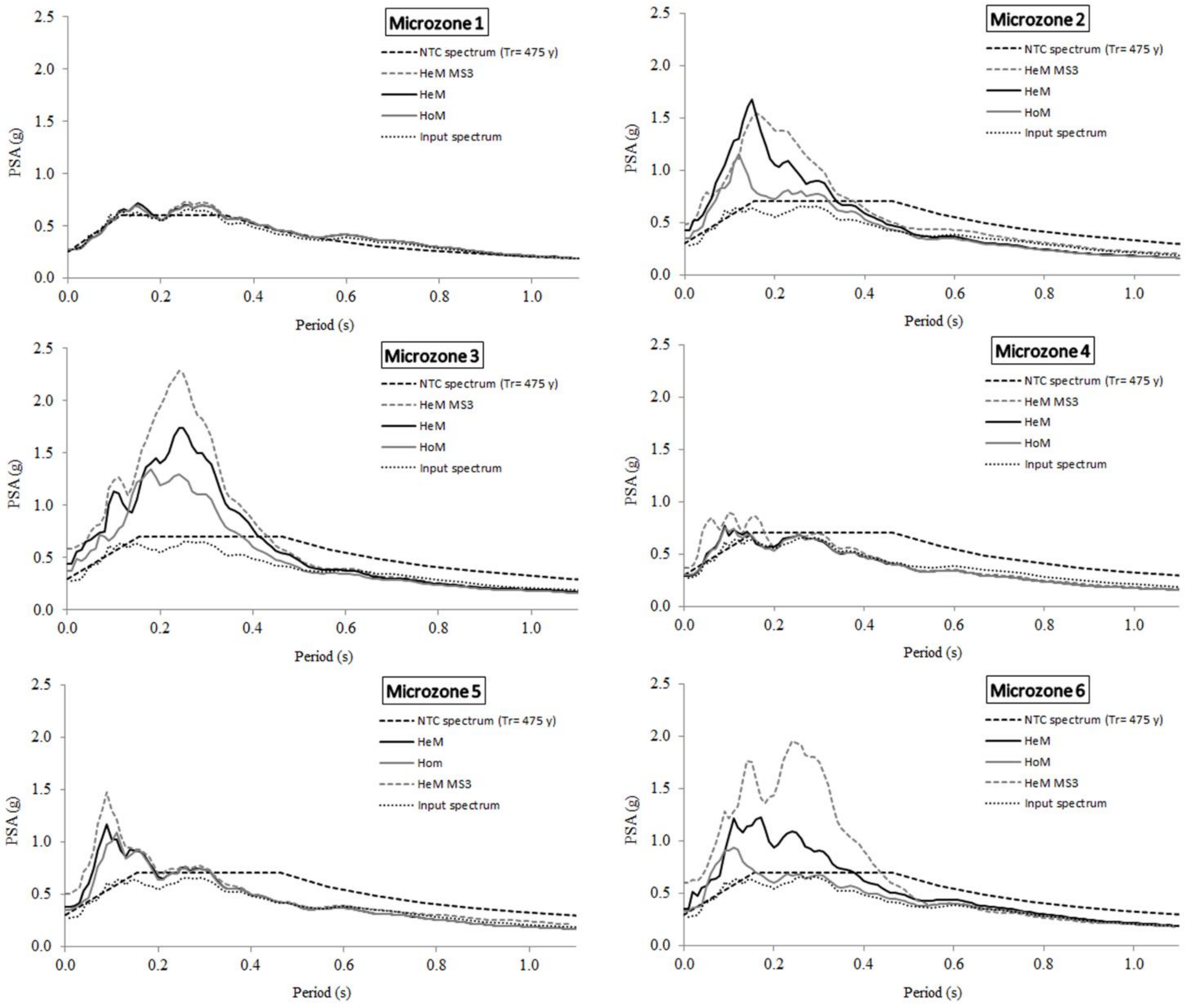

Figure 6

Elastic response spectra obtained in this study for each microzone from HeM (black line) and HoM (grey line) models compared with the spectrum obtained using the linear-equivalent approach in the SM3 study from HeM model (dashed grey line) and the corresponding NTC18 spectrum (dashed black line).

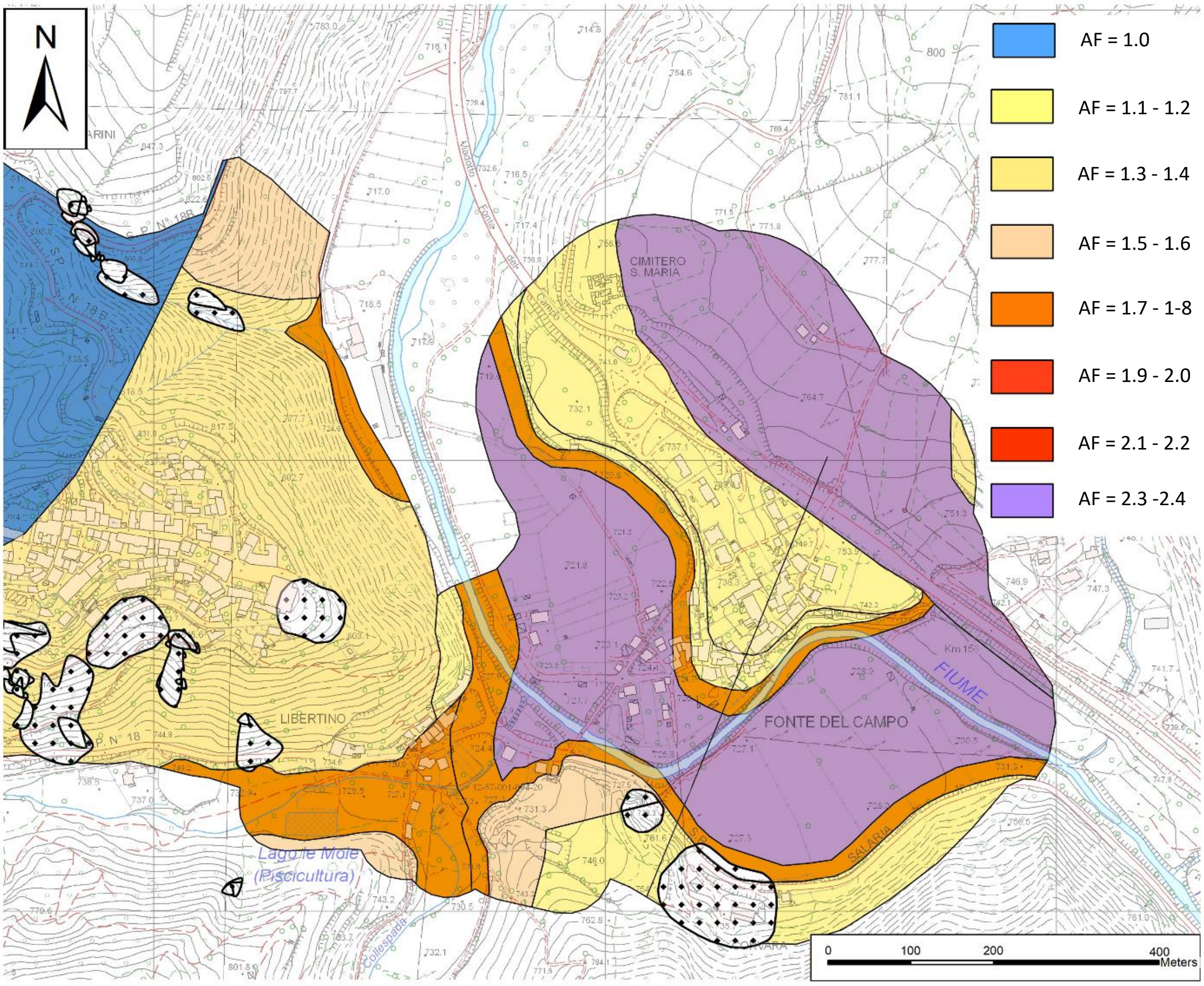

Figure 7

Seismic Microzonation map of the Fonte del Campo area (Municipality of Accumoli) as resulted from the SM3 study.

6. Global analysis of the SM3 results

As previous mentioned, during this project, 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 previous defined (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 has been computed with reference to the 137 municipalities (for a total of 4209 homogeneous microzones), in the three 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 (Figure 8).

Median values of AF decrease from the T1 interval (where AF median values is equal to 1.5) to the T3 interval (where AF median values is equal to 1.2). For each interval of periods, most of the AF values are located close the median values, with a slightly asymmetrical distribution for T2 and T3 period ranges (Figure 8).

