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Multidisciplinary approach for the seismic microzonation of Pescara del Tronto (AP-Central Italy)

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ABSTRACT: After the 2016 Central Italy seismic sequence, ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale) and OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale) started a series of surveying activities in Arquata del Tronto municipality, to support the Italian Department of Civil Protection (DPC) in the emergency management and, subsequently, for the preliminary Seismic Microzonation (SM) studies. A multidisciplinary approach was carried out to evaluate a reliable subsoil geotechnical model in Pescara del Tronto settlement, completely destroyed in the early stage of the sequence. This issue was addressed by means of detailed geological and geomorphological surveys, active and passive geophysical methods. 2D numerical simulations along three main sections were performed and results were compared to the observed recordings to validate the model. Only two areas have been therefore classified as suitable for new settlement, since little or moderately prone to landslide and site amplification.

1 INTRODUCTION

The seismic sequence started in Central Italy with the Mw 6.0 earthquake on August 24, 2016, and on-going to the early months of 2017, caused about 300 casualties and the complete destruction of many villages across Lazio, Umbria, Marche and Abruzzo regions. Soon after the first main shock, ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale,) and OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale), as partners of the CMS-Centre for Seismic Microzonation and its Application (https://www.centromicrozonazionesismica.it/en/), supported the Italian Department of Civil Protection (DPC) in the emergency management and, subsequently, for the Seismic Microzonation (SM) studies. In this paper the L3SM - Level 3 Seismic Microzonation of Pescara del Tronto is presented. Pescara del Tronto is a village in the Arquata del Tronto municipality, completely destroyed in the early stage of the sequence. As recommended by the Guidelines for Seismic Microzonation (SM Working Group 2015), L3SM is assessed by the application of experimental or numerical techniques. The former approach was investigated in Laurenzano et al. (2018), where the Authors presented the local site response on the bases of seismic noise measurements and strong- and/or weak-motion earthquake recordings at thirteen sites in Arquata del Tronto and Montegallo (AP) municipalities. The latter approach, based on 2-D numerical simulations, is presented here. The study benefits of a multidisciplinary approach, aiming at the correct evaluation of the hazard, due to the very high number of earthquake-induced landslides and the site amplification in the area. The numerical modeling was constrained by the new field data. It refers to the traditional equivalent linear visco-elastic approach (Schnabel, 1972), and the effects of nonlinearity are approximated by performing a series of linear analyses in which the average, or secant shear modulus and the damping ratio are varied until their values are consistent with the level of the strain induced in the soil. The equivalent linear method uses linear properties for each element that remain constant throughout the history of shaking and are estimated from the mean level of dynamic motion. The method does not directly provide information on irreversible displacements and the permanent changes that accompany liquefaction, since oscillatory motion only is modeled. The interference and mixing phenomena that occur between different frequency components in a nonlinear material are missing from an equivalent linear analysis (Hosseini et al. 2010).

2 GEOLOGICAL OUTLINE AND LANDSLIDE SUSCEPTIBILITY

The Pescara del Tronto village stands in the lower sector of the slope that runs from the summit of Monte Macchialta (1750 m) down to the Tronto river (about 650 m). The average slope is about 30°, and the area is characterized by an overall concave profile in the middle-upper sector and a slightly convex one in the lower part. The area shows different outcropping lithotypes and it is characterized, moreover, by a complex tectonic and structural structure, determined by the overthrowing front of the Sibillini Mts. Thrust (Cantalamessa et al. 1992). This important tectonic element runs just uphill the village of Pescara del Tronto and causes the superimposition of the Umbrian-Meso-Cenozoic carbonate succession on the Miocene turbidite sediments belonging to the Laga formation. This latter represent the geological substrate outcropping along the study area. For the SM purposes, according to the prevailing lithofacies and to the arenitic/pelitic ratio (A/P), the Laga Formation was divided into four separate lithological subunits (Figure 1 and Table 1 for details). Thereafter, a Quaternary continental succession, commonly attributed to fluvial and slope depositional environment, covered the Miocene turbiditic substrate. As regards the Quaternary covers, due to the complex morphology of this territory, they are diffuse and characterized by high lithological and thickness

