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Site effects in Saletta damaged area of Amatrice municipality (Central Italy) after the 24th August 2016 earthquake

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ABSTRACT: This work presents the results from numerical analyses in the damaged area of Saletta hamlet (Amatrice municipality), aiming at discussing factors leading to the observed damages after the 24th August 2016 Mw 6.0 earthquake and the following aftershocks. The area of Saletta was in fact highly ravaged by the first earthquake and during the whole seismic sequence.

Geological-technical detailed field investigations were combined with an Electrical Resistivity Tomography and several noise measurements for better evaluating the main geological-morphological variability over the study area. Following insights from the reconstructed geological setting, a continuous coring borehole was drilled and a down-hole test performed together with a passive 2D small array and an active 1D MASW measurement. All these data were used to obtain the subsoil model for the numerical analyses that were carried out using both 1D and 2D approaches, including linear and equivalent linear ones, aiming at evaluating site effects.

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1 INTRODUCTION

The problem of estimating the influence of site conditions on ground motion is well known since the 1985 Mw 8.1 Mexico City earthquake (Singh et al. 1988). Useful tools for the technicians who are responsible of earthquake-resistant design may now adequately take into account this influence thanks to the introduction of seismic response analyses in the European (EC8) and national prescriptions (NTC18).

The analysis of the influence of local effects on seismic response at ground surface is also the main issue of seismic microzonation studies, a planning tool applied in Italy since 1980 (Brambati et al., 1980) and devoted to identifying zones in urban areas that are homogenous in seismological and geological characteristics for seismic hazard purposes (Working Group SM, 2008).

Although the assessment of local seismic response and seismic microzoning start from a common position of the problem, the two procedures are organized at different scales and different way are used to synthesize the results of the numerical modelling (Figure 1).

Following this methodological distinction and the benefits of using the two different scales of the problem, we present in this paper the case study of Saletta, a hamlet of Amatrice municipality in central Italy, heavily struck by the 24th August 2016 Mw 6.0 earthquake and related aftershocks.

Firstly, after illustrating the frame of this study and the local geology, we discuss the new geophysical and geotechnical data. Aftershock data are available at one seismic station (MZ01, EmerTer, 2018). All these data were used to constrain the subsoil model and to assign a velocity of the S waves (Vs) to each geological-technical unit (as described in the third section).

Then, we present results coming from one-dimensional (1D) and two-dimensional (2D) seismic response analyses and compare experimental transfer functions (i.e., standard spectral ratio analyses at MZ01 station) with the numerical ones. Moreover, we focus our attention on the distribution of the parameters which synthesize the results (i.e., Amplification Factor, AF). Finally, we discuss the different complementary outputs obtained from numerical simulations, according to the scheme proposed in Figure 1, giving insights concerning the two methodologies recalled in the present paragraph.

2 FEATURES OF THE STUDY AREA

2.1 *General overview of the area*

The first largest event, Mw 6.0 earthquake recorded on the 24th August 2016, had a destructive impact on four municipalities: Amatrice, Arquata del Tronto, Accumoli and Montegallo. In

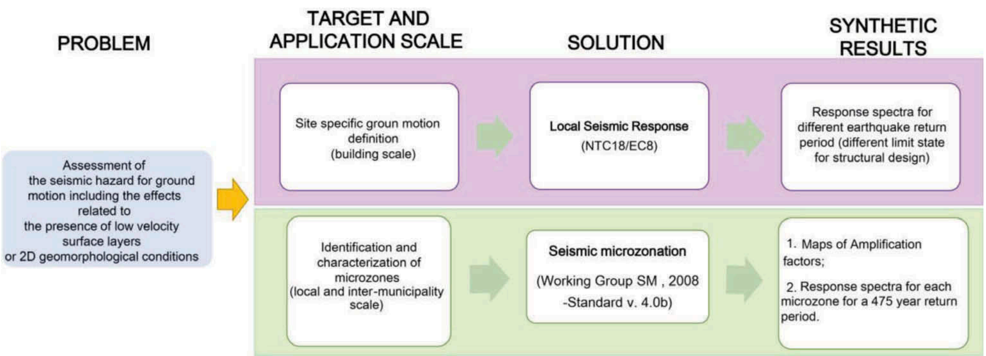

Figure 1. Flowchart describing the two different consolidated methodologies able of quantifying site effects: 1) site specific characterization and analyses (Local Seismic Response) and 2) extended characterization and analyses (Seismic Microzonation). Both are defined in terms of application scale and expected products (synthetic results).

particular, Amatrice municipality suffered the most extensive damages, both in terms of human losses and damages to structures and facilities. Saletta, which is one of its hamlet, is the subject of this study (Figure 2). It showed an European Macroseismic Scale-98 Intensity (I_{EMS98}) equal to 10, and experienced heavy damages and collapse of residential buildings (Tertulliani & Azzaro, 2016).