For comparison, also the building code AF values obtained as the ratio between the integral of the acceleration response spectra derived from NTC18 for the four soil classes B, C, D and E, and for a soil class A with reference to the three selected intervals of periods were computed. A 475 years return period was fixed, coherently with the choice adopted for input motion selection in SM3 studies (Luzi et al. 2019 this issue). The AFs were computed for all the 8091 municipalities of the whole Italian territory with reference to the centroid of each administrative boundary corresponding to the geographic barycentre of the neighbourhood which contains the municipality building (according to the Italian National Institute of Statistics, ISTAT database; https://www.istat.it/it/archivio/104317). Figure 9 shows the statistical distribution of the obtained building code AF values for all the Italian municipalities. The statistical distribution of the building code-based AF values limited to the 137 municipalities where SM3 studies where performed are reported in Figure 10. The usefulness of such a comparison (between the dataset of all the Italian municipalities and the sub-dataset of the 137 municipalities) is reported here for completeness and aiming at providing useful insights that will make eventually possible the extension of the general results obtained in section 8 for the whole Italian territory (not only in Central Italy).

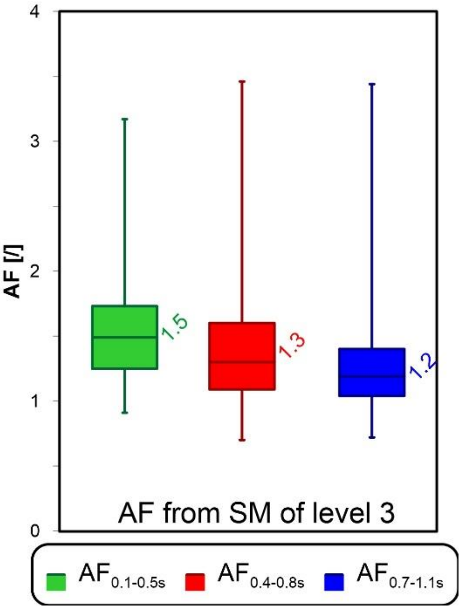

Figure 8
AF distribution for the 137 municipalities in Central Italy (derived from SM3 studies for a 475 yrs return period) as whisker plots (minimum, 25% - percentile, median, 75% - percentile and maximum). Colours indicate the period range of integration (T1 is in green, T2 in red and T3 in blue). Labels refer to median values.

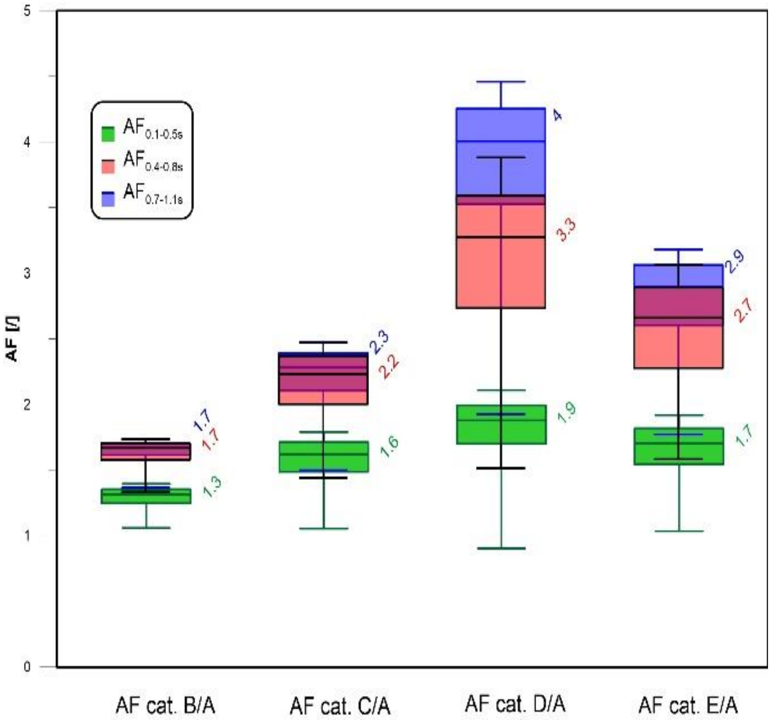

Figure 9
AF distribution for the whole Italian territory (derived from soil B/soil A, soil C/soil A, soil D/soil A and soil E/soil A, NTC18 spectra) as whisker plots (minimum, 25% - percentile, median, 75% - percentile and maximum). Each box refers to a NTC18 soil classes (B, C, D or E), while colours indicate the period range of integration (T1 is in green, T2 in red and T3 in blue). Labels refer to median values.

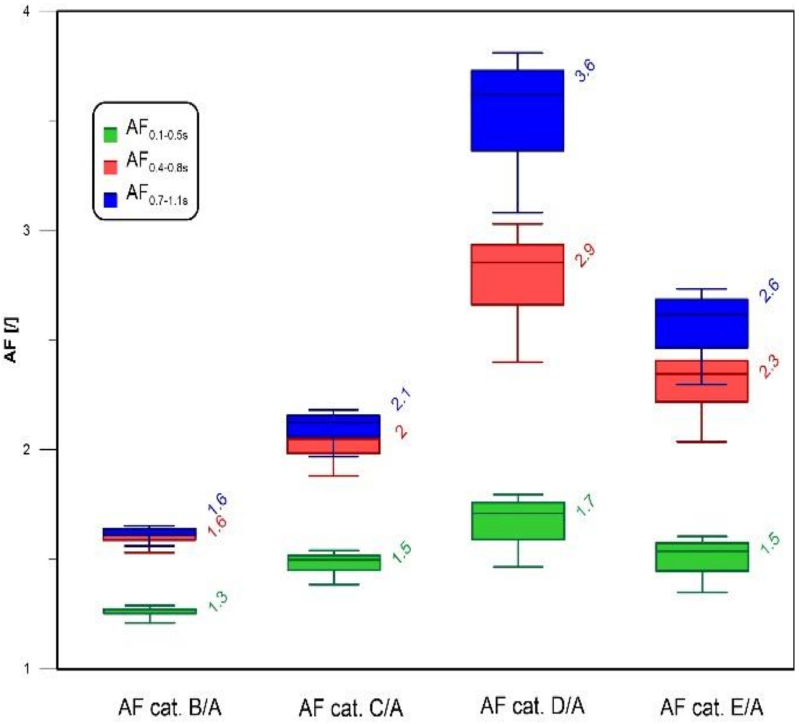

Figure 10
Distribution of AFs for the 137 municipalities in Central Italy (derived from soil B/soil A, soil C/soil A, soil D/soil A and soil E/soil A, NTC18 spectra) as whisker plots (minimum, 25% - percentile, median, 75% - percentile and maximum). Each box refers to a NTC18 soil class (B, C, D or E), while colours indicate the period range of integration (T1 is in green, T2 in red and T3 in blue). Labels refer to median values.

Comparing the results in Figures 8-10, it can be observed that the AF median values calculated for all the four soil classes with reference to the NTC18 spectra, both for the 137 Central Italy municipalities of the area heavily damaged by the 2016-2017 earthquake and all the Italian territory, 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 0.1-0.5 s period range, AFs from SM3 and technical code are generally comparable: for soil B category the NTC18 slightly underestimates the AFs while the opposite can be noticed for class D; for C and E classes the AFs are almost the same. It should be pointed out that in the distribution of AF from SM3 studies, as first approximation, the NTC18 subsoil categories have not been considered. This is because SM3 AFs were directly derived from level 3 SM maps, i.e. from microzones for which no equivalent shear wave velocity Vs,h values were generally available in the output of studies.

Nevertheless, PSA spectra shown as an example in Figure 6 (Fonte del Campo case study) highlight the overestimation of the AFs in medium-to-high period range (0.4-1.1s) and the underestimation in short period range by the Italian technical code with respect to SM3 spectra.

However, in order to compare AFs pertaining to the same soil category, a comparison among AFs from NTC18 and SM3 studies for selected areas was undertaken. In the following the case of Amatrice municipality, where the Regional Department of Civil Protection funded eighteen down–hole tests carried out and interpreted by the Italian Centre for Seismic Microzonation, is presented. In particular, two different localities (San Capone and Sommati hamlets) whose soil profiles belong to B and C subsoil categories have been chosen as examples. The AF values in the three considered ranges are extrapolated from the SM3 maps (after subsoil category identification) and compared in the Table 5 with the corresponding ones computed on the relative NTC18 spectra on the same point.