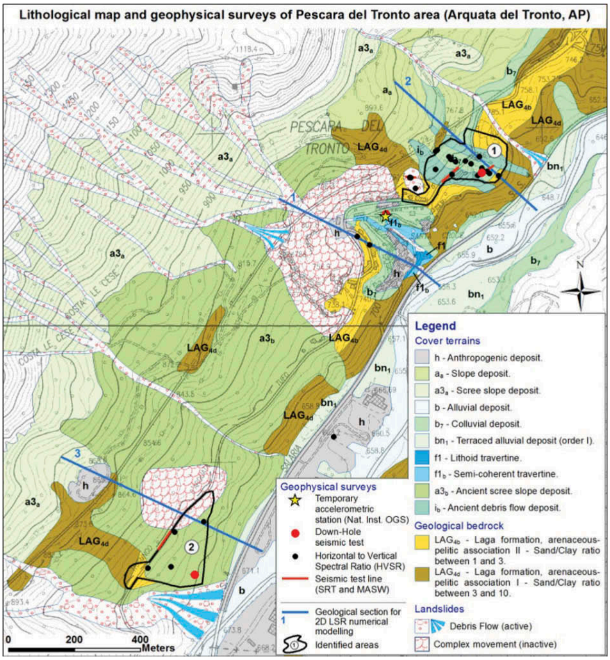

Figure 1. Lithological map of Pescara del Tronto village area, where geophysical surveys, seismometrical station, 2D numerical profiles and new settlement areas are shown.

Table 1. Geotechnical characterization of the units (please refer to the Figure 1 legend for the acronyms definition)

Lithology	Vs (m/s)	γ (kN/m^3)	ν	Dynamic Behaviour (G/G0- γc and D- γc)
Sandy alluvial covers, Semicoherent Travertine (f1b)	300	19.0	0.40	Seed et al. 1970
Coarse debris, colluvial gravels, gravelly landslide bodies (a3$_a$, h, bn, a, h, i$_b$)	300	20.0	0.40	Rollins et al. 1998
Lithoid Travertine (f1), Altered rocks, Breccias	500	22.0	0.40	Linear 2%; D= 2%
LAG4$_b$	700	24.0	0.30	Linear 1%; D= 1%
LAG4$_d$ altered/fractured	900	24.0	0.30	Linear 1%; D= 1%
LAG4$_d$	1300	25.0	0.30	Linear 1%; D= 1%

variability. An important role is played by travertine deposits, on which the ancient downtown of Pescara del Tronto village is set, and by anthropogenic deposits, made of heterogeneous and heterometric materials. They were mainly observed within the hit village, at the buildings foundation, constituted by rubbles of old houses, probably destroyed by past earthquakes.The presence of consistent volumes of Quaternary covers along slopes, induced also a high number of landslides along the whole territory. That leads the authors to necessarily implement a landslides susceptibility analysis for the Pescara del Tronto area, at least at the same scale of the on-course SM level-3 study.

Merging all the available information, i.e. the areas defined as susceptible to seismic amplification during the SM study, and those affected by landslide hazard, two areas, suitable for the reconstruction, were finally identified. They are not too far from the destroyed village, A1 north of the old settlement and A2 southwest of it (Figure 1).

