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Integrated geophysical methods for the seismic site characterization of Arquata del Tronto (AP)

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ABSTRACT: Between August 24th 2016 and January 18th 2017 a long-lasting seismic sequence accounting more than fifty-thousand events and two main shocks with Mw≥6.0 hit a wide portion of Central Italy. After the early emergency period, the Italian Institute for Environmental Protection and Research (ISPRA) started a series of scientific activities aimed at the site characterization of Arquata del Tronto town, that suffered tens of deaths and the almost complete destruction of the historical centre, providing scientific and technical support to the Seismic Microzonation study of the municipality. Different surface geophysical methods were applied to properly address the issues related to: 1) the construction of a reliable subsoil model; 2) the geotechnical characterization of geological units, 3) the preliminary identification of areas susceptible to local seismic amplification. Down-Hole seismic tests helped in depicting more accurately the subsoil model at each site and in improving the geotechnical characterization of many geological units.

1 INTRODUCTION

The long-lasting seismic sequence that struck Central Italy from the 24th August 2016 until the end of January 2018 gave an impressive demonstration of site-effects occurrence resulting in completely destroyed villages, hundreds of casualties and a huge number of seismically induced landslides. Soon after the early emergency period caused by the first (Mw 6.0) and following main shocks (Chiaraluce et al. 2017) the CMS-Centre for Seismic Microzonation and its Application (https://www.centromicrozonazionesismica.it/en/) was involved in supporting the National Civil Protection Department starting a series of scientific activities concerning site characterization of the five most damaged towns around the epicenters, namely, Accumoli, Amatrice, Arquata del Tronto, Capitignano and Montegallo. This preliminary effort was further prolonged in the frame of a large-scale microzonation intervention planned by the Government and coordinated by CMS that led to the L3SM - Level 3 Seismic Microzonation (Gruppo di Lavoro MS 2008) of these and other 133 municipalities close to the epicenters. The L3SM in Italy is the most detailed level of microzonation that provide a map of ground intensity shaking at urban scale (1:10.000 or greater) through a detailed subsoil mechanical characterization based on numerical analyses. In this work we present the main results of the geophysical investigations conducted for the L3SM study of seven villages located within the Arquata del Tronto territory.

2 GEOLOGICAL AND SEISMIC OUTLINE OF THE STUDY AREA

The Arquata del Tronto territory is located in the Italian Central Apennine chain, at the base of the southern slope of Monte Vettore. From a geo-structural point of view this territory is located close to the Sibillini Mts. Thrust (Cantalamessa et al. 1982), a NS oriented east-verging tectonic structure along which the Mesozoic Umbria-Marche carbonatic units overthrust the Messinian turbiditic deposits of the Laga Formation. Secondary structures, associated to this main tectonic element, deformed further the Laga deposits into anticlines and synclines, plunged and displaced by minor faults. Starting from the early-middle Pleistocene the main orogenic belt, while continuously uplifting, started to be offset by a regional system of NNW-SSE trending active normal faults causing the very high seismicity of this Central Apennine sector (Cello et al. 1997, Galadini & Galli 2003, Boncio et al. 2004, Cheloni et al. 2014). Due to the seismicity associated to these tectonic elements, Arquata del Tronto in the past suffered macroseismic intensities equal to IX degree of the Mercalli–Cancani–Sieberg scale (MCS) (https://emidius.mi.ingv.it/CPTI15-DBMI15). However after the 30th Oct 2016 Mw 6.5 event, a macroseismic intensity equal to X MCS was assigned to almost all the villages pertaining to Arquata del Tronto municipality (Galli et al. 2017). The geological bedrock is locally represented by the Laga Formation, a cemented siliciclastic turbidites composed by an alternation of arenaceous and pelitic stratified deposits (see Milli et al. 2007 and the references therein). Only close to the Capodacqua village the geological substratum consists of carbonatic units pertaining to the Umbria-Marche geostructural domain. As regards the Quaternary covers, due to the complex morphology of this territory, they are diffuse and characterized by high lithological and thickness variability. They are mainly composed by slope and alluvial sediments, as well as by landslide deposits, grouped on the basis of their morphogenesis. Lacustrine and mixed origin deposits, derived from alluvial and debris-flow processes, are also present. The alluvial units outcropping along the Tronto river plain consist of coarse poorly rounded calcareous-arenaceous elements, with variable fine content, whereas old alluvial terraces mainly consist of fine to medium pebbles in sandy-silty matrix. Eluvio-colluvial and mixed deposits, originated by denudation and weathering along slopes, are composed by etherometric arenaceous-calcareous gravels with silty or clayey-sandy matrix.