For this reason, the Department of Civil Protection of Italy commissioned Research Institutions to support a preparatory study for the area most affected by the seismic events of 2016 (Art. 14 of the OCDPC394 of the 19th September 2016). Following this phase (PHASE1), due to the prolongation and widening of the seismic sequence, 138 studies of seismic microzonation in as many municipalities were specifically funded by the Government Commissioner for the reconstruction (Commissarial Decree of the 24th May 2017) (hereafter PHASE2). The activities presented in this paper refer to the entire process including PHASE1 and PHASE2.

2.2 *Integrated subsoil model*

Saletta hamlet is located on a SE-NW elongated depositional terrace resting on the eastern side of the Tronto River, and bounded to SW by an outer edge down-sloping on the steep flank of the Fosso Lagozzo valley (Figures 2–3). The terrace is composed of 10–20 m thick Pleistocene fluvial silty sands (SMtf unit in Figures 3, 4 and 6). The SMtf unit unconformably overlies the Messinian Laga Formation, here consisting of a well bedded and gently SE-dipping sequence of lower sandstones (SFGRS unit) and upper siltstones (SFALS unit). Remnants of older and younger gravelly fluvial terraces of Quaternary age (GMtf and GPes units), each few metres thick, are found respectively up and down-slope of the sandy terrace. To NE, the Saletta terrace is partly covered by few metres of poorly consolidated colluvial silt (MHec) filling a small SE-NW trending gully, at the eastern periphery of the hamlet.

The A-B and C-D cross-sections, shown in Figures 4 and 7, describe a 10–20 m-thick sands (SMtf) overlaying stiffer sandstone or siltstone rocks (SFALS and SFGRS). SFGRS is the seismic bedrock assumed in the numerical simulations.

The geophysical data consist of: i) an Electrical Resistivity Tomography (ERT); ii) seven noise measurements (and their HVSR curves); iii) waveforms from a down–hole test; iv) two dispersion curves from multichannel arrays (one acquired in active mode MASW, the other in passive mode 2D ARRAY). In particular, observing the HVSR curves at each station recorded along the geological-technical cross-section disposed parallel to the main axis of the fluvial terrace (section A-B in Figure 4), a significant amplification increasing toward SE is visible in the range of frequency between 2–6Hz, likely related to the lateral subsoil heterogeneity.

The dispersion curves of Rayleigh waves, obtained from the passive 2D small array and the MASW measurement, were jointly inverted in order to define a subsoil shear-wave velocity model.

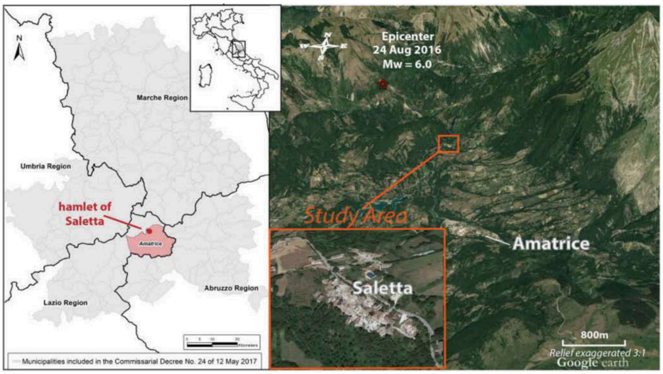

Figure 2. Geographic position and bird's eye view (from Google earth) of Amatrice area, with focus on Saletta hamlet.

