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EXPERIMENTAL AND NUMERICAL EVALUATION OF COMPLEX SITE EFFECTS IN ARQUATA DEL TRONTO AFTER THE 2016 CENTRAL ITALY EARTHQUAKE

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Abstract: *This work deals with the experimental and numerical evaluation of the local seismic response of Arquata del Tronto area (Marche region, Central Italy), severely struck by the Mw 6.0 August 24th 2016 earthquake. The Arquata del Tronto village and the surrounding hamlets of Borgo and San Francesco are located about 9 km NE of the August 24th 2016 mainshock epicentre. In detail, Arquata main village arises above an elongated WNW-ESE-trending ridge of the central Apennines thrust-belt (Central Italy), at elevations about 170 m higher than the underlying alluvial valleys where Borgo and San Francesco are built on. Despite their proximity (less than 500 meters), Arquata del Tronto, Borgo and San Francesco reported a quite different damage distribution after the August 2016 mainshock, suggesting that the seismic response of the area may be controlled by site effects. In order to explore this hypothesis, we evaluated the 2D numerical local seismic response along three representative geological cross-sections crossing Arquata del Tronto, San Francesco and Borgo; additional 1D analyses were carried out at strategic points along the cross-sections in order to explore the 2D physical phenomena governing the local response. Geomechanical properties of lithotypes were deduced by in situ tests.*

The satisfactory agreement between numerical amplification functions in linear range and experimental amplification functions obtained by the Generalized Inversion Technique (GIT) applied to a large number of aftershocks confirms the substantial reliability of the subsoil models.

Numerical analyses representative of the 2016 mainshock were carried out and processed in terms of peak and integral ground motion parameters. A comparison with the observed damage pattern was then undertaken in order to provide general implications about site response and seismic microzonation in similar geological and morphological settings.

Introduction

Nowadays, the study of local seismic response of site characterised by complex geological and morphological features represents a crucial challenge and the difficulties mainly arise from both the reconstruction of a suitable and thorough geological/geotechnical subsoil model and limitations of geophysical and numerical methods in such contexts (Pagliaroli et al., 2015).

Historical earthquakes in many cases showed concentration of building damage in the centres located on the top of a relief greater than that occurred on a flat morphology at comparable epicentral distance (Paolucci 2002) evidencing the importance of topographic amplification effects. Despite this observation, few instrumental strong motion stations are deployed on these sites and generally, when available, data show that recorded amplification is higher than numerically predicted one (Geli, 1988). This discrepancy mainly arises from the difficulty to

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represent in the model adopted for the numerical analyses, the geological and geotechnical site characteristics and the above mentioned limitations of the numerical models.

On August 24th, 2016, a M_W 6.0 earthquake (source National Institute of Geophysics and Volcanology – INGV) with epicentral area located near the village of Accumoli (Lazio Region), hit the Central Italy. The mainshock was followed by aftershocks located southeast and northwest of the epicentre, and in particular by Mw 5.9 and Mw 6.5 seismic events occurred on 26th and 30th October, respectively, about 25 km to the NW of the previous mainshock.

The impact of the 2016 seismic sequence and in particular of the August 24th 2016 event was highly destructive, causing ~300 casualties and extensive and irregularly distributed damage. In particular, a severe and heterogeneous pattern of damage was observed in the hamlets located along the Tronto River, suggesting the potential role of site effects in amplifying/localising the ground motion phenomena.

This paper presents the results of the experimental and numerical evaluation of the local seismic response of Arquata del Tronto village and of the surrounding hamlets of Borgo and San Francesco (Marche Region, Central Italy), heterogeneously damaged by the August 24th 2016 earthquake (Pagliaroli et al., 2019; Galli et al., 2016), although mutual distance of three villages is less than 500 meters away. Historical documents reported that also after the Mw=6.9 Valnerina (January 9th, 1703) earthquake an increasing level of damage was observed moving from Borgo toward Arquata del Tronto ridge (VII-VIII MCS, IX MCS respectively; Rovida et al., 2016), highlighting possible occurrence of ground motion amplification. Figure 1 reports a qualitative zonation of the damage distribution defined after the reconnaissance activity of some of the authors following the August 24th event (Lanzo et al., 2018). The damage categories proposed by Bray et al., (2000) were considered, ranging from D0 (no damage) to D5 (collapse of the structure).