3 SPECTRAL RATIO TECHNIQUE FROM AMBIENT VIBRATIONS RECORDINGS

Preliminary geophysical investigations have been aimed at the characterization of sites in terms of fundamental frequencies of the soil, exploiting the horizontal to vertical spectral ratio technique (Nakamura 1998) from ambient vibration recordings. A total of 104 single station ambient vibrations recordings were performed. Such an extensive use of noise measurements proved to be beneficial to fast and efficiently identify areas potentially affected by seismic motion amplification phenomena. In addition, a preliminary assessment of the distribution of fundamental resonance frequency (F_0) values, inferred from frequency peaks along HVSR curves, was also possible. In case of multiple-peak HVSR curves (few cases), the lowest frequency peak was considered as the F_0 estimate. Noise recordings were performed using the GEOBOX 4.5 velocimeter (SARA Electronic Instruments, www.sara.pg.it) and the TROMINO velocimeter (http://moho.world/). The sampling frequency during the signal recording was set to 200 Hz and 128 Hz respectively. Using the open source GEOPSY software (http://www.geopsy.org), the standardized procedure recommended in SESAME 2004 was implemented for processing of the signals and the validation of the HVSR curves. In the following Figure 1 we synthesize the F_0 distribution as inferred exploiting the HVSR technique. Along the Tronto river between Borgo and Trisungo, the F_0 spans in the 3–5 Hz range (as retrieved also for Pretare and Piedilama villages, at north of our studied area by Imposa et al., 2017) and it increases up to 10 Hz closer to the valley edges where alluvial covers thickness decreases, suggesting the possible identification of the buried interface between alluvial deposits and Laga Formation as the main seismic impedance contrast. Note, conversely, that for either Pescara del Tronto and Arquata del Tronto historical centre, located in very different morphological conditions (the former along a steep slope and the latter at the top of a cliff), the inferred F_0 values were almost equal (2–4 Hz) and even lower than those inferred for the villages located along the alluvial plain. As an example, in Figure 2 the HVSR curves for the Trisungo and Capodacqua hamlets are shown.

