Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0080

XVII European Conference on Soil Mechanics and Geotechnical Engineering
ECSMGE 2019 Reykjavik

From the seismic microzonation studies to the site scale: the case of Arpino (Italy)

Des études de microzonage sismique à l'échelle du site: le cas d'Arpino (Italie)

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ABSTRACT: This paper summarizes the main results of the first level seismic microzonation study performed for Arpino, a small town located in a highly seismic region in Central Italy. Based on these results, further investigations were performed at Arpino Bove test site, selected as representative for one of the microzones prone to ground local amplification. Geophysical and geotechnical surveys were performed at the selected site, including a borehole, a down-hole test, a seismic dilatometer test, noise measurements and several resonant column tests on undisturbed samples. The experimental results were compared and used for 1D ground response analyses to quantify the amplification of seismic ground motion at the site scale.

RÉSUMÉ: Cet article résume les principaux résultats de l'étude de premier niveau sur la microzonage sismique réalisée à Arpino, une petite ville située dans une zone de sismicité relativement importante du centre de l'Italie. Sur la base de ces résultats, d'autres investigations ont été effectuées sur le site d'essai 'Arpino Bove', qui peut être considéré comme représentatif de l'une des microzonessoumise à une amplification locale du mouvement sismique. Des investigations géophysiques et géotechniques ont été effectuées pour le site choisi, y compris un sondage, un essai down-hole, un essai au dilatomètre sismique, des mesures de bruit effectuées en place et des essais de colonne résonante réalisés au laboratoire sur des échantillons intacts. Les données expérimentales ont été comparées et utilisées pour effectuer des analyses 1D de la réponse locale du mouvement sismique visant à quantifier l'amplification du mouvement sismique à l'échelle du site.

Keywords: seismic microzonation, ground response analysis, site investigation, site amplification, site scale

1 INTRODUCTION

Seismic Microzonation (SM) represents a highly useful tool for seismic prevention and risk assessment in land management, for the design of buildings or structures and for emergency planning. The purpose of a SM study is to identify, at a sufficiently large scale (i.e. municipal or sub-municipal scale), different areas where local conditions may significantly modify the expected seismic ground motion with respect to a reference site or instability phenomena may occur causing major permanent deformations or collapse to buildings, structures and infrastructures (SM Working Group 2015).

This paper summarizes the main results of the first level SM study performed for Arpino (Manuel 2013), a small town located on the hillside area of Lazio-Abruzzi Apennine chain (central Italy) that experienced several important seismic events in the past (the 1915 Avezzano, M_w 7.0, and the 1654 Sorano-Marsica, M_w 6.3, among the others).

After the seismic sequence that hit Sora (about 8 km NW of Arpino) on February 2013 with low to moderate magnitude events (M_w 4.8 for the mainshock of 16th February 2013), a set of seismic stations was installed in Arpino (Famiani et al. 2013). The selection of the recording site was based on the first level SM study, detecting the geological formation more suitable for hosting the rock reference from the ones characterized by different seismic amplification. In this respect, the station located at Arpino Bove provided a strong amplification in terms of Standard Spectral Ratio (SSR).

Based on these results, a pilot test site (Arpino Bove) was selected as representative for one of the microzones prone to ground local amplification where future industrial development is planned. Further geophysical and geotechnical investigations were performed at the selected site. The experimental results were compared and used for 1D ground response analyses to quantify the amplification of seismic ground motion at the site scale.

2 SEISMIC MICROZONATION OF ARPINO MUNICIPALITY

Arpino is located in the south-eastern edge of Lazio Region, and particurarly in the south of the intermountain basin of Sora on the hillside area of Lazio-Abruzzo chain.

In the regional seismicity map of Lazio, Arpino is classified as seismic zone 1, as clearly demonstrated considering the important damages produced by several historical earthquakes and taking into account the proximity of various seismogenic active sources in the range of 6 and 30 kilometers.

