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The subsoil model for seismic microzonation study: The interplay between geology, geophysics and geotechnical engineering

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ABSTRACT: The development of a reliable subsoil model is crucial to optimize the results of the advanced (3rd level) seismic microzonation. The definition of the model needs the contribution of distinct scientific skills (geologists, geophysicists, geotechnical engineers), that should interact, during the entire zonation process, to solve and reduce the complexity of the problem.

This paper describes the methodology adopted in the recent experience of seismic microzonation studies carried out in Central Italy after the 2016 seismic sequence, addressing some critical aspects from the planning phase of the field investigation to the definition of the subsoil model for the numerical analyses. The interplay among different skills was crucial in identifying the subdivision of the cover units, especially when classification based on lithology and genesis was not consistent with the results of geophysical measurements.

1 INTRODUCTION

The “Guidelines for Seismic Microzonation” are a national reference document for seismic microzonation studies (SM Working Group, 2015) and define three levels of analysis characterized by increasing complexity and different final goals, whose achievement requires synergy among different disciplines such as geology, geophysics and geotechnical earthquake engineering.

The basic level (1st level) of zonation aims at defining a “qualitative” subdivision of the considered area into different microzones (Homogeneous Microzones in Seismic Perspective), characterizes by homogeneous stratigraphic and topographic features, in the perspective of the future assessment of the local seismic response. The achievement of this goal requires the reconstruction of a preliminary subsoil geological model, summarising the stratigraphy in terms of cover terrains and/or geological substratum of each homogeneous microzone. The final result is the distinction between zones in which site effects are not expected to occur and those prone to local amplification. The 1st level study is based on the collection and elaboration of previous geological, geophysical and geotechnical data, without any mandatory new investigation. This level of analysis is generally preparatory for more advanced studies and only in few cases can be considered exhaustive.

The advanced level (3rd level) aims at the quantification of the amplification effects of the surface ground motion through numerical analyses carried out on all the microzones prone to

local amplification. The 3rd level study is based on the implementation of an original geological field mapping, a consistent number of geophysical measurements and detailed geotechnical investigations, aimed to obtain a geological-technical subsoil model to be converted into a geotechnical subsoil model for the numerical analyses of the seismic site response. The reliability of the results requires the solution or the reduction of the uncertainties inherited from the 1st level study due to complex 2D/3D geometry, in terms of both thickness and lateral extension, and to the variability of the shear wave velocity (V_S) and/or other geotechnical features within the same lithological unit.

The recent 3rd level microzonation studies performed, on the behalf of the Center for Seismic Microzonation and its Application (MSCenter://www.centrodimicrozonazioneismica.it), in the municipalities affected by the 2016 Central Italy earthquakes represent an example of fruitful synergic cooperation among geologists, geophysicists and geotechnical engineers in defining a reliable subsoil model for the numerical evaluation of the site effects. This paper describes the different steps of the methodology adopted by the research group, which operated on 30 municipalities of the Marche region. The adopted methodology is described in this paper with reference to a representative case study with the final aims of providing new prompts for adequately planning and optimizing the multidisciplinary investigation for the reconstruction of the subsoil model for future 3rd level seismic microzonation studies.

2 GEOLOGICAL AND GEOPHYSICAL INVESTIGATION

The 3rd level seismic microzonation studies (SM3) start from the validation of the geological model inherited from the 1st level study. The first step of the SM3 is the evaluation of the accuracy and the reliability of the Geological-Technical Map (GTmap) (Castenetto et al. 2013, see Figure 1). The GTmap is obtained by reprocessing the geological data in terms of lithostratigraphic units (Formation, member or lithosome) in terms of Geological-Technical Units (GTunits), which represent the bricks to generate the geotechnical model. For this reason, a correct definition of the GTunits and their geometry is a crucial step to ensure the quality of the final result. For the definition of a reliable GTmap, the reference geological map adopted should contain all the information necessary for a complete description of the lithological features of the lithostratigraphic units, as well as an accurate reconstruction of their mutual geometric relation.