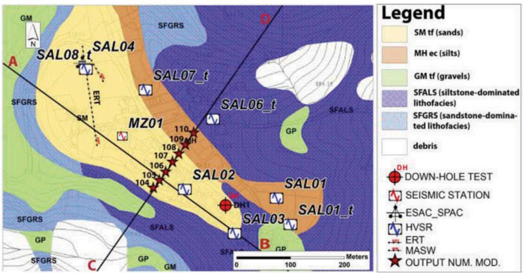

Figure 3. Geological-technical map of the study area and available investigations used for the reconstruction of the subsoil model. Red stars indicate the output point of the numerical modelling considered in this study (see Figure 7). SMtf, MHec, GMtf, SFALS and SFGRS codes are chosen according to the Italian standards for Seismic Microzonation (Working Group SM, 2008).

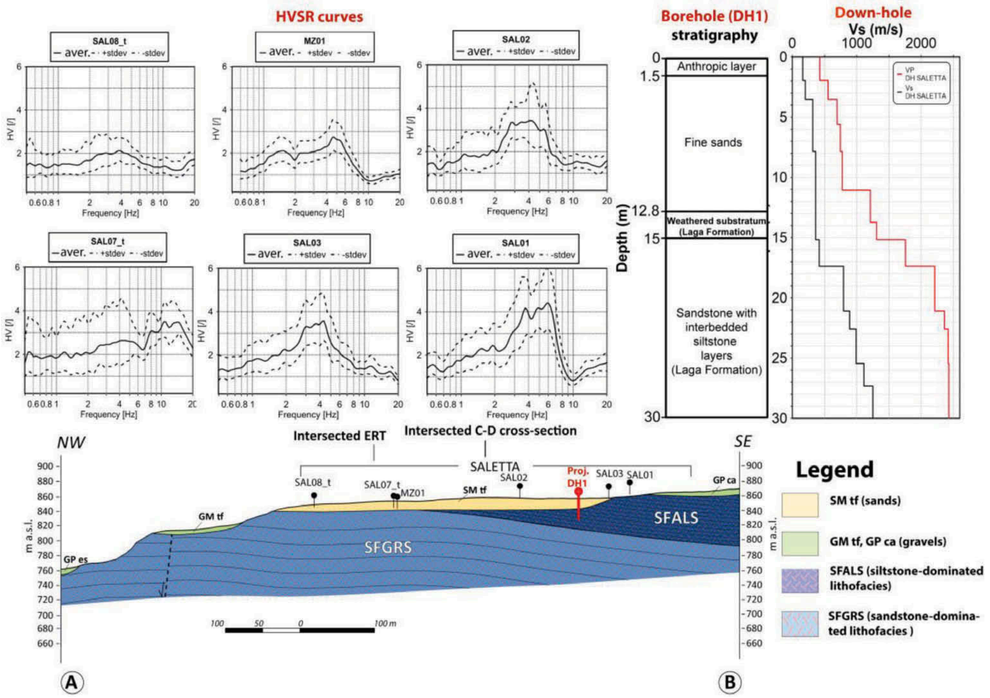

Figure 4. A-B Geological-technical cross section with noise measurements sites (see also Figure 2 for their location). The borehole DH1 is also projected on the cross- section. HVSR curves computed for the average horizontal components for each station, borehole stratigraphy and down-hole test interpretation are also reported in the top panel.

The ERT profile (Figure 5) shows an upper 10–15 m thick continuous layer of relative low-resistivity interpreted to belong to the SMtf unit, lying above lenses at higher resistivity values interpreted to belong to the SFGRS unit. These lenses define a monoclinal structure gently bending to the WNW. The ERT model is in reasonable agreement with the seismo-stratigraphic boundaries that can be read in the 2D ARRAY/MASW SAL04 profile (Figure 5).

The geotechnical data consist of: i) a continuous 30 m deep borehole with SPT tests drilled during the PHASE 2 and ii) one undisturbed specimen. The variation of normalised shear modulus, G/G0, and damping ratio, D, with cyclic shear strain amplitude γ_c was determined from a resonant column (RC) test. These curves were used to model the non-linearity of SMtf unit in the site response numerical analyses.