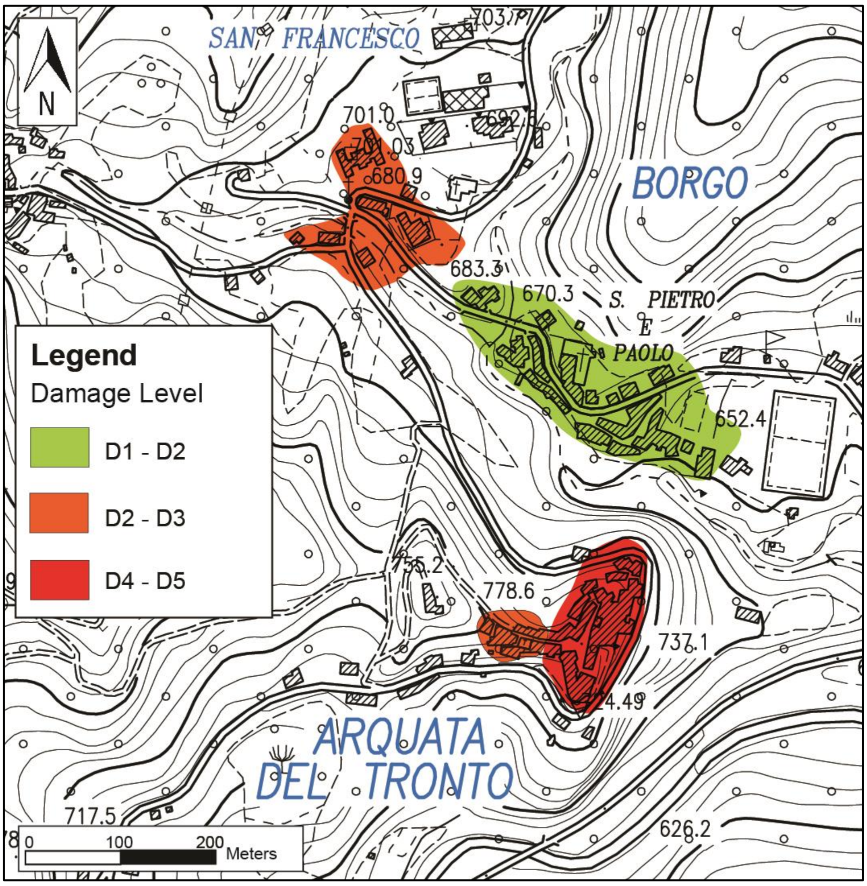

Figure 1. Damage zonation within the villages of Arquata del Tronto and surrounding hamlets of Borgo and San Francesco.

Considering the quite similar vulnerability of buildings, the mutual proximity of the villages, and their comparable distance to the August 24th 2016 mainshock epicenter (~9 km), the observed damage pattern could be related to the changes in seismic motion caused by the particular geological, geotechnical and morphological conditions of the study area.

In detail, the study area is located approximately 5 km south to the southeastern flank of Mt. Vettore, in the footwall block of the east-verging Mts. Sibillini thrust. Here the geological bedrock is represented by the Miocene pre-evaporitic member of Laga Formation (Milli et al., 2007; Marini et al., 2016; and references therein), a turbiditic succession of Messinian age, largely cropping out in the study area and mainly consisting of three lithofacies associations distinguished according to their sandstone/silt-claystone ratio: sandstone dominated (LAG4c) and sandstone prevailing (namely in order of increasing presence of the arenaceous component: LAG4b and LAG4d).

The main village of Arquata del Tronto is built on an elongated ridge made of the alternation of the above-mentioned lithofacies, which are steeply dipping and partially weathered/jointed at the top. On the contrary, Borgo and San Francesco lie in the valley of the Tronto River (Fig.2), where various Quaternary continental deposits overlay the geologic bedrock.

In this particular geological scenario, ground shaking may be affected by different factors: (i) stratigraphic amplification due to continental deposits resting on the bedrock; (ii) effects ascribed to the topographic features such as focusing/defocusing phenomena and resonance of the relief (Faccioli et al., 1997); (iii) coupling between topographic and stratigraphic effects or “atypical topographic effects” (Marzorati et al., 2011; Massa et al., 2014; Pagliaroli et al., 2015).