During the studies for SM3 of Central Italy, the geological data provided from the previous studies were verified carrying out further geological fields mapped, at the same scale of the GT map ($\geq 1:10000$). New surface geological data were addressed to the definition of a grid of representative geological cross-sections, displaying different 2D viewpoints of the 3D subsoil geometry of each investigated area.

The grid also represented a reference network along which the new indirect (geophysical) and direct (geotechnical) investigations were placed.

The geophysical survey and the other in-situ investigations were then carefully planned to properly address the issues related to: 1) the definition of a reliable subsoil model; 2) the geotechnical characterization of the geological units. Passive and active seismic surveys, aimed at obtaining information on natural frequencies of soil deposits and on shear wave velocity profiles, are crucial to constrain the geological data.

In the 3rd level studies of Central Italy, the records of ambient noise, elaborated through the Horizontal to Vertical Spectral Ratio (HVSr) technique (Nakamura 1989), provided information on site fundamental frequencies and on seismic impedance contrasts between superimposed layers. The environmental noise was recorded through 3-component velocimeters and the records were elaborated with the H/V spectral ratios technique; the Fourier spectra were calculated in the frequency range 0.5-20.0 Hz.

Multichannel analyses of surface waves (MASW) (Park et al. 1999) were performed to measure shear wave velocity profiles, providing information to correlate the lithostratigraphic units with the seismostratigraphic layers. The data acquired were processed in the phase-velocity/frequency domain, paying attention to perform the peaking along the maximum of the

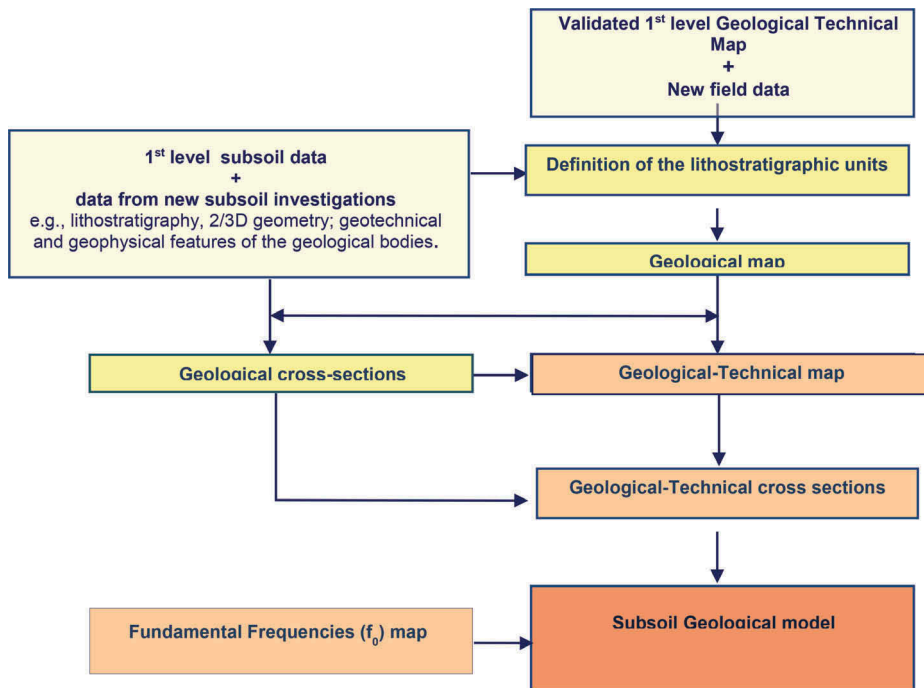


Figure 1. Methodology adopted to reconstruct the geological model for 3rd level SM studies in Central Italy (modified after Castenetto et al. 2013). Please, note that the 3rd level studies include the acquisition of new subsoil data, concurring both to the preparation of the Geological-Technical Map and to the elaboration of the cross-sections.

fundamental-mode amplitude. The inversion procedure tool needs the definition of the free parameters, that can be deduced from the fundamental mode dispersion curves, taking into account the litho-stratigraphic sequence of the investigated site. The inversion process provides a set of shear wave velocity profiles compatible with the experimental dispersion curves, employing the “neighbourhood algorithm” (Sambridge 1999, Wathelet et al. 2005, Wathelet 2008) to perform a directed-search of the best model.