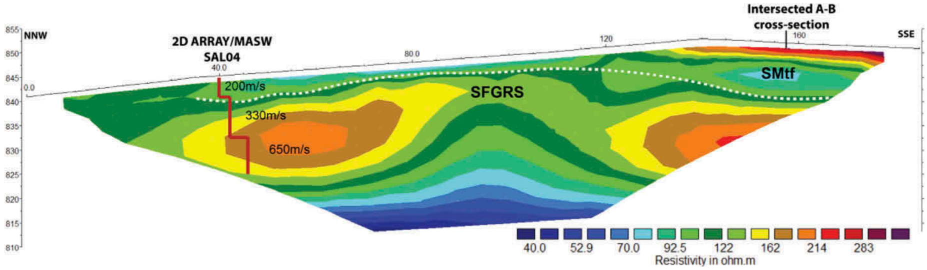

Figure 5. ERT profile with interpretation. A Vs profile obtained from the joint inversion of the dispersion curves of Rayleigh waves available at SAL04 point is also projected (red line). SAL04 location on the map is shown in Figure 2.

Table 1. Mechanical and dynamical soil parameters for the geological-technical units of Saletta.

Unit	Vs (m/s)	γ (kN/m^3)	ν	D0 (%)	G/G0 and D curves
SMtf, MHec	320	18	0.30	0.100	Rollins et al. (1998), Curves from RC test
GP, GM	450	20	0.40	0.100	Modoni & Gazzellone (2010)
SFALS	500	20	0.25	0.500	«Terre rosse, L'Aquila»
SFGRS	800	22	0.25	0.500	Elastic D = 0.5%

The integration of the geotechnical and geophysical data allow us to define and characterize the subsoil model, in terms of velocity of shear waves, Vs, and G/G0 and D with cyclic shear strain amplitude γ. Table 1 summarizes the main soil parameters for each unit used in 1D and 2D numerical analyses, namely unit weight, γ, Poisson coefficient, ν, shear wave velocity, Vs, stiffness decay, G/G0, and damping ratio, D, curves.

3 RESULTS FROM NUMERICAL MODELLING

The dynamic model was used for numerical analyses of seismic site response that were carried out using both 1D and 2D approaches, including linear and equivalent linear models.

Numerical analyses were performed using STRATA (Rathje & Kottke, 2013) and QUAD4M (Hudson et al. 1994) computer codes, based on 1D and 2D linear equivalent models, respectively. STRATA iterates the 1D analysis to follow the variation of normalized shear modulus and damping ratio with shear strain, and assumes simplified stratigraphic conditions such as horizontal soil layers of infinite extent. Seven input accelerograms were chosen respecting the NTC18 spectrum-compatibility for an earthquake, 475 year return period, on reference site (Working Group Seismic Input, 2017).

The amplification effects, which were estimated from numerical modelling in each identified microzone, were synthesized here by means of the Amplification Factor (AF) that has a triple denotation, being defined as follows:

$$AF_{Tn} = \frac{\int_{Ta}^{Tb} Sa\, dT}{\int_{Ta}^{Tb} Sb\, dT} \text{ with Tn} = \text{T1, T2, T3} \tag{1}$$

where Sa is the elastic response spectrum at the ground surface of the study site; Sb is the elastic response spectrum at the reference site (i.e., outcropping EC8 type A ground); Ta and Tb are the extremes of the evaluated interval of periods Tn. Three different ranges are assumed in this study: $0.1 \le T1 \le 0.5$s, $0.4 \le T2 \le 0.8$s, and $0.7 \le T3 \le 1.1$s. The rationale behind these three intervals is referred to the correlation among resonance periods and some building characteristics (i.e., number of floors).

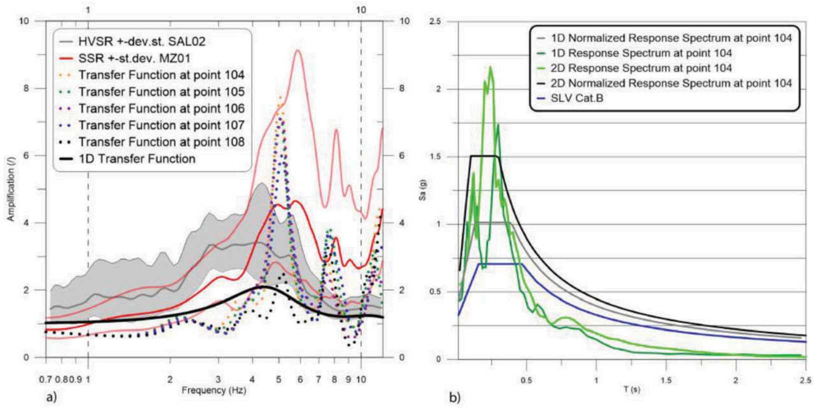

Figure 6. a) Calibration of the model (linear analysis). Location of the output control points of the 2D numerical modelling (points 104 to 108) is shown in Figure 3; 1D modelling refers to vertical profile at the intersection of A-B and C-D cross-sections; b) Comparison among the response spectra output point 104 (linear-equivalent analysis). Blue line refers to the spectrum for B type subsoil at the investigated site for the life-safety limit state (according to NTC18)