The AF values obtained from the SM3 studies are higher than the corresponding AF obtained from NTC18 response spectra at both the hamlets in the first range of period, while the contrary occurs in the other two ranges at higher periods, thus preliminary confirming the trend observed in all the SM3 dataset.

Table 5
Comparison among AF values obtained from SM3 studies and from NTC18 spectra at two example sites

Hamlet	**Latitude (WGS8)**	**Longitude (WGS84)**	**NTC18 Soil Category**	**NTC AF$_{0105}$**	**SM3 AF$_{0105}$**	**NTC AF$_{0408}$**	**SM3 AF$_{0408}$**	**NTC AF$_{0711}$**	**SM3 AF$_{0711}$**
San Capone	42.6770°	13.2879°	B	1.2	1.3	1.5	1.1	1.6	1.0
Sommati	42.6422°	13.3069°	C	1.4	2.0	1.9	1.8	2.0	1.4

The severe overestimation of the 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 controlling the shape of the spectra by enlarging the plateau at higher periods with respect to rock conditions (Andreotti et al., 2013). Moreover, it has to be considered that, where AFs are derived from 2D site response modelling, higher estimates are expected respect to the ones from NCT18 spectra in all the three period ranges. This trend is essentially referred to the fact that provisions consider only 1D soil conditions. This aspect could help providing another motivation of the NTC18 underestimation in low period (0.1-0.5s).

On the basis of the results obtained in this study, the simplified procedure proposed in 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). If data shown in Figure 1 are related with the statistical distributions of SM3-NTC18 amplification factors, this turns in an important outcome: about 90% of the buildings in Italy (and even more in the study area) have resonance periods which falls within the range 0.1-0.5 s, i.e. in the period range where NTC18 leads to amplifications comparable or lower than those computed by microzonation studies. These results point out the importance of general and objective recommendation about the approach that is more appropriate for the evaluation of the seismic action (i.e. code simplified approach based on subsoil categories or ad hoc site response numerical analyses), as indicated also in the last section.

Nevertheless, more research is necessary to ascertain the causes of discrepancies between SM3 and NTC amplification factors; in particular, AF comparisons undertaken separately for each subsoil category could significantly improve the analysis.

7. From site response analysis to SM3 map

The final step of a SM3 study is the representation of the results in a map drawing the contours of the 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, the ground motion at each point of the area under study depends on the soil profile dynamic behaviour (stratigraphic effects), on the surficial 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 the topographic and basin effects can be considered negligible in the area, the uncertainty in the identification of the microzones with homogeneous seismic behaviour and the attribution of (one or more) selected amplification parameters to drawing 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 (that is from the results of a Level 1 Seismic Microzoning study). 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 for each microzone with homogeneous seismic behaviour. If the analyses are performed with a reliable numerical solver, the reliability of the map will depend both on the accuracy of the local surface geology survey and on the quality of the data used to define in detail the stratigraphic subsoil conditions and to characterize the dynamic behaviour of the different lithotypes.

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, the taking into account of the distribution of the surficial and buried morphology effects on the area is one of the main critical aspects to extrapolate the data under 3D conditions and therefore in drawing the SM3 map. Since topographic and basin effects are typically 3D, their evaluation requires, strictly speaking, three-dimensional analyses. However, as mentioned, the implementation of 3D numerical analyses is unfeasible in practice since they are generally complicated and very time consuming in modelling and computation. Moreover, the details of the geological, geotechnical and geophysical subsoil conditions are seldom well known to define a suitable 3D model. As a result, at present, few applications of 3D numerical models have been carried out in practice. Once the values of the chosen amplification parameter have been calculated at a certain number of surface nodes of the 3D numerical model, it is possible to draw a map of the isolines of the amplification parameter 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 analysis, they can be classified as Mechanical/Empirical and Statistical prediction models (Hengl 2007). The first ones are very flexible and easy to use. They are named ‘Mechanical/Empirical’ because the user selects arbitrary or empirical model parameters without any deeper statistical analysis. No estimate of the model error is available for these models. However, in some cases, they can perform as good as the statistical ones (or better). Among the mechanical spatial prediction models, the most used in SM3 mapping is the ‘Inverse Distance Weight (IDW)’ model. In this model, the values of the selected parameter in a fixed number of points, or in the points located inside a window of a selected dimension, are interpolated by weighing the contribution of each of them according to its distance from the new interpolation point. Generally, the sum of the attributed weights is 1 and the weight function used is the inverse of the squared distance. IDW model limitations are connected with the weight function used and to the number of points (or to the window dimension) used. IDW model is also sensitive to the presence of clusters; moreover, the maximum and minimum of interpolating surface can be only obtained in the data points.

On the contrary, statistical models require the model parameters are estimated in an objective way, following the probability theory, and the predictions are supplemented with the estimate of the prediction error. A drawback is that the input dataset usually needs to satisfy strict statistical assumptions that are often unverifiable. Moreover, since several statistical data analysis steps must be followed in order to generate maps, the mapping process by these models is computationally very time consuming. If the conditions of applicability exist, among the statistical spatial prediction models, the 'ordinary kriging (OK)' technique can be usefully used in SM3 mapping.

An overview of the spatial prediction techniques and a detailed description of their characteristics, advantages and limitation are provided in Hengl (2007).

Once the most suitable spatial prediction method is identified, the isolines of the chosen amplification parameter can be plotted with reference to an appropriate interval. Starting from the isoline map so obtained, the contours of the homogeneous microzones from the point of view of local amplification can be traced assuming for the chosen amplification parameter a certain number of classes of an appropriate size (i.e. appropriate lower and upper limit of the parameter).

Generally, in order to obtain the definitive map, it is necessary to 'manually' adjust the contours of the zones obtained by means of the automatic procedure, making use of expert judgment and of the lithostratigraphic, geomorphological and instrumental data available.

Because of the difficulties related to the implementation of 3D numerical models, the SM3 studies refers usually to the results of 1D and/or 2D numerical ground response analyses (Pergalani et al. 1999; Lanzo et al. 2011; Pagliaroli et al. 2014, Madiai et al. 2015 among the others). A comparison of the spectral response of 1D, 2D and 3D models for an ideal elliptic basin filled with homogeneous material (Ohori et al. 1992) indicates that both the amplification effects and the predominant frequency become higher as more dimensions are included. On the other hand, the comparison between ground motion recordings and numerical results from 1D, 2D and 3D simulations for actual basin and hill conditions (Smerzini et al. 2011; Maufroy et al. 2016; Paolucci et al. 1999; Evangelista et al. 2016 among the others) have shown that all numerical simulations tend generally to underestimate the amplification at high periods (T>1s) with respect to the recorded signals and that 2D simulations can provide a better agreement at low periods (T<0.5s) where 3D models tend to overestimate the amplifications with respect to the recorded signals.

In the event that there are no conditions for defining and analysing three-dimensional numerical models, 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 conditions of the area to study where enough information is available to define a reliable geological and geotechnical model;
- performing of 1D and 2D local seismic response analyses on the selected vertical soil profiles and cross sections by using reliable computer programs that implement robust calculation algorithms;
- calculation of the values of the chosen amplification parameter at the ground surface of the vertical soil profiles and in a number of ground surface points of the two-dimensional model of the cross sections;
- representation of the results obtained in terms of the chosen amplification parameter on the geological map or on the map of a level 1 microzonation study (MOPS map). For 1D analyses, the value obtained for the chosen amplification parameter at the ground surface for each analysed vertical soil profile will be unique. For 2D analyses, the chosen amplification parameter will vary from point to point along the ground surface of each analysed cross section. In this case it will be necessary to define for the chosen amplification parameter a certain number of classes of an appropriate size (i.e. appropriate lower and upper limit of the parameter) and to mark on the trace of each cross section the segments related with the values of the chosen amplification parameter falling in the previously defined classes.
- 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 trace of 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 (engineering geological or MOPS) 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 (Cosentino et al. 2019 this issue).

The drawing up of the map cannot be completely automated and, in order to obtain a reliable definitive map, it is necessary to manually adjust the contours of the zones obtained preliminarily by the automatic procedure based on expert judgment, taking into account geomorphological and lithostratigraphic information, and reliable instrumental data.