HVSR data in combination with the information on the velocity-depth distribution, obtained from the MASW surveys, allow reconstructing the impedance contrast sections and profiling. These sections show the distribution of the amplitude values of the H/V spectral ratio in the subsoil, allowing to obtain the 2D geometry of the main horizontal and vertical impedance contrasts along the analysed subsoil transect (Lermo and Chavez-Garcia 1993; Lachet and Bard 1994; Ibs-von Seht and Wohlenberg 1999; Pappalardo et al. 2015, 2018; Imposa et al. 2016, 2017, Grassi et al. 2018), to be compared with the 2D geometry of layers along the geological cross sections.

All the information collected from existing data and non-invasive geophysical tests oriented the choice of the location of direct investigations aimed to measure the soil mechanical properties. Boreholes were drilled where most of the soil layers were expected to be intercepted in the shallowest 30 m, so that samples could be taken in each formation to perform laboratory tests. Down-hole (DH) tests were executed in the borehole to obtain a direct and local measurement of the soil wave velocities.

The subsoil model was then updated based on the additional information provided by the new direct investigations.

3 FROM THE GEOLOGICAL MAP TO THE SUBSOIL GEOLOGICAL MODEL

The interaction between geologists and geophysicists is of primary importance for the definition of the embedded and surface geometry of the soil deposits. Even if the classification of the GTunits is based on their geological nature (i.e., “cover units” and “geological substratum units”) and lithological features, the combination of different GTunits in a large number of vertical sequences can induce different effects at the surface.

The first objective of the geologist/geophysicist cooperation consists in comparing the vertical stratigraphic sequence of GTunits, obtained from the geological study, with the shear wave velocity profiles, obtained by Down-Hole (DH) investigation or MASW. The location of the geophysical measurements is based on sites whose stratigraphy is independently constrained by well-logs. Anyway, the mere use of the geophysical data to solve the site stratigraphy might be avoided, as it provides absolutely unconstrained results. The combination of 1D geological and geophysical data provides a former correlation between lithostratigraphy and seismostratigraphy, by assigning peculiar averaged Vs to each of the superimposed GTunits. Moreover, the combined analysis of geophysical and geological data can provide a classification of the vertical sequence of the GTunits based on the depth of the relevant impedance contrast. The result is the subsoil unit defined as “Impedance Discontinuity Bounded Unit” (IDBunit), which is directly responsible for the site resonance frequency revealed by H/V measurements. Figure 2 shows different configurations of IDBunits, which provides a correlation between the site resonance frequency and the depth of a physical stratigraphic discontinuity, whose geometry can be identified independently from the geophysical data. The IDBunit is here represented with different configurations varying from a single layer, consisting of a GT cover unit on the geological substratum in a simple two-layer system, to a multi-layer, composed of distinct, superimposed GTunits. The basal contact and the layering of a IDBunit can vary from a simple planar to very complex geometry, depending on the typology and depositional environment of the GTunits (e.g., colluvial deposits or valley infilling). The depth of a IDBunit can be constrained in the sites where the stratigraphic log, MASW or DH data and HVSR measurements are available. In fact, the depth of the Impedance Discontinuities is inferred from the resonance frequency obtained through HVSR measurement and the Vs profile from DH or MASW measurements. A sufficient number of these “control points”