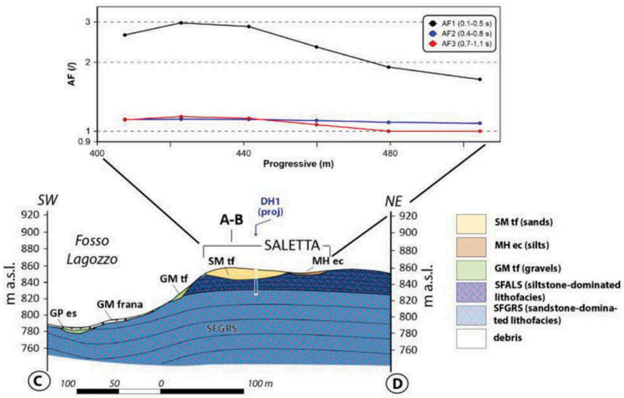

Figure 7. C-D cross-section used for the numerical analyses (bottom panel) and trend of AF (top panel) in the three period intervals: T1=0.1 -0.5s (black curve), T2=0.4–0.8s (blue curve), T3=0.7–1.1s (red curve).

3.1 *1D and 2D numerical modelling*

2D ground response analyses with reference to the whole area were carried out for both the cross section A-B and C-D. Only the results obtained for the C-D cross-section are shown in this paper for sake of brevity. In synthesis, we observe that the amplification along the direction parallel to the main morphological structure, i.e. the long axis of Saletta terrace, is lower than those obtained across the terrace (i.e. C-D cross section). This means that the C-D cross-section is most significant for the study of site effects.

With the aim of calibrating the model, 1D and 2D numerical analyses were performed, assuming a linear soil behaviour and the E-W waveform recorded at CLO station as seismic input (Luzi et al., 2015). The transfer functions were computed for a number of selected points (point 104 to 110 in Figure 3) with a focus on eventual site effects in correspondence of the projection of MZ01 seismic station and SAL02 site on the C-D cross section. Then, we compare them with the observed earthquake data (SSR at MZ01 and HVSR curve at SAL02) (Figure 6a). The 2D transfer functions at the points from 104 to 108 evidence a pronounced peak at about 5 Hz, with the point 108 showing lower amplification values in the frequency range 4–6 Hz, likely due to boundary effects from pinch-out of sands on the seismic bedrock. This peak is in a good agreement with