3 GEOPHYSICAL SURVEYS

As a consequence of the geomorphological analysis that led to the identification of only two areas suitable for the reconstruction of the hamlet (A1 and A2, Figure 11) geophysical investigations were concentrated mainly inside these two sectors along the slope. Only few investigations were performed close to the destroyed village being it completely inaccessible for safety reasons, due to the impressive volumes of ruins produced by shakes. The HVSR technique (Nakamura, 1989) was implemented first, since it allows a fast and cost-effective method for the identification of areas potentially affected by seismic motion amplification phenomena. Noise recordings were performed using the TROMINO velocimeter (http://moho.world/). The standardized procedure recommended in SESAME (2004) was implemented for recordings and processing of the signals by using the open source GEOPSY software (http://www.geopsy.org). Concerning the results of the HVSR method, the F0 values inside the A1 area varied from 2.0 to 3.9 Hz. In only 4 cases the HVSR curves were characterized by a second frequency peak (i.e. F1> F0) varying from 4.5 to 5.6 Hz. Fundamental frequencies values inside A2 area vary from 3 to about 9 Hz. The seismic refraction tomography method (SRT) was mainly addressed to the identification of the depth of the geological bedrock, the definition of the geometry and thickness of the covers and the characterization of the investigated terrains in terms of compressional waves velocity (Vp) which is related to their density (Balia et al. 2018; Calamita et al, 2019; Pegah et al. 2016). The active seismic survey were realized by using 24 vertical geophones deployed along linear arrays, to define the shear waves profiles (Vs). Down-hole (DH) seismic tests are also available in A1 and A2 areas, and close the temporary seismological station in Pescara del Tronto. All the Vs profiles show a smooth passage of the shear waves velocity within the covers (about 470 m/s) to the geological substratum (500 m/s, Sebastiano Foti, personal communication).

4 NUMERICAL ANALYSES OF SITE RESPONSE (LSR)

In order to validate the geothecnical model in the identified A1 and A2 areas, numerical analyses were carried out along 3 sections crossing the old village and the new sites (see Figure 11). Because of the geostructural complexity, the one-dimensional numerical modeling approach became unreliable to implement, therefore the analyses of local seismic response were performed in a 2D mode, using the LSR2D software (http://www.stacec.com/). In this software a pre- and post- process interface with the QUAD4M code (Hudson et al. 1994) were implemented, thus allowing the modeling of the non-linear behavior of the soils using the equivalent linear method. Table 1 summarizes values adopted in the parametrization of the main geological bodies. Since coarse and mainly gravelly terrains prevail at depth, it was impossible to carry out cyclic/dynamic laboratory tests on samples and therefore the non-linear cyclic behavior of the soils was simulated by means of the choice of literature curves of normalized and damping ratio values proposed by Rollins et al. (1998) for gravelly soils and by Seed and Idriss (1970) for sandy materials. An elastic behavior is adopted for rocky units. The seismic input was the horizontal accelerogram recorded on bedrock at Uscerno, Montegallo (AP) municipalitiy, located 10 km away from Pescara del Tronto. This event was also recorded at the OGS station in Pescara del Tronto. The model was tested along profile 1 (see Figure 1 for location). It crosses the old portion of Pescara del Tronto inhabited, up to the Tronto River, close the OGS temporary seismcic station (Figure 2). The red dots along the section indicate the control points at which the software returns the results. They are obtained in terms of horizontal timehystories, i.e. accelerograms, from which the main strong motion parameters were extracted, as PGA, Arias and Housner intensities, damage index as in Malhotra (2002). Spectral acceleration response and Fourier spectra for each node were also produced. Outputs at nodes 427 and 440 are shown in Table 2.

Discrepancies between recorded and simulated values do not exceed 10%, furthermore indexes that take into account the whole time history are even lower. A further comparison

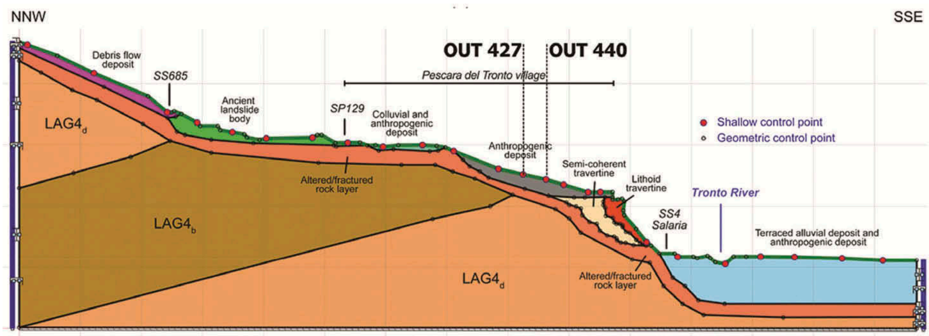

Figure 2. Modeled geotechnical section n°1 (see Figure 1 for position), where the control points (OUT 427 and 440) are mapped.