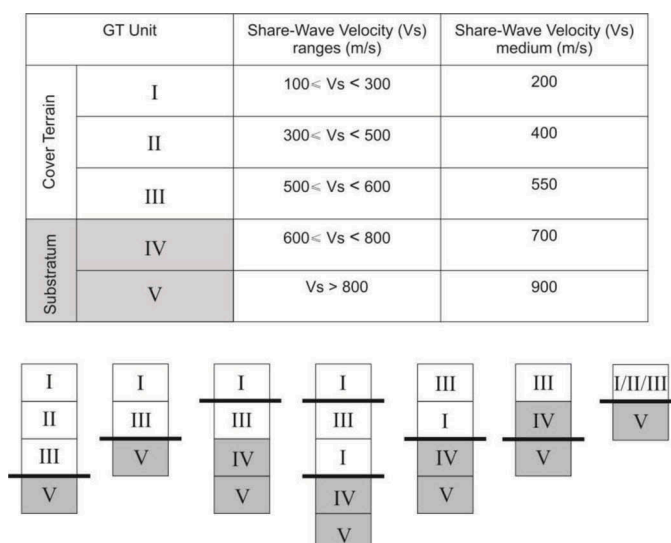


Figure 2. Relations between the GTunit and IDBunit, according to different vertical sequences of geological layers. The table reproduces the most common relationships between the GTunit and the IDBunit, derived from the analysis of the geological cross-sections in the 30 investigated municipalities.

is indispensable for defining the buried 2D geometry of the geological surfaces responsible for the modification of the ground motion. In an ideal configuration, the “control points” should be located at each intersection node of the grid of cross-sections adopted for the 2D representation of the subsoil model. Provided the correlation frequency vs. impedance discontinuity and the depth of the impedance discontinuity at the “control points”, the 2D geometry of the discontinuity can be obtained on the basis of the HVSR measurements performed along the trace of the representative cross-sections.

In the 3rd level studies of Central Italy, the buried geometries were defined only on few spaced HVSR measurements whose inversion was based on some geological constraints and on the shear wave velocity obtained by the MASW or DH data.

As an example, in Figure 3a the geological model of Monte San Martino municipality (Central Italy) is reported together with the recognised IDBunits. Note that the proposed model is a simple two-layer system that includes a single IDBunit. This consists of both cover terrains, on top, and geological substratum units, at the bottom. In this case, the main Impedance Discontinuity corresponds to the top of the seismic bedrock, lying within the geological substratum. In more complex subsurface setting, the geometry of the subsurface IDBunits could derive from the comparison between geological cross-sections and “impedance contrast sections” resulting from inversion of closely spaced HVSR measurements, integrated with the information on the velocity-depth distribution obtained from the MASW surveys. This approach was successfully adopted in the area of Arquata del Tronto, in the hamlet of Piedilama, as shown in Figure 3b (Imposa et al. 2017). In this case, two different IDBunits characterise the hanging wall and the footwall of the detected fault.

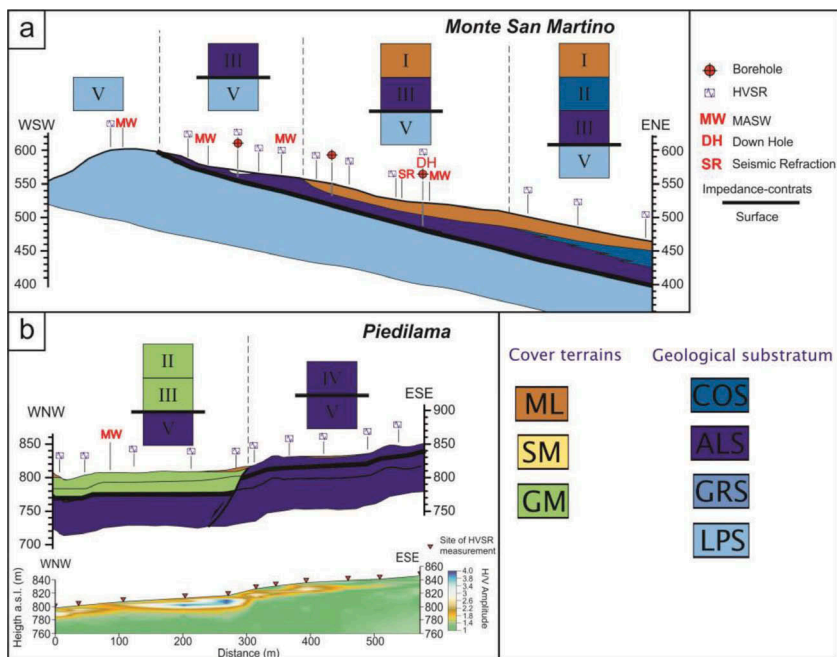


Figure 3. Examples of geological subsoil models obtained by combining geological and geophysical data. Legend: (Cover terrains) ML=low plasticity silt; SM=silty sands; GM=silty gravel; (Geological substratum units) COS=cohesive overconsolidated stratified terrains; ALS=alternation of contrasting lithotype stratified; GRS=grainy cemented stratified; LPS=lapideous stratified and silt. The acronyms for GTunits are defined in “Standard di rappresentazione e archiviazione informatica Versione 4.1.1” - Commissione tecnica per la microzonazione sismica 2018.