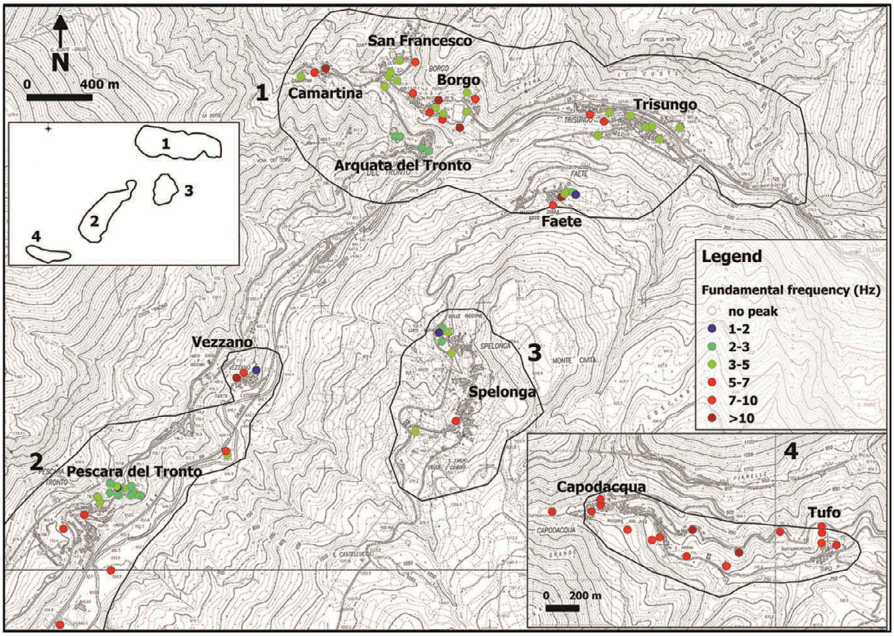

Figure 1. Fundamental frequency values along the studied localities (black perimeters) inside Arquata del Tronto territory.

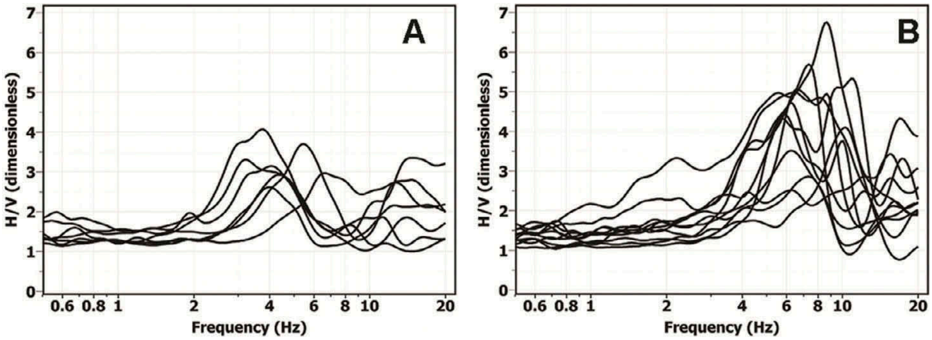

Figure 2. HVSR curves retrieved from ambient vibration recordings in Trisungo (A) and Capodacqua (B).

4 SEISMIC REFRACTION AND ELECTRICAL RESISTIVITY SURVEYS

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). The acquisition in each test site was accomplished using a Geometrics Geode (24 bit) seismograph connected to 24 vertical geophones (natural frequency 10 Hz) deployed along linear arrays using a intergeophonic distance of 2 or 3 m. The active seismic source was an instrumented hammer weighting 8 kg, both off-end and in-line shot positions were used along each survey line, stacking at least 7 shots before recording each seismogram to improve the signal to noise ratio (S/N). The sample rate was set at 0.250 ms and the recording time was 2 s in order to use off-end seismograms also for surface wave analysis. Data processing was carried out using the Rayfract software (Rohdewald 2006, Rohdewald et al. 2010). The initial