Table 2. Output indexes at node points 427 and 440 compared with the observed at OGS temporary station in Pescara del Tronto.

Index	OGS record	Output 427	Output 440
PGA (g)	0.09	0.08	0.07
Arias Intensity (m/sec)	0.03	0.04	0.03
Specific Energy Density (cm^2/sec)	1.54	1.79	1.46
Housner Intensity (cm)	3.33	3.17	2.95
Damage Index((g)^c)	0.13	0.14	0.10

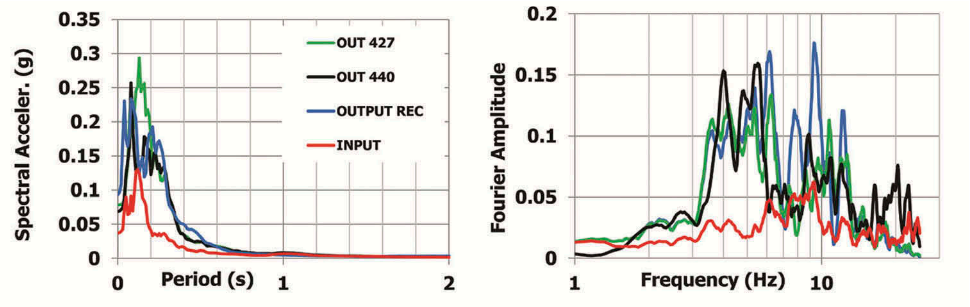

Figure 3. Comparison of the results in terms of Spectal Acceleration (left) and Fourier Spectra (right). The legend is the same for the two pictures.

was made between modeled and recorded Fourier spectra. As can be observed in Figure 3 (right panel), there is a good agreement between the spectra with a slightly overestimate of the spectral amplitude for the Output 427 in the frequency range 6-9 Hz. As far as engineering aspects are concerned, the most significant comparison to be made is the one between the response spectra with a 5% damping. In this perspective, it can be noted in the same Figure 3 (left panel) that the response spectrum modeled in correspondence of the Output 427 control point envelops the one coming from recorded data. This aspect constitutes a guarantee in terms of safety about the use of this study for practical (i.e., engineering) purposes.

The ratio between the recorded and simulated data should be as close to 1 as possible. However, there are some differences between recorded vs. simulated signals that can be explained considering that the equivalent linear method does not accurately depict the reality of the ground response process and the complexity of the subsoil. In addition, signal used to compare the results was not recorded along the modeled section, but slightly apart from it. The local soil condition at OGS station could be slightly different and explain the observed differences.

5 CONCLUSIONS

As a consequences of the Mw=6.0 earthquake, which occurred on 24th August 2016, the Pescara del Tronto village suffered an almost complete destruction. ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale) and OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale) supported the Italian Department of Civil Protection (DPC) in Seismic Microzonation (SM) studies in Arquata del Tronto municipality. A Level 3 Seismic Microzonation of Pescara del Tronto village was carried out to identify areas suitable for new settlements. Throughout a prolongated effort in field geological and geomorphological surveys supported by geophysical investigations, a numerical model was defined. It consists of 2D sections along the slope where Pescara del Tronto settlement was set. LSR2D software, based on QUADM code, was used. The output results are acceleration time-histories at fixed nodes along the sections, from which strong motion parameters (PGA, Arias and Housner intensities, …) can be extracted. A 2D modeled test section crossing the center of the old Pescara del Tronto settlement was defined at the beginning. The results were compared with the recorded time-histories at OGS temporary seismic station to constrain the model. The discrepancies between modeled and recorded values are very small and generally included within ± 10%. This agreement was considered enough satisfactory, as well as the results of the comparative analyses made in terms of response and Fourier spectra. The test showed a good prediction of ground motion parameters and in terms of the general trend of response spectra. Starting from this, the numerical model was extended to the ares A1 and A2 classified as suitable for new settlement, since little or moderately prone to landslide and site amplification for the reconstruction of the Pescara del Tronto Village.

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