4 FROM GEOLOGICAL MODEL TO THE NUMERICAL MODEL: THE CAMPOROTONDO DI FIASTRONE CASE HISTORY

The definition of the numerical model is described with reference to an exemplificative case of study analysed during the activities of 3rd level seismic microzonation of Central Italy. For the considered case study, the interplay among the different skills was essentially addressed at defining a subsoil model that could be converted in a geotechnical model for the successive numerical simulations of the seismic site response.

4.1 *Model definition and calibration on geophysical survey*

Camporotondo di Fiastrone is a small village in the Marche region, located about 60 km southwest of Ancona and about 25 km south-west of Macerata. The urban centre, where about 500 habitants live, is located on top of a 340 m a.s.l. hill. The first step for the definition of the numerical model was the definition of a proper cross section. To this aim geologists selected the suitable cross section, to be representative, as much as possible, of the configuration of the hill where the village rises up; the cross section was extended on both sides of the village centre until reaching the condition of outcropping bedrock.

Different cover units were classified following not only the geological classification (Regione Marche, 2001) but also carrying out a detailed subdivision based on lithology and origin, allowing a better identification of the mechanical soil properties to be assigned to each formation. Figure 4a shows the lithotechnical map of the area, with the location of in-situ investigations and the trace of a representative cross section oriented in the NW-SE direction. The related cross section is reported in Figure 4b, in which several lithotypes can be identified according to the Unified Soil Classification System (USCS). The geological substratum is recognized in the Laga formation, ALS_LAG3e, which is widely outcropping around the inhabited hill, while the city centre is located on the top of a layered alluvial deposit consisting of silty clay (ML_{tf}) and gravels (GW_{tf}). Further alluvial deposits were also recognized at the border of the ridge; eluvial-colluvial clayey silts and silty sands with different origin (ML_{cc} and ML_{td}) and fluvial sand-gravel mixtures (GW_{tf} and GM_{tf}) as well as silty sand or sand-silt mixture (SM_{tf}).

Ambient vibration single-station recordings were carried out along the cross section to estimate the fundamental resonance frequency through HVSR, while the stiffness of near-surface materials was characterized through 1D shear wave velocity (V_s) profiles by means of MASW tests.

The joined application of these techniques was primarily aimed at defining both the depth and the morphology of the interface between the cover soils and the seismic bedrock. This latter is locally represented by the Laga formation, consisting of stratified pelitic layers and interbedded thin arenaceous layers. The fundamental frequency measured on the top of the hill ranges between 2.4 and 2.6 Hz. It increases along the NW flank of the hill up to about 5 Hz indicating a decrease of the alluvial cover thickness. The geophysical characterization was further integrated by a Down-Hole seismic test that allowed more accurate geotechnical characterization of many geological units. The down-hole measurements were used to constrain better the results of the MASW tests and to refine the shear velocity model. In particular, the shear wave velocity measured in layered alluvial deposit (GM_{tf} , GW_{tf} , ML_{tf}), ranging between 235 to 490 m/s; in the geological substratum (ALS-LAG_3), V_s ranging between 573 to 690 m/s, clearly highlights that it cannot be assumed as seismic bedrock. Figure 5 shows the vertical profiles of the IDBunit and the depth of a physical stratigraphic discontinuity.