In the following of this paper, 1D and 2D numerical results obtained at and along representative points and sections located in the three neighbouring hamlets struck by the 24th August 2016 earthquake are presented. The main goal of this work is to quantitatively evaluate the irregular amplification pattern experienced during the earthquake, to investigate the causes, and to offer a valid methodology for the evaluations of site effects in such complex configurations.

Methods

This work integrates geological, geophysical, and geomechanical approaches aimed at defining the subsoil model. Furthermore, the ground motion amplification was estimated by using both numerical modelling and experimental methods.

Particular efforts were devoted to defining an accurate subsoil model, achieved in a first phase by the interpretation of the already available and new geological, geophysical, morphological, geotechnical, and geomechanical data acquired in the study area.

The presence of two temporary seismological stations located at the top of Arquata del Tronto (MZ80 in Fig. 2) and in the Camartina valley (MZ85 in Fig. 2), allowed us the comparison of our numerical amplification functions with the spectral amplification functions computed experimentally by applying the Generalized Inversion Technique, hereafter GIT (Laurenzano 2018). In the following, we briefly present the steps of the adopted methodology, the main results and the critical issues.

Geological surveys

Several geological surveys were carried out with the aim to constrain the lithology, geometries and thickness of the lithotypes. The area we mapped (about 1 km^2 in surface extension) extends from the north of San Francesco village to the south of Arquata del Tronto, and encompasses the villages of Camartina (to the west) and Borgo (to the east) hamlets (Fig. 2).

The ridge where the Arquata del Tronto village arises is mainly elongated in the WNW-ESE direction and made of the alternation of different lithotypes belonging to the Laga Formation. The lithotypes are structurally arranged in a monocline geometry (45-50° dipping to WSW) representing the reverse limb of a E-verging anticline. Where the sandstone-poor lithotypes (LAG4b), crop-out, the ridge profile is transversally affected by saddles getting it a 3D shape.

Borgo and San Francesco hamlets are located about 200-500 m north of the Arquata del Tronto village and rise on valleys (Pianella and Camartina valleys, respectively), where the Laga Formation is covered by up to 30-40 m thick of continental quaternary deposits, mainly consisting of debris flow and coarse fluvial deposits (Fig. 2).