As an example, the used data 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 Table 6 and Figure 11 the main characteristics and the response spectra of the applied seismic input are summarized. In Figure 12 the lithotechnical map and the location of geophysical and geotechnical investigation are shown (3 boreholes, 7 HVSR and 2 MASW and Seismic Refraction). Figure 13 shows the main frequency F_0 and the amplification amplitude A, from the HVSR investigation, and the shear wave velocity profiles from the MASW investigation. In Table 7 and Figure 14 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 was achieved from the results of the 2D numerical analyses performed by QUAD4M computer program (Hudson et al. 1994) at one cross sections (Figure 12 – Section 1). Figure 15 shows the trace of the analysed cross section, with the values of the amplification parameter ($AF_{0.1-0.5}$ in this case) calculated from the numerical analysis results, while Figure 16 shows the subdivision in segments on the cross section traces according to the amplification parameter classes and the SM3 final map. Finally, to complete the obtained results, the ground acceleration response spectrum for each area defined in SM3 map, calculated as the average obtained for the 7 applied input signals, is shown in Figure 17.

Table 6
Main characteristics of natural accelerograms selected as input motion for Scheggino (A = subsoil category A attributed based on available geological information at recording station)*

Acc.	**Event**	**Date**	**Mw**	**Epic. Distance (km)**	**Station (code-name)**	**Comp.**	**Site class. EC8**
#1	Central Italy	30.10.2016	6.5	22.6	MZ19-Pasciano Cimitero	NS	A*
#2	Central Italy	26.10.2016	5.4	27.9	Poggio Vitellino INGV	EW	A*
#3	Central Italy	30.10.2016	6.5	18.6	ACC-Accumuli	EW	A*
#4	Central Italy	26.10.2016	5.9	10.8	CLO-Castelluccio di Norcia	EW	A*
#5	Central Italy	26.10.2016	5.9	10.8	CLO-Castelluccio di Norcia	NS	A*
#6	Central Italy	30.10.2016	6.5	19.2	MMO-Montemonaco	NS	A*
#7	Central Italy	30.10.2016	6.5	10.5	T1212-Avendita PG	NS	A*

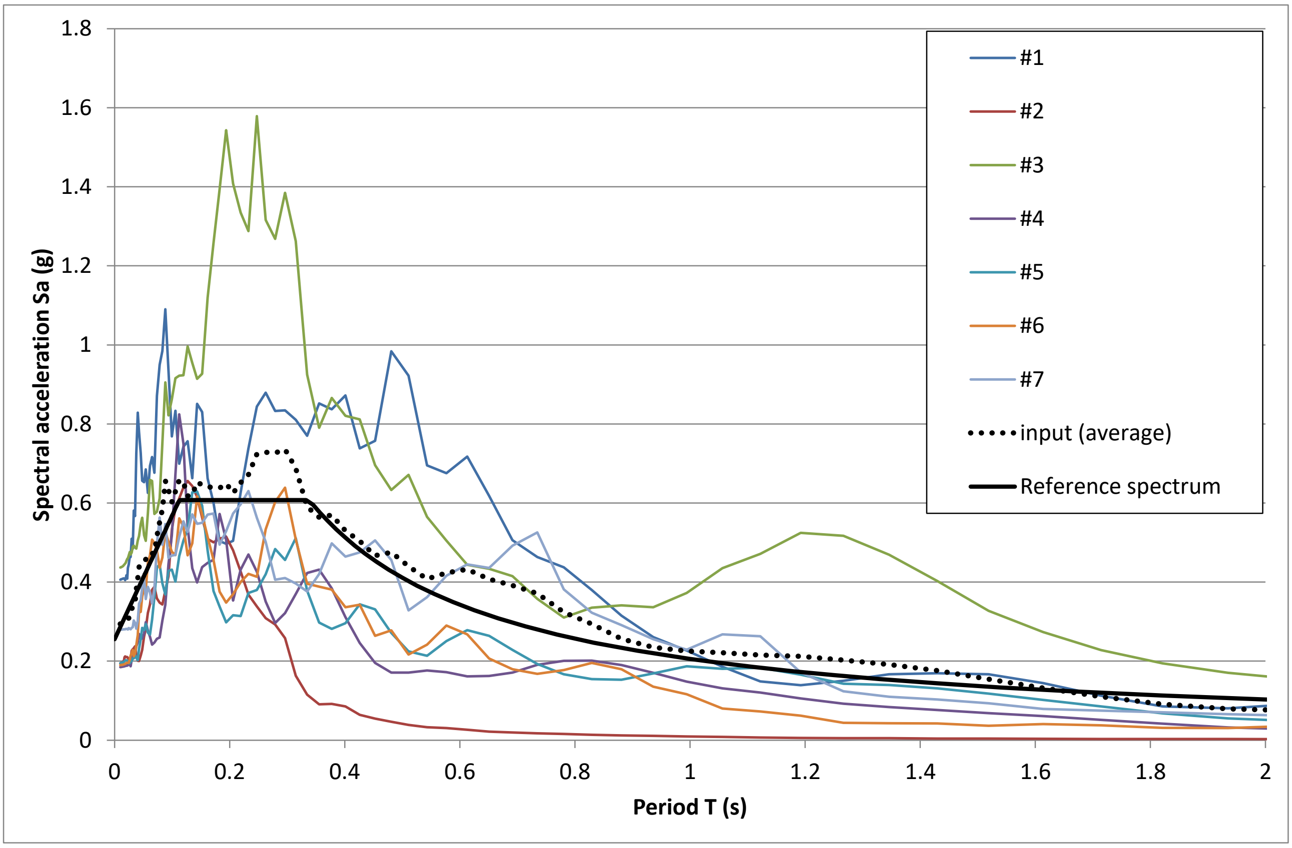

Figure 11
Response spectra of the 7 accelerograms selected as input motion for Scheggino (see Table 5 for the list of signals); the comparison between the average spectrum with the reference one is also reported

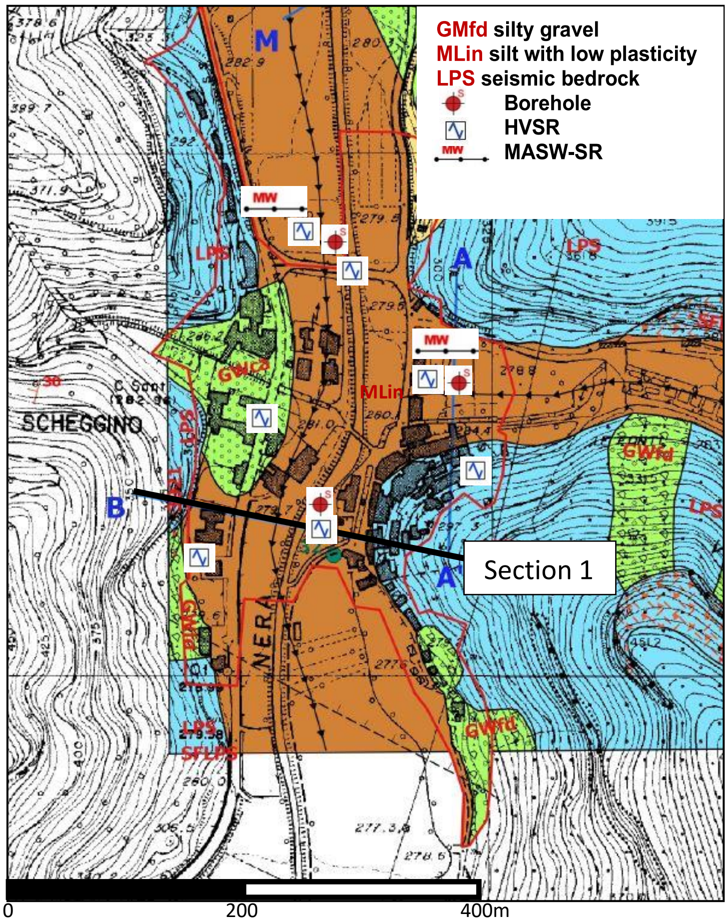

Figure 12

Lithotechnical map and location of geophysical and geotechnical investigations at Scheggino