The depth of the seismic bedrock was finally inferred comparing the fundamental frequency measured by HVSR technique with that numerically computed carrying out visco-elastic analyses along the 1D soil column corresponding to the location of the HVSR measurements and adopting the shear wave velocity profile resulting from the V_s model. Figure 6a shows, as an example, the satisfying agreement between experimental (red) and numerical (black) curves. The same approach was also adopted to validate the shear wave velocity measured by surface

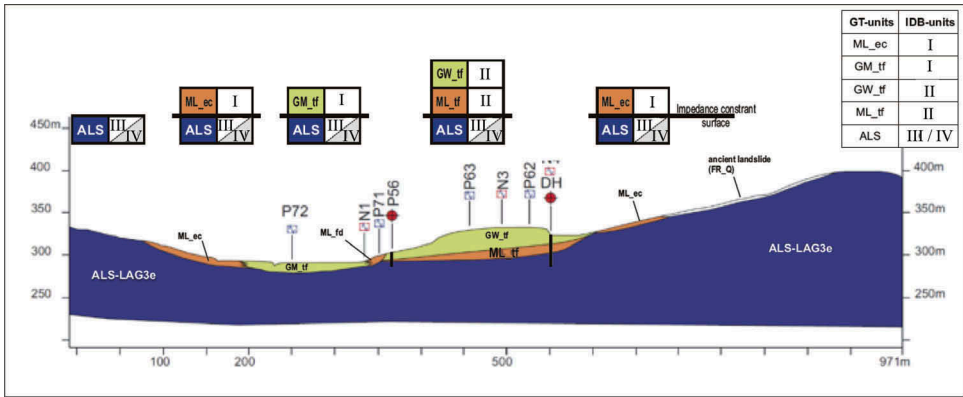


Figure 5. Camporotondo di Fiastrone: relation between GTunits and IDBunits; main vertical impedance contrast along the microzones vertical profiles.

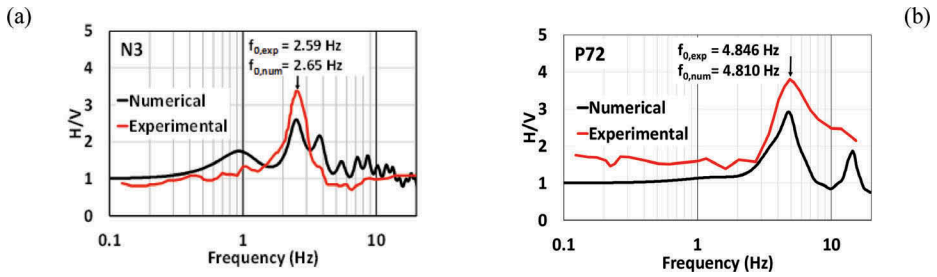


Figure 6. Camporotondo di Fiastrone: comparison between experimental H/V and numerical curve (a,b).

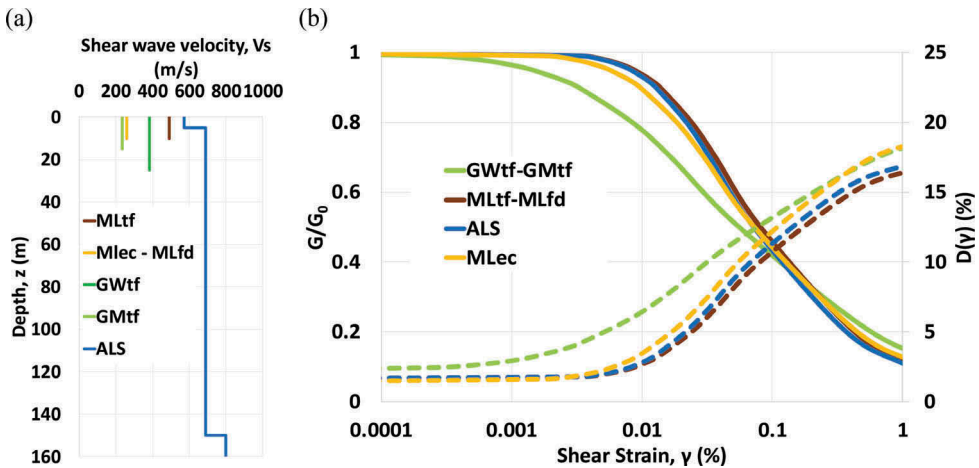


Figure 7. Shear wave velocity profiles (a) and $G/G_0-\gamma$ and $D-\gamma$ curves (b) assigned to soil deposits in the numerical analyses.