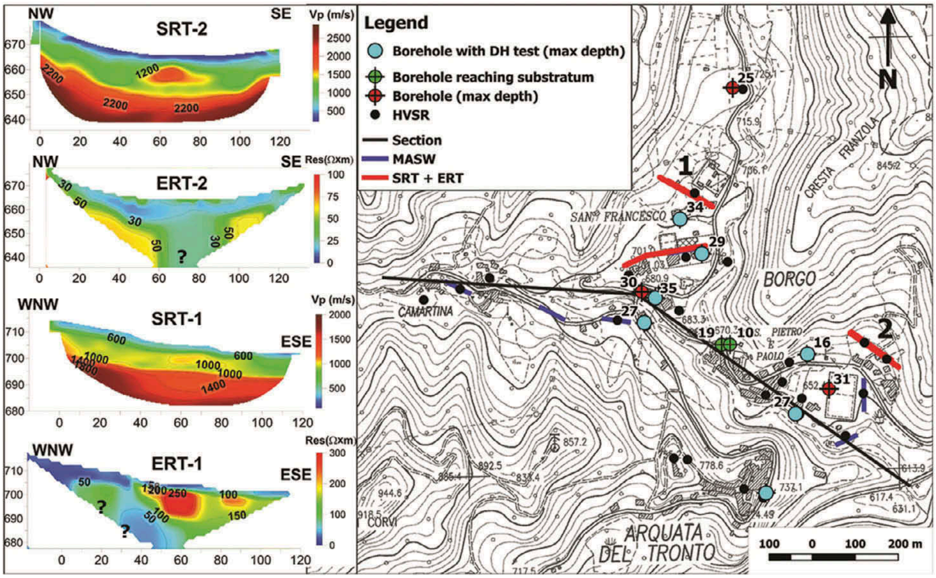

Figure 3. Example of joint application of SRT and ERT surveys inside Borgo and San Francesco localities (red lines). HVSR site (black dots) and SW test sites (blue lines) are also indicated. The continuous black line is the geotechnical section depicted in Figure 5.

Vp model for inversion was obtained, when possible, from the interpretation in terms of seismic layers (Plus Minus) otherwise using a 1D gradient (Gebrande 1986) extended to the whole profile. The initial model was then optimized by 2D WET tomographic inversion (Schuster & Quintus Bosz 1993) with an RMS error of the final 2D models generally < 2%. Electrical resistivity tomography (ERT) surveys were used jointly with SRT ones to improve the preliminary geological models based on field surveys. The resistivity method was mainly addressed to the improvement and/or increasing of the geological and geotechnical information about the Quaternary covers. ERT surveys were implemented especially inside the damaged hamlets of Borgo, Faete and San Francesco, where it was possible to image the sub-surface spatial heterogeneity of geological units (in terms of resistivity) in presence of complex morphology, facing also many logistic difficulties. The setup adopted during the surveys consisted of a IRIS Syscal R2 georesistivimeter connected via two multi-core cables to 48 electrodes deployed along a straight profile. The resistivity of the subsurface was estimated by using Res2Dinv software (https://www.geotomosoft.com/) that implements an inversion routine based on the smoothness-constrained least-squares method (Loke & Barker 1996). To enhance the quality and/or the resolution of the ERT, resistivity measurements were made using different arrays (e.g. Wenner-Schlumberger and Pole -Dipole) and data have been merged before the inversion procedure, obtaining 2D resistivity models with associated RMS <10%. In Figure 3 we show just two examples of a joint application of ERT and SRT methods, in order to highlight the issues faced for retrieving a reliable subsoil model for these sites, even considering geological constrains derived from field surveys. Incidentally, given the geological complexity, the 1D characterization by Surface Waves (SW) proved to be unreliable for these sites.

5 SURFACE WAVES AND DOWN-HOLE TESTS

To evaluate the stiffness of near-surface materials, a total of 19 sites were characterized with 1D shear waves velocity (Vs) profiles by means of Surface Waves (SW) methods, mainly adopting the multichannel setup (MASW) described in Park et al. 1999, otherwise simulating a multichannel array using one receiver (MSOR, see for instance Lin & Ashlock 2016) for

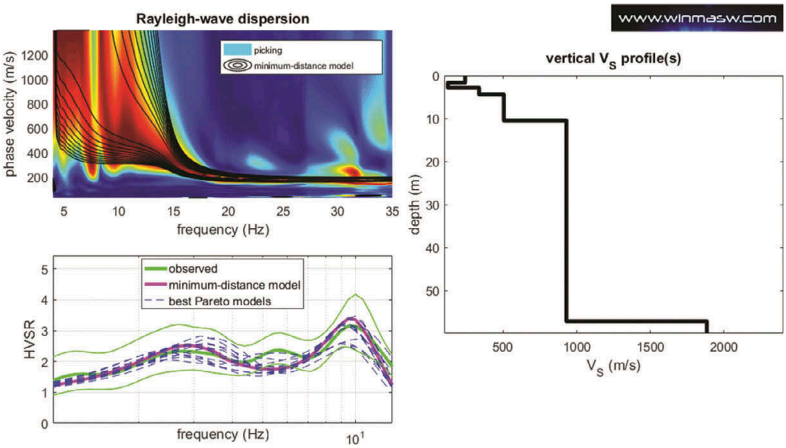

Figure 4. Example of Rayleigh-wave dispersion and HVSR curve joint inversion.