The geological and geomorphological setting of Arpino territory is strongly eterogeneous going from the valley side of the Liri river constituted of travertine and young alluvial soil to the hillside mostly composed of fluvio-lacustrine deposits and to the mountain side where calcareous rock belonging to the carbonatic shelf outcrops.

The first level SM study of Arpino, as provided by Manuel (2013), divided the territory in nine areas called “MOPS” with different geological and lithological features and an homogeneous seismic behaviour can be supposed based on these differences.

The area where calcareous rock outcrops is divided in two MOPS (S1 and SA1, Figure 1) depending on the slope: S1 if the slope is less than 30%, and SA1 if it is higher than 30%. The first one is a stable area since the rock can be considered as a seismic bedrock, while the second one is suitable for topographic amplification. All the landslides are indicated as unstable areas and named ZI (ZI1 and Z12).

The other five areas (SA2, SA3, SA4, SA5 and SA6, Figure 1) are prone to seismic amplification for the presence of different deposits with different thickness lying on the seismic calcareous bedrock.

SA2 is the largest area and consists of Plio-Pleistocenic fluvial and lacustrine deposits of the “Santopadre” formation (Angelucci 1970, Carrara et al. 1995) with a thickness up to about

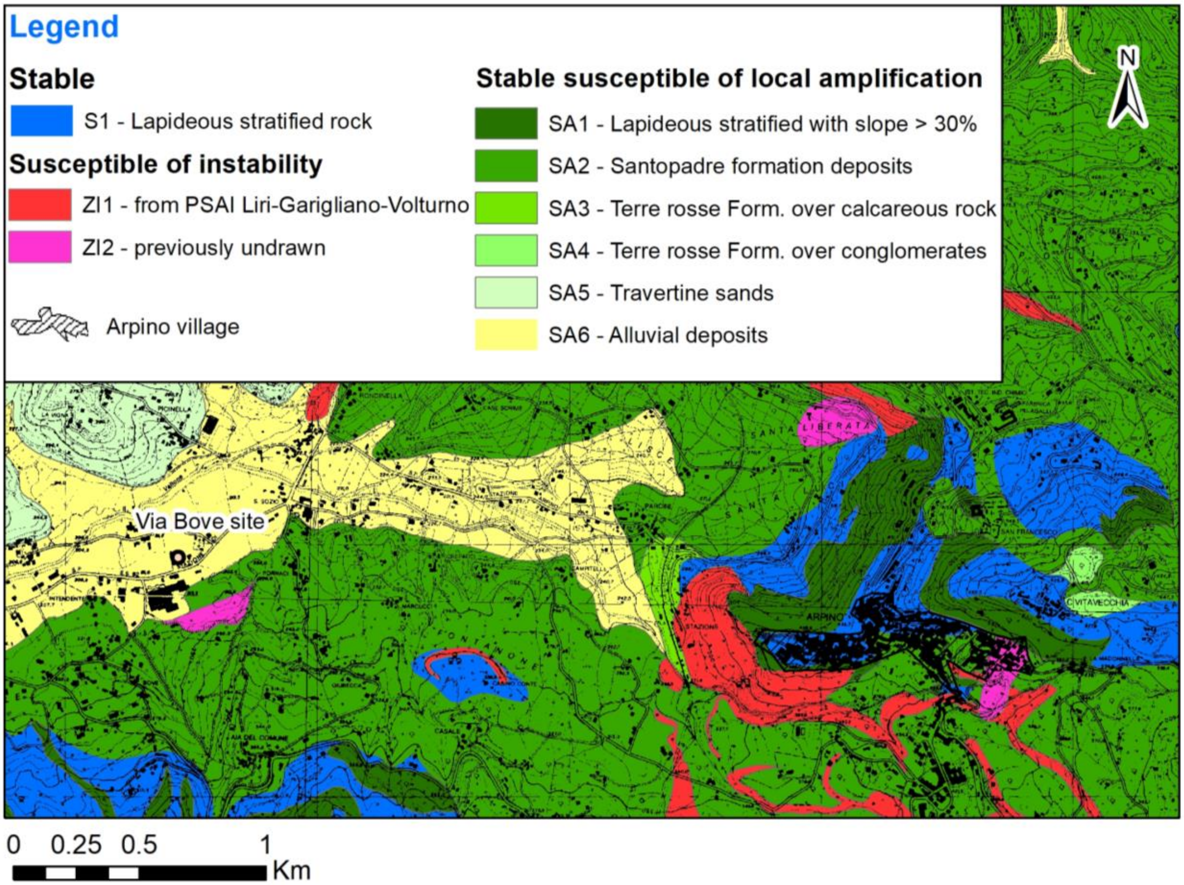

Figure 1. Map of the MOPS for the Arpino municipality and location of the area of study "Arpino Bove" (modified after Manuel 2013).

some hundred meters. This formation is divided in two parts: the lower one is composed of coarse to fine grained silty sandstone and clayey siltstone, deposited in a fluvio-lacustrine and palustrine environment; the upper one is composed mainly of old alluvial sediments constituted by calcareous conglomerates and sandstone locally interbedded with siltstone. The genesis of this formation is responsible for an extreme vertical and horizontal lithological variability that does not allow to associate one lithostratigraphic succession for the entire formation and provides different local seismic behaviour inside the area.