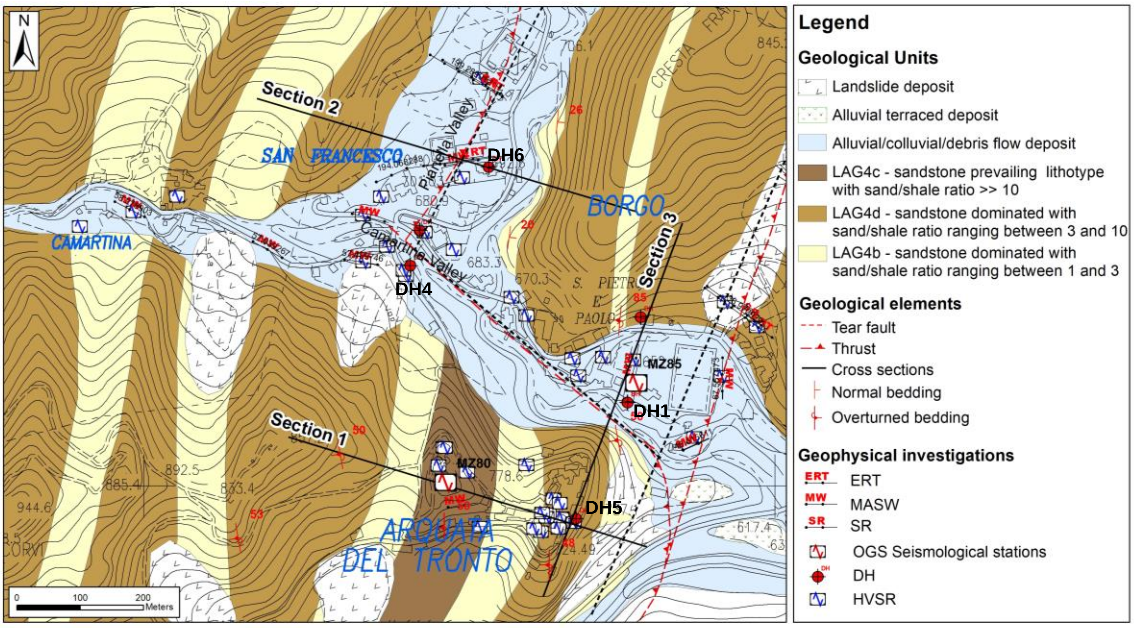

Figure 2. Geological map of the study area with the location of the three representative sections and of the investigation dataset used for this work.

Data collecting and acquisition

In the study area, a considerable number of geognostic and geophysical investigations has been performed following the 24th August event, as part of the seismic microzonation activities coordinated by the Italian Centre for Seismic Microzonation and its application (CentroMS; https://www.centromicrozonazionesismica.it/en/). In particular, data used for this study consist of down-hole (DH), Multichannel Analysis of Surface Waves (MASW), Electrical Resistivity Tomography (ERT), Horizontal to Vertical Spectral Ratios (HVSR) tests and recordings of four of the thirteen temporary seismological stations installed by The Italian National Institute of Oceanography and Experimental Geophysics, hereinafter OGS, from September 30th, 2016 to February 17th, 2017. The location of in situ investigations is shown in Fig. 2.

Additional MASW and HVRS measurements were subsequently performed in Pianella and Camartina valley, in order to better constrain thickness of the Quaternary covers, and to evaluate shear wave profiles and resonance frequencies.

Several HVRS tests were carried out on the Arquata del Tronto ridge with the aim to investigate preferential directions of the amplification (i.e., polarisation of ground motion), being an indicator of topographic site effects (Burjanek et al. 2014). HVSR technique has the undoubted advantage that does not required a reference station, difficult to be identified in this particular context. Even if this is a no-conventional use of HVSR, following the work of Chavez-Garcıa et al. (1996), in the last two decades it has been extended to topographic effects evaluation experiencing encouraging results (e.g. Paolucci 1999; Lovati et al., 2011; Marzorati at al., 2011; Massa et al., 2014; Pagliaroli et al., 2015).

Geomechanical surveys

The geological surveys revealed partially weathered-jointed conditions of the rocky material forming the top portion of the Arquata del Tronto ridge. On this regard, we performed in-situ geomechanical tests by using a Schmidt hammer (e.g., Aydin, 2008), in order to define the relationships between the uniaxial compressive strength and the facies characteristics of the strata. In detail, we selected three sites across the Arquata del Tronto village corresponding to the weathered upper portion of lithotypes LAG4c, LAG4b, and LAG4d and performed a series of in-situ measurements on sub-vertical exposures of the rock mass. Later we performed a statistically reliable number of measurements of the hardness index by applying the push rod of the Schmidt hammer in the central part of the bedding layer. Finally, we converted the hardness index into the uniaxial compressive strength (measured in MPa) by using the conversion chart provided within the Schmidt hammer stuff.

The Subsoil model assessment

The cumulative interpretation of all collected data allowed us to draw three geological cross sections for the 2D numerical analyses, and to achieve the mechanical characterization of soils and rocks.

Noise measurements performed at San Francesco and Borgo hamlets allowed us to constrain the geometries and the thickness of the Quaternary covers filling the valleys north of the Arquata ridge. In detail, all the H/V curves referring to San Francesco hamlet show fundamental frequencies lower than those measured at Borgo (3.5 Hz and 6 Hz, respectively). Moreover, San Francesco highlights a level amplitude of the H/V curves higher than 4 with maximum peaks of 6 and 7, whereas Borgo H/V generally drops below 4. This observation, together with information coming from boreholes stratigraphy (DH1 and DH6 in Fig. 2) and from geological surveys, highlight that the Quaternary cover in San Francesco is thicker than in Borgo. Moreover, the higher amplitude experimented by the H/V curves in San Francesco could be related to a greater impedance contrast, due to the presence of the stiff arenaceous lithotype (LAG4c) as seismic bedrock in the area.