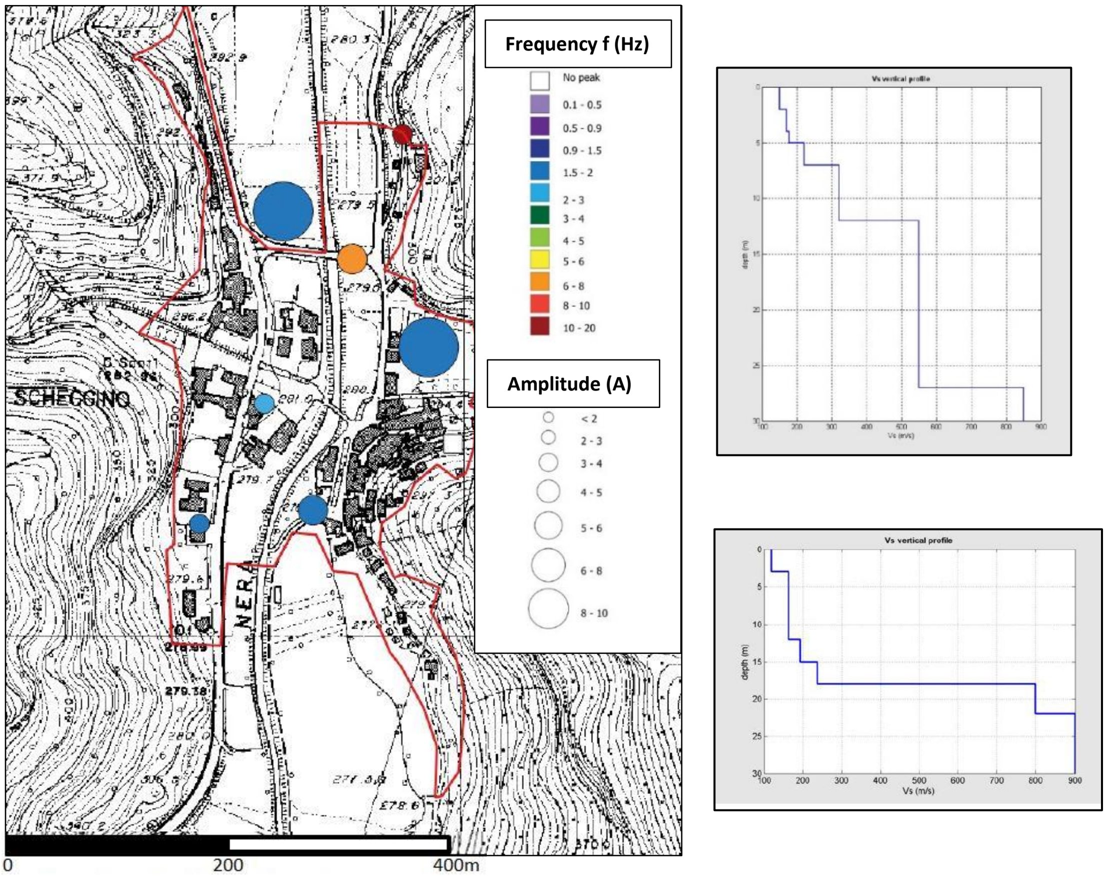

Figure 13

Results of the geophysical investigation at Scheggino in term of main frequency and amplification amplitude (HVSR) and Vs velocity profiles (MASW)

Table 7
Main parameters of the subsoil model at Scheggino

	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

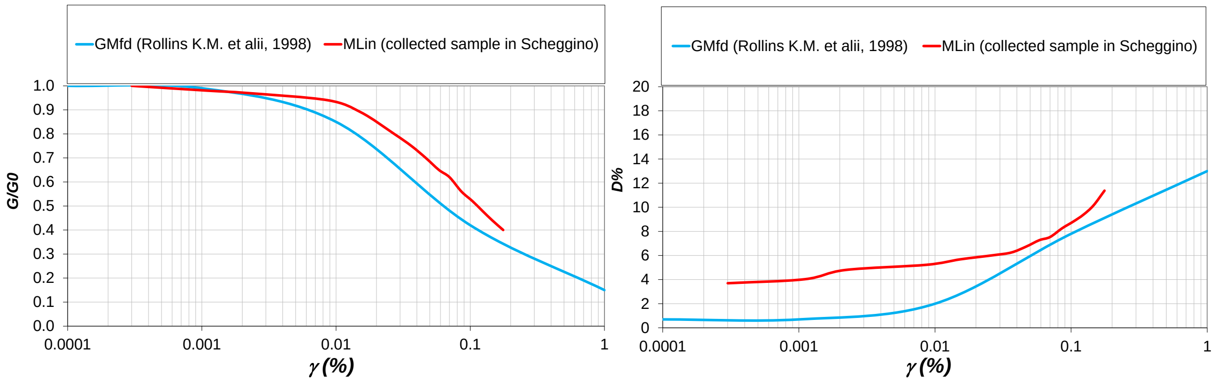

Figure 14
Normalized shear modulus G/G_0 and damping ratio D versus shear strain γ for the main lithotechnical units at Scheggino

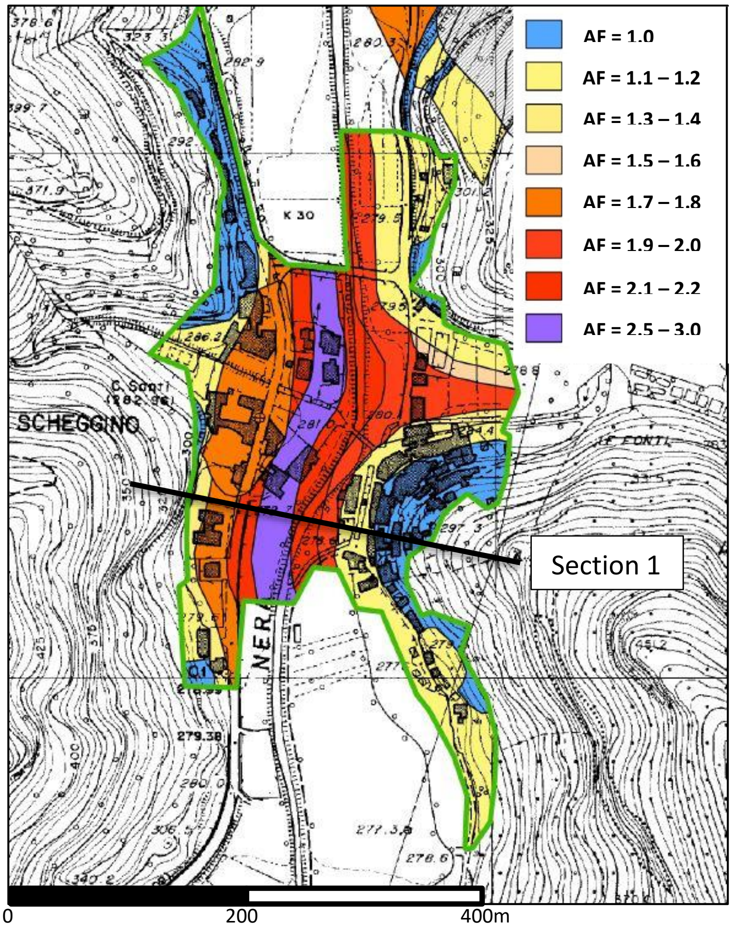

Figure 15
Seismic Microzonation map (SM3) of the Municipality of Scheggino

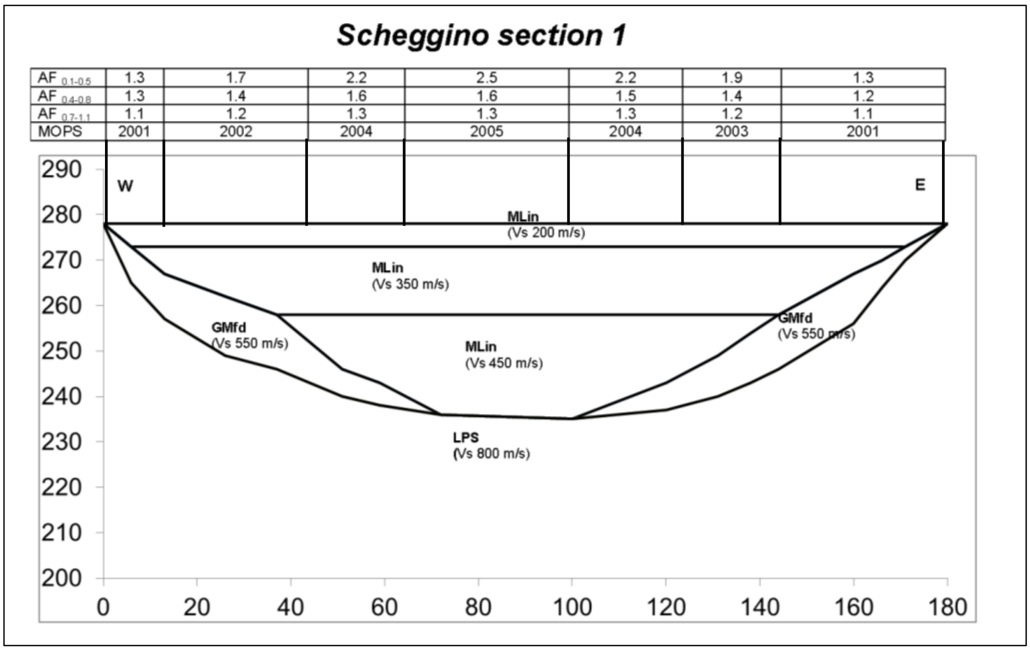

Figure 16

Subdivision in segments on the lithotechnical cross section traces and amplification factor (AF) values according to the MOPS classes and the SM3 final map (GMfd=silty gravel, MLin=silt with low plasticity, LPS=seismic bedrock).