Both calcareous rock and Santopadre conglomerates are often overlaid by karstic alteration deposits, mainly constituted of clay and silty clay and indicated in the MOPS map (Figure 1) as SA3 and SA4.

The MOPS named SA5 is represented by travertine Pleistocene deposits and covers the area close to the actual Liri river bed.

The valley sides of Arpino are constituted of recent alluvial deposits reported as SA6 in the MOPS Map.

3 GEOTECHNICAL CHARACTERIZATION OF THE TEST SITE

The selected test site “Arpino Bove” is located in the river valley, at an elevation of 213 m a.s.l., in a nearly flat area which was identified as an area of possible future industrial expansion. This area is characterized by the presence of soft recent alluvial sediments, suggesting possible local amplification of the ground motion.

The test site was investigated in 2015-2016 by one borehole to a depth of 68.50 m below the ground surface, one down-hole test (DH1) to 40 m depth, one piezocone test (CPTU1) to 21.10 m depth and one seismic dilatometer test (SDMT1) to 23.20 m depth. Five undisturbed samples were retrieved from the borehole. The maximum depth reached by the CPTu and the SDMT was limited by the push capacity of the rig. One ambient noise measurement single station (AR-MZS1) was also installed at the site. The location of the soundings and recording station is shown in Figure 2.

Figure 2. Map of the site investigation in Arpino Bove.

The borehole log allowed recognizing the following stratigraphic sequence from the ground surface (in brackets the abbreviation used in this study):

0.0–0.5 m: topsoil
0.5–2.5 m: clayey silt to sandy silt (MAT1)
2.5–3.9 m: sandy silt to silty sand (MAT2)
3.9–5.6 m: fine to medium gravel in sandy-silty matrix (MAT3)
5.6–11.0 m: alternating layers of sandy silt and silty sand to sand, with some organic silt levels (MAT4)
11.0–22.6 m: clayey-sandy silt (MAT5)
22.6–24.4 m: coarse gravel in clayey-sandy matrix (MAT6)
24.4–26.3 m: stiff clay (MAT7-a)
26.3–68.5 m: stiff to very stiff marl clay, altered in the top 2 m, including tectonic shear surfaces below 34.5 m (MAT7-b)

The ground water table (GWT) was found at a depth of about 1.5 m below the ground surface.