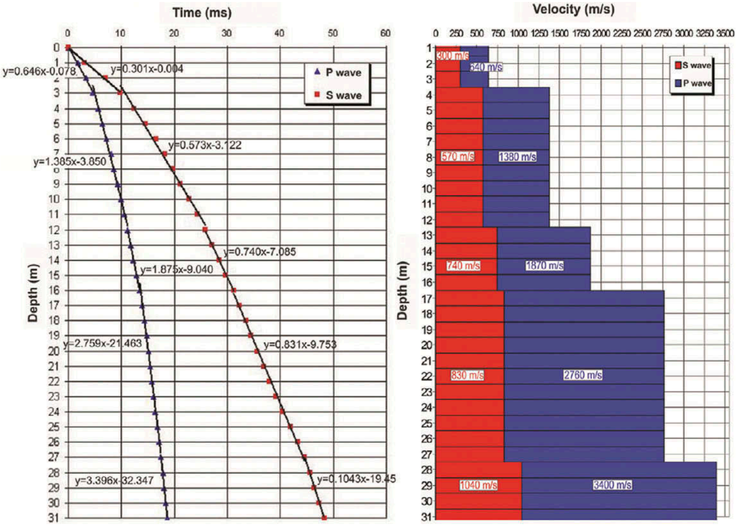

Figure 5. Example of processing for the DH3 site. Corrected travel times (left panel) were used for the velocity estimates within each depth interval (according with the borehole stratigraphy). Final velocity profiles are also shown (right panel).

some sites with restricted access for safety reasons. The multichannel setup was the same described before for the SRT, recording the vertical component of Rayleigh waves artificially generated by using an active seismic source. The length of each profile was adapted to the real site conditions but generally an intergeophonic distance of 2–3 meters and a minimum offset of 5–10 meters were used. Forward and reverse shots along survey lines were always acquired (Foti et al. 2018) in order to verify the site condition compliance with the hypothesis of a horizontally layered medium. The survey data were analyzed by using winMASW software by Eliosoft (http://www.winmasw.com/) and the phase velocity spectra were inverted jointly with HVSR curves according to the FVS-Full Velocity Spectrum approach (Dal Moro 2014, Dal Moro & al. 2015). The joint inversion scheme implemented in the software is based on a multi-objective evolutionary algorithm that exploit a Pareto-based ranking system to identity the fittest models and proceed with the optimization procedure (Dal Moro and Pipan 2007;

Dal Moro and Ferigo 2011). An example of the results obtained by using the joint inversion approach is presented in the following Figure 4 (a site along the Tronto river valley).

The down-hole (DH) seismic method was applied extensively since, despite its relatively high cost it provides significant information on the elastic properties of soils that are essential in analyzing the soil behavior under static and dynamic loads. Moreover, in spite of surface seismic methods, velocity inversions can also be efficiently detected and the accuracy and resolution doesn't decrease with depth. To generate the artificial seismic input, an instrumented 10 kg sledgehammer at fixed distance of 3 m from the borehole was used, first striking it over a steel plate for generating P waves and then horizontally on a wooden beam firmly fixed to the ground to generate S waves, using opposite directions impacts to ease the identification of S-waves arrivals. The sledgehammer input and the receiver outputs were recorded by a tri-axial Geostuff BHG-3 geophone connected to a Pasi 16S-seismograph, sampling each borehole at depth intervals of 1 m. The data were processed by using the commercial software Win_DownHole (http://www.wgeosoft.ch/). P and S waves arrival times were picked along the seismograms and then transformed into corrected vertical travel-times, in order to calculate Vs and Vp values for depth intervals. In Figure 4 we show an example of data processing for the DH3 site located inside Borgo hamlet along the Tronto valley (see Figure 5). The geological substratum (i.e. the Laga Formation) was found below 27 meters in depth.