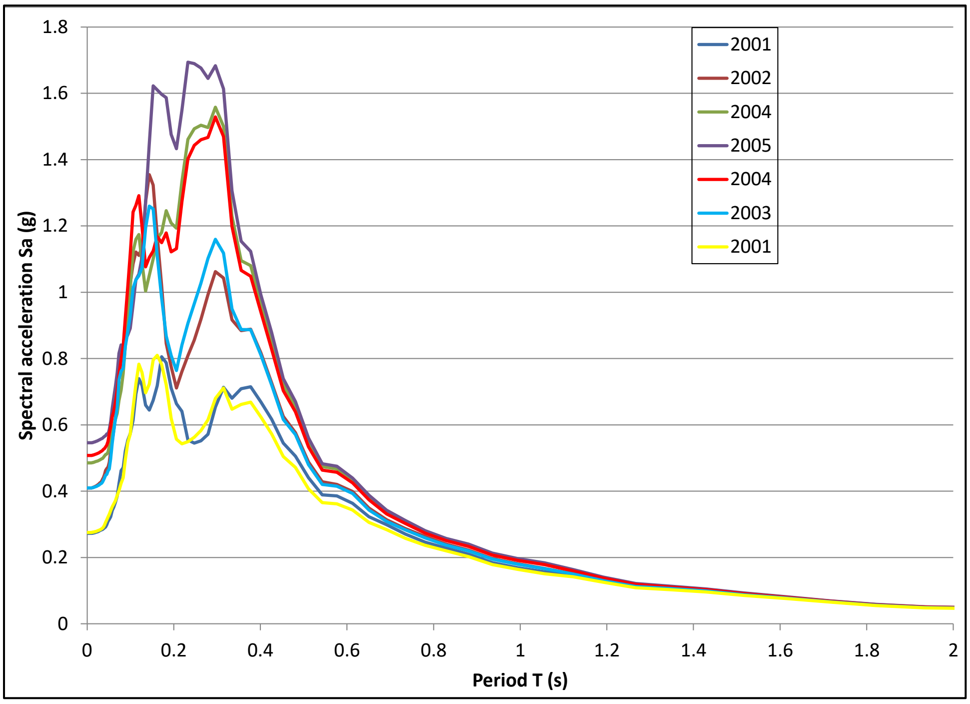

Figure 17

Ground acceleration response spectrum for each area (MOPS) defined in SM3 map, calculated as average of the 7 applied input signals

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

Appropriate measures and actions can be taken 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) including in urban/territory planning tools the results of appropriate Microzonation Studies.

On the first point, the recent Italian building code NTC18 (Ministero delle infrastrutture e dei Trasporti, 2018) included very important novelties concerning the seismic aspect, unlike the previous Italian building code NTC08 (Ministero delle infrastrutture e dei Trasporti, 2008). 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, and the simplified approach based on standard spectra depending on subsoil and topography categories is possible only in presence of regular and simple geo-morphological and geological situations.

As regards the second point, the SM3, as defined by the guidelines standardized and published in Working Group ICMS (2008, 2011), is essentially a tool of basic knowledge in urban and territory planning: by 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 the strategic buildings, to set intervention priorities in the existing inhabited areas; it allows 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, as in the project here presented (Mori et al 2018, present issue). The two most important tools for seismic risk mitigation, namely NTC18 code and SM3, operate therefore with different objectives; however, the sharing, between the two tools, of some aspects such as the assessment of local seismic hazard, produced ambiguity in the definition of the boundaries between SM3 and NTC18 and on the possible use of SM3 output in the seismic design.

According to Pagliaroli (2018), some acceptable uses of SM3 results in supporting the seismic design are the following:

- Use of database of investigations compiled for the SM3 study. This allows: i) to be more aware in planning the investigation survey at the building scale, ii) to access large scale investigations, the cost of which is generally unsustainable at least for ordinary design (e.g., geophysical investigations for the identification of deep buried morphologies and/or deep seismic bedrock);
- Use of SM3 maps detailing areas where instability phenomena may occur. If the building falls in one of these areas, the designer is alerted and should consider additional subsoil investigations and quantitative stability analyses depending on the design phase and type of instability phenomenon (liquefaction, slope instability, cavity collapse, settlements);
- Use of acceleration response spectra computed in the SM3 study (if available). These spectra, if properly regularized in code-based spectral shape (a procedure was proposed by working group ICMS 2008), could be a tool allowing the designer to choose objectively if the seismic action could be evaluated according the NTC18 simplified approach (i.e., subsoil categories) or ad hoc site response numerical analyses are necessary.

Following the level 3 SM 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” (Presidency of the Council of Ministers, 2018). In particular to define the design spectra, the designer has to preliminary compare the spectra deriving from the 3 SM studies with the NTC18 simplified approach spectra. If the SM3 spectrum exceeds punctually 30% the NTC18 spectra and the integral of the SM3 spectrum exceeds 20% the NTC spectra in the period rage of interest, the simplified NTC18 approach can be regarded as non-conservative. In this case the designer should perform additional investigations in the significant subsoil volume and is strongly encouraged to perform ad hoc site response analyses to define the seismic actions. Moreover, in case of complex surficial or buried morphologies, the designer should evaluate to use directly the SM3 response spectra for the design if these actions derived from 2D analyses carried out in the SM3 study are considered more accurate and conservative than standard 1D site response analyses he performed at building site.

9. Summary and conclusions

The Seismic Microzonation is nowadays a world-wide accepted tool for the mitigation of seismic risk. An advanced level 3 SM study (SM3) is a complex multidisciplinary process in which four main interdisciplinary steps can be recognized: 1) selection of reference input motions, 2) definition of subsoil model, 3) performing of numerical analyses and estimation of amplification factors, 4) identification of zones with different geotechnical hazard potential and drawing up of SM3 maps.

Some critical issues pertaining to the abovementioned steps are discussed in the paper with reference to the level SM3 studies carried out in Central Italy after the 2016-2017 seismic sequence in 137 municipalities most damaged by the earthquakes.

Regarding the input motion, for each of the 137 municipalities, a specific acceleration response spectrum, as prescribed by the Italian building code NTC18 for outcropping and flat rock conditions and 475 years return period was assumed as reference. A set of 7 real unscaled accelerograms matching on average the reference spectrum in the period range 0.1-1.1 s was selected. The time-histories to be used as input for site response analyses were extracted from the Italian ITACA database by constraining the selection mainly on the basis of the regional seismological conditions.

For the definition of subsoil model large volumes need to be investigated in a SM3 study. Expensive in-hole geophysical tests were therefore carried out only in selected points (no more than 1-2 sites for each municipality). 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, for the soil and rock characterization. Regarding the soil nonlinear behaviour, no more than two undisturbed samples for cyclic/dynamic laboratory tests were available in each municipality. The choice of properties was therefore based on “Standard” literature curves available for the different lithotypes and a “local” database of the nonlinear curves, built on the basis of the cyclic/dynamic laboratory tests carried out in all 137 municipalities, classified according to the main controlling factors, i.e. confining pressure, state and index properties. An example (Fonte del Campo site in the

Municipality of Accumoli) on the role of the subsoil model definition on the site response results is therefore presented in the paper.

To date, the 3D analysis is not a feasible approach in SM3. The limited data generally available on cyclic behaviour as well as the large number of numerical simulations to be carried out generally force to adopt the "standard" equivalent linear approach, both for 1D and 2D analyses. The critical issue is mainly the selection of a suitable amplification factor to be used in the identification of areas seismically homogeneous and drawing up of SM3 map. Particularly, three Amplification Factors with reference to the 5% damped elastic response spectra in pseudo-acceleration have been calculated in this study, considering three different intervals of periods: $0.1 \leq T1 \leq 0.5s$; $0.4 \leq T2 \leq 0.8s$ and $0.7 \leq T3 \leq 1.1s$, related to the geometrical characteristics of the buildings, ascertained with a statistical study.