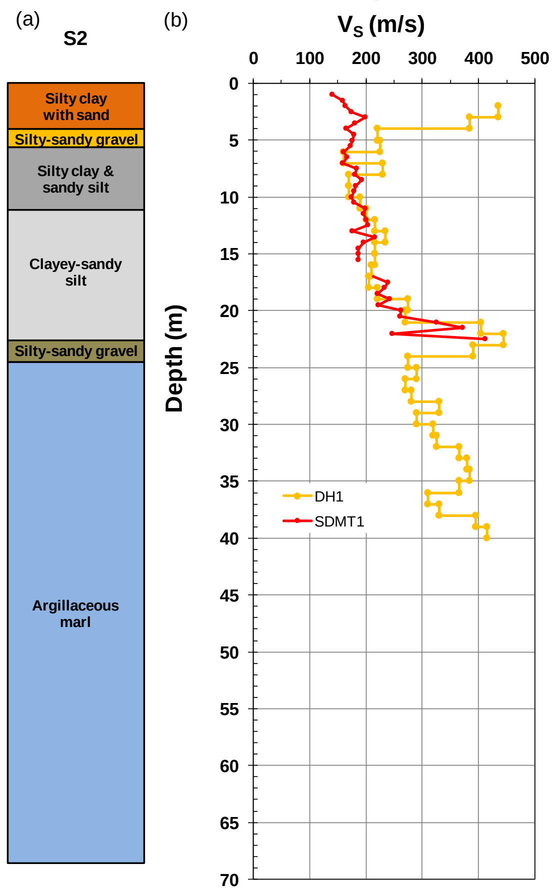

Figure 3. (a) Schematic stratigraphic profile. (b) V_S profile obtained from DH and SDMT.

Figure 3a shows a schematic stratigraphic profile obtained from the borehole log.

Figure 3b shows the profiles of the shear wave velocity V_S measured by down-hole (DH1) and seismic dilatometer (SDMT1). Apart from the upper 6 m, the two V_S profiles are in good agreement. V_S generally increases with depth, consistently with the stratigraphic profile, showing higher values in correspondence of the stiff gravel layer at 22.6–24.4 m depth.

Physical and mechanical dynamic properties of each prevalently fine-grained lithologic unit identified in the stratigraphic sequence were determined from laboratory tests performed on five undisturbed samples. The dynamic properties, namely shear modulus G and damping ratio D from low to medium-high strain levels γ, were determined using a Stokoe fixed-free Resonant Column (RC) apparatus; the amplitude decay method was used to estimate the damping ratio. The information about GWT level was used to estimate the effective confining pressure to perform the RC tests on the undisturbed samples. The depth of sampling and the main properties of the soil tested samples (unit weight, γ_n, liquid limit, w_L, plasticity index, PI, water content, w, and void ratio, e_0) are summarized in Table 1.

Table 1. Main properties of the tested samples

Sample	**S1-C1 (MAT1)**	**S1-C2 (MAT2)**	**S1-C3 (MAT4)**	**S1-C5 (MAT5)**	**S1-C6 (MAT7)**
depth (m)	1.45	3.60	7.65	20.30	31.90
γ_n (kN/m^3)	20.0	19.4	18.9	19.2	20.0
w_L (%)	39	33	38	35	48
PI (%)	24	15	20	18	30
w (%)	20.6	27.5	29.3	26.5	23.7
e_0 (-)	0.55	0.66	0.77	0.55	0.59

4 SITE RESPONSE ANALYSIS

4.1 Numerical modelling

One dimensional ground response numerical analyses were performed at the test site using STRATA (Kottke and Rathje, 2009) computer program that performs equivalent linear analyses in a frequency domain, in total stress, for elastic bedrock conditions.

4.2 Geotechnical model

For the purpose of 1D ground response numerical modelling, each lithological unit has to be characterized by means of: unit weight γ_n, curves of normalized shear modulus with respect to initial modulus G/G_0 and damping ratio D versus shear strain γ, shear wave velocity V_S.