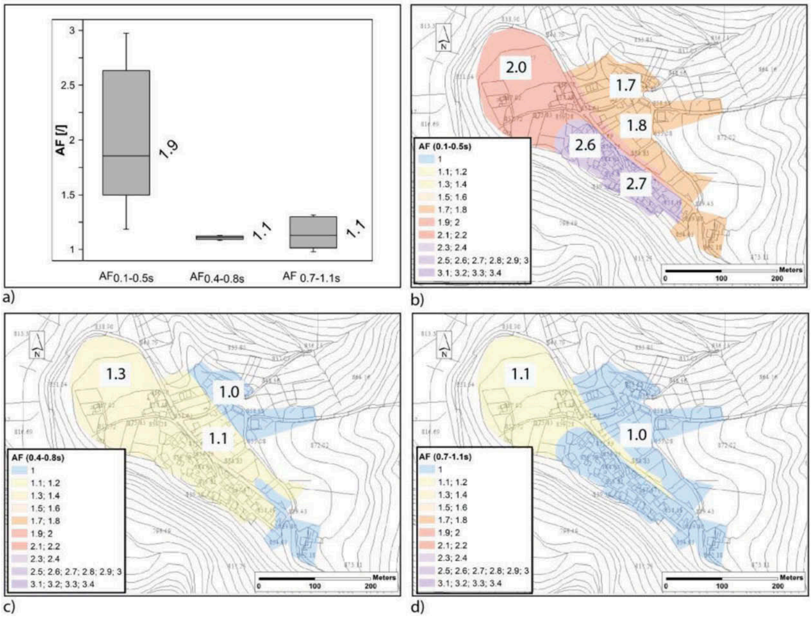

Figure 8. a) Box-whisker plots of AFs for the hamlet of Saletta, derived from the 2D numerical modelling along C-D cross-section (minimum, 25th percentile, median, 75th percentile and maximum are plotted; labels refer to median values); b), c), d) Seismic microzonation maps for the T1=0.1 -0.5s, T2=0.4 -0.8s, T3=0.7 -1.1s intervals, respectively.

the one read in the experimental Transfer function (SSR) available at MZ01, despite the slightly different sismostratigraphic models between MZ01 and 104–108 points (presence of SFALS vs. presence of fractured SFGRS). The 1D modelling shows a slightly shift in the frequency band of amplification to lower values (at about 4.2 Hz) respect to the 2D modelling and earthquake observed data. Otherwise, 1D Transfer function shows a better agreement with the frequency band of amplification individuated by the HVSR curve, which anyway is not a proper experimental transfer function (it is also noteworthy that HVSR curves are computed under the assumption of waves propagated through a site with horizontal layers).

For completeness, Figure 6b shows the elastic response spectra at point 104 from 1D and 2D linear-equivalent analyses performed using as a seismic input the E-W waveform recorded at CLO station together with their respective regularized spectra (Liberatore & Pagliaroli, 2014) and the spectrum for B type subsoil at the investigated site for the life-safety limit state (according to NTC18).

3.2 *Seismic microzonation maps for ground motions and observed damage*

Figure 7 shows the results of the numerical analyses in terms of AF for the cross-section C-D. As can be seen, the higher AF values, even greater than 2.5, were found for the interval of period 0.1–0.5s, where the SMtf layer is thicker and AFs are computed closer to the slope, while there are no significant fluctuations of AFs distribution between 0.4 and 1.1s with values lower than 1.3. Following insights from the reconstructed geological setting and the numerical modelling, three maps were eventually realized, one for each interval of period (Figure 8). Box-whisker plots of AFs derived from the 2D numerical modelling along C-D cross-section (minimum, 25th percentile, median, 75th percentile and maximum) are plotted in Figure 8a.

Moreover, with the aim of presenting a review of available buildings data potentially useful for inferences about the possible interactions between surface geology and buildings, we analyse the areal damage pattern obtained from an emergency Copernicus satellite relief. It derives from post-event satellite image trough visual interpretation. We combine them with the description of typology, number of floors and age of buildings at census sections from the 2011 Italian National Institute of Statistics census (ISTAT, 2011).

On this regard, we are aware of the fact that comparisons between the highest amplification factors and the damage observed from Copernicus would be not fully appropriate for two reasons: 1) the Copernicus damage relief refers to a single event, while the AFs (and maps of them) have to be considered as a scenario, being the output a "convolution" of seven different seismic inputs; 2) also repeating the numerical modelling for the first large shock, we neither have the pre-event vulnerability data at each building nor a not-cumulative damage relief after the same event. Notwithstanding these cautions, observing that the majority of buildings has 2÷3 storeys and roughly comparing this information with AF maps (Figure 8 b-d), we might infer a highest vulnerability of the buildings right in the period range where also the local hazard (AF) is the highest, i.e., 0.1–0.5s.

4 CONCLUSIONS

In this study, we investigated the ground motion amplification phenomena in the hamlet of Saletta (Amatrice municipality), struck by the 2016–2017 Central Italy seismic sequence, by means of 1D and 2D numerical modelling.

About the seismic response, we investigate the eventual 2D site effects due to the combination of the presence of the lateral/vertical geological heterogeneities and of terraced morphology. The variability of the transfer functions obtained from 2D numerical modelling compared to those from 1D modelling points out that the use of a suitable model, which allows the dimensionality of the problem to be taken into account, is one of the most crucial steps in these numerical analyses.

About the seismic microzoning, this study helps decision makers to individuate the interval of periods that requires more cautions in the earthquake-resistant design, i.e., 0.1–0.5s. In terms of local hazard zonation, these results are fundamental for appropriate urban planning, especially where the expected vulnerability is higher, i.e., historical city centres.

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