To explore the results derived from SM3 studies in terms of ground motion amplification, statistical distribution of the AFs has been computed with reference to the 137 municipalities (for a total of 4209 homogeneous microzones). A preliminary comparison between AFs from SM3 and simplified approach by NTC18 (based on subsoil categories) is presented. It has been observed that the AF median values calculated for all the four soil classes with reference to the NTC18 spectra are greater than the AF median values from SM3 studies in T2 and T3 ranges of period. On the contrary, in the 0.1-0.5 s period range, AFs from SM3 and technical code are generally comparable even if NTC18 sometimes appears non-conservative. The adequacy of NTC18 soil factors Ss, controlling the amount of stratigraphic amplification and Cc controlling the shape of the spectra by enlarging the plateau at higher periods with respect to rock conditions should be explored with additional research.

The final step of a SM3 study is the representation of the results in a map drawing the contours of the zones (microzones) characterized by different ranges of a selected amplification parameter. This is a complex task, affected by a high level of uncertainty. Since topographic and basin effects are typically 3D, their evaluation requires, strictly speaking, three-dimensional analyses. However, because of the difficulties related to the implementation of 3D numerical models, the SM3 studies refers usually to the results of 1D and/or 2D numerical ground response analyses. A procedure to obtain a SM3 map starting from 1D/2D analyses is proposed in the paper and illustrated for a relevant case study (Municipality of Scheggino).

The procedure is based on a multidisciplinary approach that requires skills in geology, geotechnics, geophysics, spatial prediction procedures implemented in GIS platforms. The drawing up of the map cannot be completely automated and, in order to obtain a reliable definitive map, it is necessary to manually adjust the contours of the zones obtained preliminarily by the automatic procedure based on expert judgment.

The Italian building code NTC18 prescriptions and the SM3 studies refer to different scales and quite separate and distinct field (building construction the first one and urban/territory planning the second). However, as both tools require the quantitative assessment of site effects, some ambiguities in the definition of the boundaries between SM3 and NTC18 and on the possible use of SM3 output in the seismic design still exist (Pagliaroli 2018). The paper closes with remarks regarding some uses of SM3 output in supporting seismic design. The most relevant proposal, implemented in the "Ordinanza n. 55/2018" by the Presidency of the Council of Ministers, regards the use of response spectra computed in the SM3 study to decide if the design seismic action should be evaluated according the NTC18 simplified approach (i.e. subsoil categories) or via ad hoc site response numerical analyses.

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)". Thanks to the "Centro per la Microzonazione Sismica e le sue Applicazioni" which coordinated the project.

References

Andreotti G, Lai C.G, Bozzoni F, Scandella L (2013) New Soil Factors for the Italian Building Code (NTC08) Derived from 1D fully Stochastic Ground Response Analyses. Proc. XV ANDIS Conference "L'Ingegneria Sismica in Italia", June 30- July 4 2013, Padova.

Ansal A, Tönük G, Kurtuluş A (2009) Microzonation for Urban Planning. In: Tankut AT (Ed.) Earthquakes and Tsunamis, Geotechnical, Geological, and Earthquake Engineering 11: 133-152.

Ansal A, Kurtuluş A, Tönük G (2010) Seismic microzonation and earthquake damage scenarios for urban areas. Soil Dynamics and Earthquake Engineering 30: 1319–1328

Aversa S, Crespellani T (2016) Seismic Microzonation: an essential tool for urban planning in seismic areas. UPLanD-Journal of Urban Planning, Landscape & environmental Design, n. 1, 1: 121-152.

Bard PY, Bouchon M (1985) The two dimensional resonance of sediment filled valleys. Bull. Seism. Soc. Am. 75: 519–541.

Bilotta E, Evangelista L, Landolfi L, Silvestri F (2011) Site response analysis for microzonation: a comparison of different numerical approaches and amplification factors. Proc. 5th Int. Conf. on Earth. Geotech. Eng. (ICEGE), January 2011: 10-13, Santiago, Chile.

Bommer JJ (2002) Deterministic vs. probabilistic seismic hazard assessment: an exaggerated and obstructive dichotomy. J. Earthq. Eng., n. 6 (Special Issue 1): 43–73

Bommer JJ, Acevedo AB (2004) The use of real earthquake accelerograms as input to dynamic analysis. Journal of Earthquake Engineering, 8, (4): 1–50

Bozzano F, Caserta A, Govoni A, Marra F, Martino S (2008) Static and dynamic characterization of alluvial deposits in the Tiber River Valley: New data for assessing potential ground motion in the City of Rome. J. Geophys Res, 113: B01303.

Calvi GM, Pinho R, Crowley H, (2006) State-of-the-knowledge on the period elongation of RC buildings during strong ground shaking. Proceedings of the 1st European Conference of Earthquake Engineering and Seismology, Geneva, Switzerland, paper 1535.

Caserta A, Martino S, Bozzano F, Govoni A, Marra F (2012) Dynamic properties of low velocity alluvial deposits influencing seismically-induced shear strains: the Grottaperfetta valley test-site (Rome, Italy). Bull Earthquake Eng, 10:1133-1162.

Celikbilek A, Sapmaz G (2016) Risk Management and Microzonation in Urban Planning: an analysis for Istan- bul. Disaster Science and Engineering, 2, (2):59-66.

Caielli G, De Franco R, Di Fiore V, Albarello D, Amanti M, et al. (2019) Extensive geophysical prospecting for seismic microzonation. Bulletin of Earthquake Engineering (this issue)

Ciancimino A, Foti S, Alleanza GA, Amoroso S, Bardotti R, Biondi G, Cascone E, Castelli F, D'Onofrio A, Lanzo G, Lentini V, Madiai C, Vessia G (2019) Dynamic characterization of soils in Central Italy through laboratory testing. Bulletin of Earthquake Engineering (this issue)

Cosentino G, Carbone G, Pennica F et al. (2019) GIS tools for seismic microzonation data management and cartographic representation. Bulletin of Earthquake Engineering (this issue)

Crespellani T (2014) Seismic Microzoning in Italy: a brief history and recent experiences. Ingegneria Sismica, vol. XXXI, n.2: 3-31.

Cundall P, Hansteen E, Lacasse S, Selnes PB (1980) NESSI, Soil Structure Interaction Program for Dynamic and Static Problems. Norges Geotekniske Institute, Norway (Report 51508-9)

Darendeli MB (2001) Development of a new family of normalized modulus reduction and material damping curves. PhD theis, The University of Texas at Austin, pp. 394,
available at: https://repositories.lib.utexas.edu/bitstream/handle/2152/10396/darendelimb016.pdf

European Commission (1998) Eurocode 8: Design of structures for earthquake resistance

Evangelista L, Landolfi L, D'Onofrio A, Silvestri F, (2016) The influence of the 3D morphology and cavity network on the seismic response of Castelnuovo hill to the 2009 Abruzzo earthquake. Bull Earthquake Eng, 14: 3363-3387

Hengl T (2007) A Practical Guide to Geostatistical Mapping of Environmental Variables. EUR - Scientific and Technical Research Reports. Office for Official Publications of the European Communities. ISBN: 978-92-79-06904-8

Hudson M, Idriss IM, Beikae M (1994) QUAD4M: a computer program to evaluate the seismic response of soil structures using finite element procedures and incorporating a compliant base, Dpt. of Civil and Envir. Eng., Univ. of California Davis, Davis

Idriss IM, Sun JI (1992) User's Manual for SHAKE91, Center for Geotechnical Modelling, Department of Civil Engineering, Univ. of California, Davis

INGV (2007) Progetto S1 - Proseguimento della assistenza al DPC per il completamento e la gestione della mappa di pericolosità sismica prevista dall'Ordinanza PCM 3274 e progettazione di ulteriori sviluppi, Convenzione DPC-INGV, http://esse1.mi.ingv.it/ (last accessed: Septmber 2018)

ITASCA (2011) FLAC 7.0: User Manual, Licence Number SN: 213–33-760- key 29753 (IFSTTAR); 213-039-0127-30821 (DST- Sapienza).

Kottke AR, Rathje EM (2008) Technical Manual for Strata, PEER Report 2008/10, Pacific Earthquake Engineering Research Center College of Engineering, University of California, Berkeley, available at: http://peer.berkeley.edu/publications/peer_reports/reports_2008/web_PEER810_KOTTKE_Rathje.pdf.

Kuhlemeyer RL, Lysmer J (1973) Finite element method accuracy for wave propagation problems. J. Soil Mech. Found. Eng. Div. ASCE 99 (SM5):421–427

Lanzo G, Silvestri F, Costanzo A, D'Onofrio A, Martelli L, Pagliaroli A, Sica S, Simonelli A (2011) Site response studies and seismic microzoning in the Middle Aterno valley (L'Aquila, Central Italy). Bull Earthquake Eng., 9:. 1417-1442.