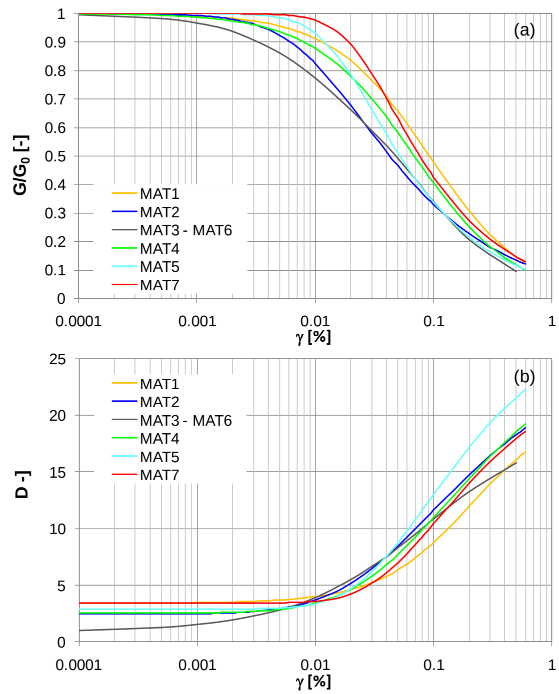

Figure 4. Curves of: (a) normalized shear modulus and (b) damping ratio vs. shear strain assumed for the different lithological units in numerical analyses.

Unit weight, normalized shear modulus and damping ratio curves, for prevalently fine-grained material, were obtained from laboratory tests as described in Section 3. Particularly, the $G(\gamma)/G_0$ curves were obtained from the RC experimental data by choosing the best fitting between the Yokota et al. (1981) and Ramberg