In the following Figure 5 we show the 2D subsoil model reconstructed by Capotorti et al. (2017) along the section crossing three villages along the Tronto river (see Figure 2). The buried contact between the alluvial deposits and the geological bedrock was the main target and it was finally inferred using the whole data coming from field surveys, near-surface geophysics and few old boreholes. Since the geological setting along the section in Figure 5 could be considered relatively simple (i.e. one layer over bedrock), one could be tempted to infer the thickness of the covers exploiting the simple relationship $H=Vs/(4F_0)$ as, for instance, in Ibs-von Seht & Wohlemberg 1999. In this case, considering the available F_0 values and Vs equal to 450 m/s (i.e. the mean value obtained for GR deposits by MASW analyses- see Figure 6 bottom-left panel), the inaccuracy that would be obtained in covers thickness estimates is apparent.

The DH tests confirmed, indeed, the overall complexity of the subsoil with unexpected high 2D variability of the Vs values inside the alluvial covers. By the comparative analysis of the Vs models retrieved by surface waves (SW) and borehole (DH) methods it is clear that, owing to the complexity of the subsoil model along the section, even an accurate geotechnical characterization such as that achieved by the DH tests can be ineffective just few tens of meters away from the test site.

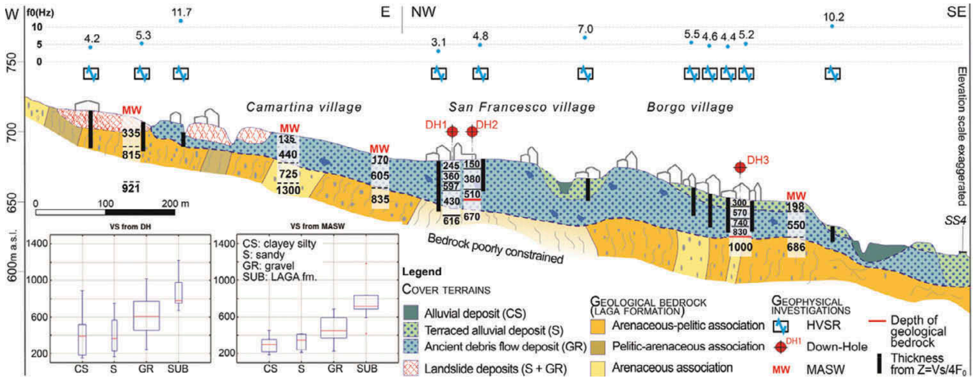

Figure 5. The subsoil model along the section in Figure 2 (modified from Capotorti et al. 2017). DH tests were performed few months after the end of the whole near-surface campaign. Comparison of the estimates of Vs values for each geological unit as derived from each method is shown (bottom-left panel).

6 CONCLUSIONS

Arquata del Tronto is a “diffuse” town that includes many small inhabited villages located in various morphological contexts, either at the top of hills, along steep slopes or inside narrow valleys. In such a complicated morphological context, representative of most of the Central Italy earthquake-prone areas, the properties of soil layers (lithology, thickness, ground water level) can have an high variability within relatively short distances and this affects the variability of the subsoil models of each locality. Issues for planning, performing and interpreting geophysical investigations were faced and despite the uncertainties related to data and methods, our results show the usefulness of an integrated approach in depicting complex geological settings and in geometrically constrain subsoil models. In this regard, seismic boundaries are of major importance for a reliable SM study: according to the Italian Regulation (NTC18, 2018), the seismic bedrock depth is where S waves reach a velocity of more than 800 m/s.

It is noteworthy that in the Arquata del Tronto area the geologic bedrock (namely the Laga Formation) and the seismic bedrock depths often correlate poorly. Being the seismic bedrock depth sometimes greater, the velocity profiles become relevant for many tens of meters in depth therefore making the Vs_{30} parameter useless. On the other side, velocities exceeding 800 m/s (i.e. the seismic bedrock) were found also at shallow depths, particularly within the alluvial deposits along the Tronto river valley, thus further increasing the complexity of the local subsoil model.

In our opinion the case study of Arquata del Tronto highlights the need in such territories of a high number of (direct and indirect) investigations to achieve an accurate geotechnical characterization, planned mostly on the basis of the actual geomorphologic complexity.

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