Lo Presti D, Luzi L, Pergalani F, Petrini V, Puci I, Signanini P, (2002) Determinazione della risposta sismica dei terreni a Castelnuovo Garfagnana. Rivista Italiana di Geotecnica, : 61-74

Luzi L, Pacor F, Felicetta C, Puglia R, Lanzano G, D'Amico M (2019) 2016-2017 Central Italy seismic sequence: strong-motion data, seismic hazard and design earthquake for the seismic microzonation of Central Italy. Bulletin of Earthquake Engineering (present issue)

Madiai C, Facciorusso J, Gargini E, Vannucchi G, Baglione M (2015) A Methodology for Advanced Seismic Microzoning Using 2D Analyses: The Case Study of Barberino di Mugello, Florence, Italy. Engineering Geology for Society and Territory, 5:. 1081-1084

Madiai C, Facciorusso J, Gargini E (2017) Numerical Modeling of Seismic Site Effects in a Shallow Alluvial Basin of the Northern Apennines (Italy). Bulletin of the Seismological Society of America, 107: 2094-2105

Marcellini A, Bard PY, Iannaccone G, Meneroud P, Mouroux P, Romeo W, Silvestri F, McGuire RK (2001) Deterministic vs. probabilistic earthquake hazards and risks. Soil Dynamics and Earthquake Eng., 21: 377-384

Martino S, Lenti L, Gelis C, Giacomi AC, Santisi D'Avila P, Bonilla F, Bozzano F, Semblat JF (2015) Influence of lateral heterogeneities on strong motion shear strains: simulations in the historical center of Rome (Italy). BSSA, 105(5): 2604-2624

Maufroy E, Chaljub E, Hollender F, Bard PY, Kristek J, Moczo P, De Martin F, Theodoulidis N, Manakou M, Guyonnet-Benaize C, Hollard N, Pitilakis K (2016) 3D numerical simulation and ground motion prediction: Verification, validation and beyond – Lessons from the E2VP project. Soil Dynamics and Earthquake Engineering, 91:. 53-71

McGuire RK (2001) Deterministic vs. probabilistic earthquake hazards and risks. Soil Dynamics and Earthquake Eng., 21:377-384

Michel C, Gueguen P (2013) Experimental Method: Contribution of Ambient Vibration Recordings to the Vulnerability Assessment. In: Gueguen P. (ed) Seismic Vulnerability of Structures, ISBN: 978-1-84821-524-5: 161-212

Ministero delle infrastrutture e dei Trasporti (2008) Norme Tecniche per le Costruzioni (NTC08). Decreto Ministero Infrastrutture. GU Serie Generale n. 29 del 04-02-2008 - Suppl. Ordinario n. 30

Ministero delle infrastrutture e dei Trasporti (2018) Norme Tecniche per le Costruzioni (NTC18). Decreto Ministero Infrastrutture. GU Serie Generale n. 42 del 20-02-2018 – Suppl. Ordinario n. 8

Mori F, Gaudiosi I, Tarquini E, Bramerini F, Castenetto S, Naso G, Spina D (2019) HSM: a synthetic seismic hazard parameter. Bulletin of Earthquake Engineering (this issue)

MS-AQ Working Group (2010) Microzonazione sismica per la ricostruzione dell'area aquilana. Regione Abruzzo—Dipartimento della Protezione Civile, L'Aquila, 3 vol. and CD-Rom, www.protezionecivile.gov.it/jcms/en/view_pub.wp?contentId=PUB25330 (in Italian)

Mucciarelli M, Masi A, Gallipoli MR, Harabaglia P, Vona M, Ponzo F, Dolce M (2004) Analysis of RC Building Response and Soil-Building Resonance based on Data Recorded during a Damaging Earthquake (Molise, Italy, 2002). Bulletin of the Seismological Society of America 94(5):1943-1953

Nakamura Y (1989) A method for dynamic characteristics estimation of subsurface using microtremors on the ground surface. Quaterly Rept. RTRI, Jpn. 30: 25-33

Ohori M, Koketsu K, Minami T (1992) Seismic Responses of Three-Dimensionally Sediment-Filled Valleys due to Incident

Plane Waves. J. Phys. Earth., 40: 209-222

Pagliaroli A, Lanzo G (2008) Selection of real accelerograms for the seismic response analysis of the historical town of Nicastro (Southern Italy) during the March 1638 Calabria earthquake. Engineering Structures, 30: 2211-2222

Pagliaroli A, Moscatelli M, Raspa G, Naso G (2014) Seismic microzonation of the Central Archeological Area of Rome: results and uncertainties. Bulletin of Earthquake Engineering, 12: 1405–1428

Pagliaroli A (2018) Key issues in Seismic Microzonation studies: lessons from recent experiences in Italy. Rivista Italiana di Geotecnica - Italian Geotechnical Journal, n. 1/2018, pp. 5-48, DOI: 10.19199/2018.1.0557-1405.05.

Pagliaroli A, Pergalani F, Ciancimino A, Chiaradonna A, Compagnoni M, de Silva F, Foti S, Giallini S, Lanzo G, Lombardi F, Luzi L, Macerola L, Nocentini M, Pizzi A, Tallini M, Teramo C (2019) Site response analyses for complex geological and morphological conditions: relevant case-histories from 3rd level seismic microzonation in Central Italy. Bulletin of Earthquake Engineering (this issue).

Paolucci R, Faccioli E, Maggio F (1999) 3D Response analysis of an instrumented hill at Matsuzaki, Japan, by a spectral method. Journal of Seismology, 2: 191–209

Pergalani F, Romeo R, Luzi L, Petrini V, Pugliese A, Sanò T (1999) Seismic microzoning of the area struck by Umbria-Marche (Central Italy) Ms 5.9 Earthquake of the 26 September 1997. Soil Dynamic and Earth. Eng., Elsevier Science, 18: 279-296

Presidency of the Council of Ministers (2017). Ordinance No. 24 of 12/05/2017 (ODPCM 24/2017)

Presidency of the Council of Ministers (2018) Ordinance 55 del 24/04/2018. Available at: https://sisma2016.gov.it/wp-content/uploads/2018/04/ordinanza-n.-55-delocalizzazioni-con-modifiche-approvate-ed-AEDES-con-allegato-24.04.18.pdf, last accessed September 2018, in italian)

Puglia R, Klin P, Pagliaroli A, Ladina C, Priolo E, Lanzo G, Silvestri F (2009) Analisi della risposta sismica locale a San Giuliano di Puglia con modelli 1D, 2D e 3D. Rivista Italiana di Geotecnica, Vol. LXIII(3): 62-71

Rollins KM, Evans MD, Diehl N (1998) Shear modulus and damping relationships for gravels. Journal of Geotechnical and Geoenvironmental Engineering, 124(5):396-405

Seed HB, Idriss IM, (1970) Soil moduli and damping factors for dynamic response analyses, Report no. EERC 70-10. Earthquake Engineering Research Center, University of California, Berkeley, California

Sánchez-Sesma FJ, Crouse CB, (2015) Effects of site geology on seismic ground motion: early history. Earthq. Eng. Struct. Dyn., 44, 7: 1099–113

Schnabel PB, Lysmer J, Seed HB (1972) SHAKE A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites, Earthquake Engineering Research Center, Report N. EERC 72-12, University of California, Berkeley

Smerzini C. Paolucci R. Stupazzini M. (2011) Comparison of 3D, 2D and 1D numerical approaches to predict long period earthquake ground motion in the Gubbio plain, Central Italy. Bulletin of Earthquake Engineering 9(6):2007-2029

STACEC srl (2017) LSR 2d (Local Seismic Response 2d), Licenza d'uso S/2273 D/2490, Politecnico di Milano.

Vucetic M, Dobry R (1991) Effect of soil plasticity on cyclic response. Journal of geotechnical engineering, 117(1): 89-107

Working Group ICMS (2008) Indirizzi e criteri per la microzonazione sismica – Guidelines for seismic microzonation. Conferenza delle Regioni e delle Province Autonome-Dipartimento della Protezione Civile. English version available at http://www.pro- tezionecivile.gov.it/httpdocs/cms/attach_extra/ GuidelinesForSeismicMicrozonation.pdf.

Working Group ICMS (2011) Contributi per l'aggiornamento degli Indirizzi e criteri per la microzonazione sismica. Ingegneria Sismica, anno XXVIII, 2: 68 pp.

Working Group ISTAT (2016) Caratteristiche dei territori colpiti dal sisma del 24 agosto 2016, ISTAT report.