Table 1. Soil properties used for site response analyses.

Lithotype	H m	γ kN/m ³	V_S m/s	V_P m/s	ν -	$G/G_0(\gamma)$ and $D(\gamma)$ -
ML _{ec}	0÷8	20.00	237	581	0.4	ML _{ec} (IP=20÷36)
ML _{tf}	0÷10	21.00	490	1508	0.441	R&O Pollenza, Urbisaglia
ML _{fd}	0÷10	21.00	237	581	0.4	R&O Pollenza, Urbisaglia
GW _{tf}	0÷25	19.75	383	1086	0.429	Kukusho et al. (1981)
GM _{tf}	0÷15	19.75	235	576	0.4	Stokoe et al. (2004)
ALS_LAG3e	0÷5	21.00	573	1791	0.443	ALS
ALS_LAG3e	5÷150	22.50	690	2565	0.461	ALS
Bedrock	-	22.50	800	2974	0.461	$D_0=0.5\%$

Resonant column (RC) tests were carried out on 21 undisturbed samples retrieved from boreholes drilled in as many villages located in a narrow area struck by the Central Italy earthquake. The results were collected and classified based on the detailed geological classification carried out by the geologists team. As a result, a database of curves was finally obtained. The assigned $G/G_0(\gamma)$ and $D(\gamma)$ curves were obtained calibrating the Ramberg-Osgood (1943) model on the results of the whole data set of curves pertaining to each lithological unit. As a matter of fact, in the case of Camporotondo the curve assigned to ML_{ec} geological unit was obtained modelling the results of 10 RC tests carried out on as many specimens of the same lithological unit taken on site and at surrounding villages during microzonation studies. In the same way, the database of laboratory results allowed to characterize the non-linear and dissipative response of ML_{tf}, ML_{fd} and ALS-LAG3. As regards to the soils that cannot be sampled, the database was further enriched collecting data from literature referring to soils characterized by comparable grain size distribution. In this specific case, the $G/G_0-\gamma$ and $D-\gamma$ curves obtained by Kokusho et al. (1981) and Stokoe et al. (2004) testing round gravel were associated to the GW_{tf} and GM_{tf} formations, respectively (Figure 7b).

Table 1 summarizes the physical and mechanical properties adopted in the numerical analyses.

4.2 2D analyses and results

The seismic response of the cross section shown in Figure 4b was investigated under seven input motions selected from the Italian Accelerometric Archive ITACA (itaca.mi.ingv.it/, Luzi et al. 2008) and compatible with the average acceleration response spectra expected to occur on the rock outcropping on site with a probability of exceedance $P_{VR}=10\%$ in 50 years (NTC2018). The analyses were performed through the QUAD4M software (Hudson et al. 2003), which operates in total stress through the linear-equivalent approach in the time domain.

The site topography and the irregular geometry of the soil layers were reproduced through triangular mesh elements, whose size increases with the soil stiffness, allowing wave frequencies up to 15 Hz to propagate reliably, according to the rule proposed by Kuhlemeyer e Lysmer (1973).

A hysteretic behaviour was assigned to all materials, except for the bedrock, characterized as a visco-elastic medium. The decay of the normalized shear modulus, G/G_0 , and the increase of the damping ratio, D , with shear strain, γ , was introduced in the numerical model through the curves plotted in Figure 7b. A linear visco-elastic behaviour was set for the bedrock with a damping ratio $D_0=0.5\%$.

The infinite extension in depth of the bedrock was simulated by dashpots attached to the bottom nodes in the normal and shear directions, as suggested by Lysmer and Kuhlemeyer (1969). The layered soil was artificially extended on the lateral sides and the vertical displacements of the extreme nodes were restrained to simulate the free-field conditions.