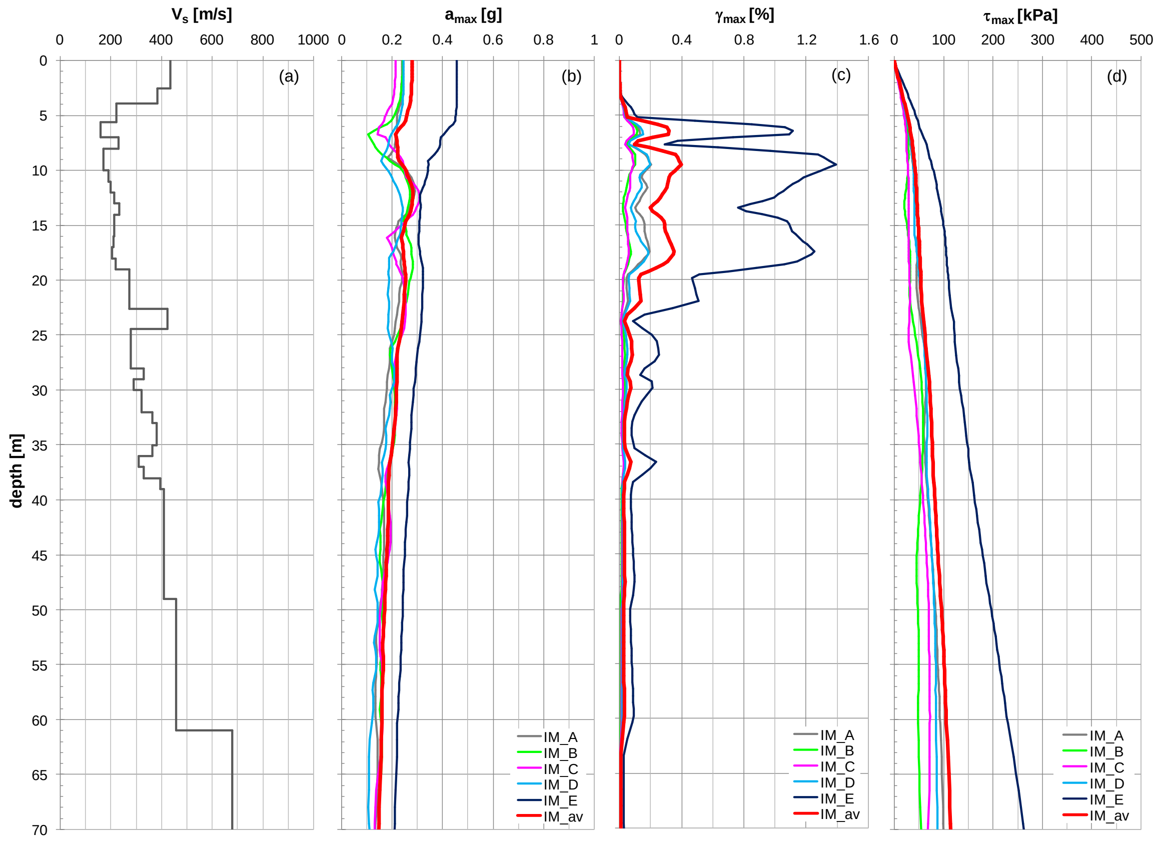

Figure 5. Profile of shear wave velocity V_S used as input profile in the site response analysis (a), and profiles of maximum acceleration a_{max} (b), shear strain γ_{max} (c) and shear stress τ_{max} (d), obtained from the numerical analyses performed at Arpino Bove test site.

and Osgood (1943) models; the Yokota et al. (1981) model was used to fit the RC data for obtaining the $D(\gamma)$ curves. For gravelly soils in sandy-clayey matrix, a unit weight $\gamma_n = 20$ kN/m^3 and the $G(\gamma)/G_0$ and $D(\gamma)$ curves proposed by Rollins et al. (1998) were assumed. Figure 4 shows the $G(\gamma)/G_0$ and $D(\gamma)$ curves assumed for all the different lithological units to perform the numerical analyses.

As described in Section 3, S-wave velocity profile at the investigated site was determined primarily from the results of DH and SDMT tests. Since these direct surveys reached a maximum depth of 40 m, the V_S profile from this depth to the top of the seismic bedrock (assumed to be located at 170 m of depth) was obtained indirectly by the inversion of the ellipticity curve derived by H/V spectral ratio (HVSR) from AR-MZS1. The HVSR inversion was performed using DH results as a constraint for the surficial layers. Using this approach DH and HVSR results match at the depth of 40 m. The need of a deeper interface is related to the presence of a clear peak at 1.4 Hz and amplitude of about 5 in HVSR curve. The inversion was performed using the "Dinver" program, part of the Geopsy software (http://www.geopsy.org). The V_S profile used for numerical modelling is finally plotted in Figure 5a to depth of 70 m from ground level. From 70 m depth to the top of the seismic bedrock (for which a V_S = 1400 m/s was supposed) the V_S profile was assumed gradually increasing to about 900 m/s.

4.3 Seismic input

The adopted seismic input motion consists of a set of five horizontal acceleration time histories (IM_A, IM_B, IM_C, IM_D, IM_E) expected at the site on outcropping rock for a 475 year return period.

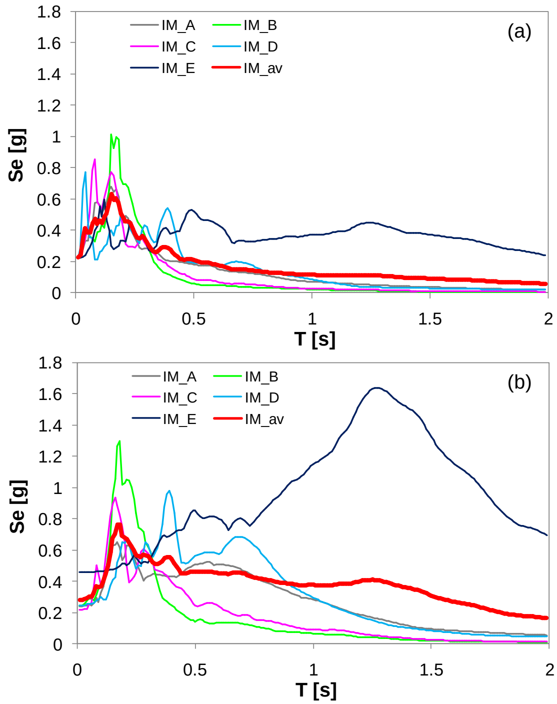

Figure 6. Acceleration elastic response spectra (5% of critical damping) (a) on outcropping rock and (b) at the ground surface.