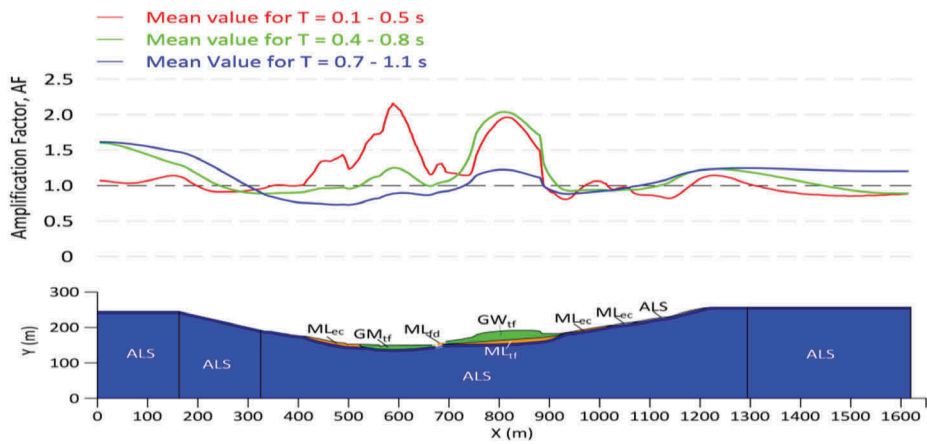


Figure 8. Variability along the cross section of the amplification factor in the three analyzed ranges of periods.

Figure 8 shows the results in terms of mean amplification factors of spectral acceleration, defined as the ratio between the elastic response spectrum resulting on surface and that of the input motion integrated over three period ranges 0.1-0.5 s, 0.4-0.8 s and 0.7-1.1 s. The peak values of the amplification factor are associated to the soft silty gravel layer GM_{tf} in the range of period 0.1-0.5 s consistently with the resonance frequency measured on site (see Figure 6). Independently of the range of periods, high amplifications are observed in correspondence of GW_{tf} layer, where both topographic and stratigraphic effects occur. Since the built-up area of the town is settled exactly on the GW_{tf} formation, the huge damages suffered by the on-site masonry structures were likely influenced by site effects.

5 CONCLUSIONS

The microzonation studies carried out on 30 municipalities of Marche region struck by the 2016 Central Italy seismic sequence have been a fruitful occasion for an effective interplay among geologists, geophysics and geotechnical engineers. The polling of different and complementary skills allowed to define a rational procedure for the definition of a reliable soil model to get a robust seismic zonation. From this successful opportunity of collaboration, some key points and new prompts arise for adequately planning and optimizing the multidisciplinary investigation for the reconstruction of the subsoil model for seismic microzonation studies.

The main key points arisen from this experience can be summarized as follows:

- The definition of a consistent subsoil model starts with the collection and careful analysis of the available information. On this basis, the geologist can define a preliminary 3D geometry of the lithostratigraphic units or lithosomes to be converted, with the contribution of the geophysicists, into a grid of 2D litho-technical cross-sections, displaying “Impedance Discontinuity Bounded Units”.
- Any disagreement between the soil profiles derived from the available geophysical data, and the geological boundaries of the litho-technical subsoil units, require the implementation of a new joint geological and geophysical surveys aimed at identifying the “stratigraphic or tectonic expression” of the interface detected by geophysical surveys and, therefore at defining a new subsoil profile.
- A subsoil model based on the interpretation of existing data and non-invasive geophysical measurements is a useful tool to define the location of direct investigations with the aim of maximizing the number of soil units intercepted.

- The mechanical characterization of the different soil units requires the collaboration between geologists and geotechnical engineering in order to identify the peculiarity of each soil unit and correctly assign the non-linear and dissipative characteristics when it is not possible to carry out specific laboratory tests.
- The results of all the laboratory tests carried out for the microzonation studies should be collected and classified based on the geological classification to enrich the database of available $G/G_0(\gamma)$ and $D(\gamma)$ curves and adopt more specific curve to characterize the behaviour of each soil units.
- In most of the cases, it is necessary to extend the investigation beyond the area involved in the microzonation studies, in order to reproduce in the numerical analyses the site amplifications due to the irregular geometry of soil layers and ground level. This aspect can be only partially improved by adopting both advanced numerical model and software to perform seismic response analyses.

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