They are those suggested for Arpino by the Lazio Region for performing third Level SM (http://www.regione.lazio.it/prl_ambiente/?vw=contenutidettaglio&id=199) and are on average consistent with the site response spectrum provided for the municipality by the Italian building code (NTC 2018), since they were selected from the European Strong Motion Database on the base of local seismological parameters and of the regional seismic hazard for free field conditions on rock or stiff soil. The acceleration elastic response spectra *Se* of the single signals, adopted as input motions on outcropping rock (reference motion) for numerical analyses, are shown in Figure 6a, as a function of the period *T*. Figure 6a also shown the average spectra (IM_av) of the five seismic input.

4.4 Results of numerical analyses

The profiles of maximum acceleration a_{max}, shear stress τ_{max}, and shear strain γ_{max} obtained from the numerical analyses performed at Arpino Bove test site are represented in Figure 5 to depth of 70 m from ground level. At greater depths a_{max} profiles tend to a value of about 0.15g. Figure 6b shows the acceleration elastic response spectra (5% of critical damping) at the ground surface for the different input signals.

Moreover, according to the aim of SM a significant amplification factor *AF* was chosen to summarise the results of the performed numerical ground response analyses. As suggested in the latest revision of the Italian SM guidelines (Working Group ICMS 2011), in this study *AF* was calculated as the ratio between the integral of the acceleration elastic response spectrum obtained at the ground surface S_{out} and the integral of the acceleration elastic response spectrum of the input motion on outcropping bedrock S_{inp} in a given range of periods [*a*, *b*]. The general form of the amplification factor used in this study is therefore:

$$\mathrm{AF_{a,b}} = \frac{\int_a^b S_{out}\,dT}{\int_a^b S_{inp}\,dT} \tag{1}$$

Particularly, three different period range of integration were considered, namely [0.1s, 0.5s], [0.4s, 0.8s] and [0.7s, 1.1s], according to the guidelines drawn up in the framework of the SM studies performed following 2016-2017 seismic sequence in central Italy (OPCM 2017). The *AF* values are summarized in Table 2.

Table 2. Values of the amplification factor (Eq. 1)

	FA		
	(0.1÷0.5)s	**(0.4÷0.8)s**	**(0.7÷1.1)s**
IM_A	1.40	3.00	3.66
IM_B	1.50	2.69	2.92
IM_C	1.58	2.96	3.23
IM_D	1.58	2.95	3.59
IM_E	1.55	1.95	2.83
IM_av	1.52	2.71	3.25

5 CONCLUSIONS

The results of the ground response analyses performed at the site scale for the area of study allowed to point out the following conclusions:

- the acceleration elastic response spectra on outcropping rock and at the ground surface provide similar results, excepted IM_E input supplying an output of a_{max} = 0.46g and consequently increasing the average output to a_{max} = 0.28g (the average a_{max} for the input motions is 0.23g);
- the site amplification is moderate for the low period range while is high for period greater than 0.4 s, according to the value of the fundamental frequency of the soil deposits;
- the non-linear soil behavior, particularly pronunced for IM_E results, leads to an increase of the site amplification;
- in-depth analyses would be provided in the future to investigate the weight of uncertainty for V_S values from DH and SDMT in the upper 6-7 m of depth and to verify the impact of different seismic input;
- this pilot study could be reproduced also for the other microzones prone to ground local amplification to implement a third level SM.

6 ACKNOWLEDGEMENTS

Studio Prof. Marchetti is acknowledged for cooperating in the site investigation, Eng. Nick Civetta and Eng. Elisa Gargini for cooperation in perfoming DH tests and processing data.

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