Regarding noise measurements carried out at the Arquata del Tronto ridge, an interesting observation derives from the analysis of ground motion polarisation. We found the presence of a different preferential polarization of the noise in the stations situated on the SW edge with respect to those to NE of the crest. Moreover, in some cases in the same station the presence of two picks differently polarised can be observed. These findings strongly suggest that the ridge could be affected by 3D site effects. All HVSR curves at the Arquata del Tronto ridge generally highlight the presence of multiple peaks, markers of a possible broad band amplification related to the coupling of stratigraphic and topography effects. We interpreted this phenomenon as probably linked to the upper weathered-jointed portion of different rocky lithotypes cropping out on the ridge but also inferred by the interpretation of borehole stratigraphies and down-hole data. In particular, a down-hole performed directly on LAG4d outcrop (DH5, location in Fig. 2), provided information on the thickness of the upper weathered-jointed portion, estimated about 15 m, since at a depth of about 15-16 m the DH5 test shows an increase of the shear wave velocity (Vs) from 750 m/s to 1000 m/s (Pagliaroli et al., 2019). This latter value was assigned to unweathered LAG4d lithotype.

The Vs values assigned to the others Laga Formation lithotypes were generally derived from MASW and DH tests carried out in the study area and reaching the bedrock. In particular, the Vs of the less arenaceous lithotype (LAG4b) was assumed equal to 700 m/s on the basis of DH4 test. Moreover, in the absence of direct investigations, the shear-wave velocity of LAG4c lithotype was assumed equal to 1200 m/s considering DH data on an equivalent lithotype acquired in the Amatrice area, 15 km south of Arquata del Tronto (CentroMS, unpublished data).

Finally, the Vs to the weathered-jointed portion of the LAG4c and LAG4b lithotypes were attributed taking into account the results of the mechanical surveys performed on the ridge. As we observed a progressive increasing of the hardness index with the increasing grainsize of the bedding (from claystone to sandstone), we assigned a Vs of 900 m/s and 650 m/s to the LAG4c and LAG4b, respectively, proposing a correlation between hardness index collected by using the Smith hammer and the stiffness of the rock materials.

Regarding the nonlinear properties adopted in this work, literature curves for gravelly soils (Rollins et al., 1998) were employed for landslide cover and alluvial soils given the prevalent coarse grain-size composition. Rocky lithotypes, characterised by high values of stiffness, were considered as linear visco-elastic materials with a damping ratio D in the range 0.5% -1%.

Subsoil model calibration

To verify the reliability of the subsoil model, we compared the numerical amplification functions with the corresponding experimental functions obtained by the application of the Generalized Inversion Technique (GIT) to earthquake recordings belonging to the 2016-2017 Central Italy seismic sequence at the sites MZ80 (Rocca di Arquata) and MZ85 (Borgo) (Laurenzano et al., 2018).

As GIT technique was applied only to events having M<5 (maximum PGA of about 0.05g), the experimental amplification functions are not affected by the soil nonlinearity behaviour, thus depending only on mechanical properties in the linear range (V_S, V_P) and surficial/buried morphologic features. Following this assumption, we carried out 1D and 2D linear site response analyses and we computed results at the locations of MZ80 and MZ85 seismological stations.

The 1D analyses were carried out by using the STRATA code (Kottke et al., 2013) in the frequency domain, whereas the 2D simulations were carried out by using the finite element time domain QUAD4M computer code (Hudson et al. 1994).

Following this calibration step, the subsoil model was slightly updated, remaining generally consistent with direct geological, geophysical and geotechnical information, in order to capture the experimental response in terms of resonance frequencies and amount of amplification. We report in Table 1 the final physical and mechanical material properties of the materials assumed for the three sections, whereas a sketch of the 2D mesh adopted to discretise Sections 1, 2, and 3 is shown in Fig. 3.

Fig. 4a,b reports the comparisons between the results of the 1D-2D numerical analyses and experimental amplification functions obtained by GIT application computed for Arquata del Tronto and Borgo at specific control nodes, showing a satisfactory agreement.

The shapes of 1D-2D and GIT amplification functions obtained for control node in Section 1 (Fig. 4a) are quite similar, despite is evident the higher amplification showed by the GIT function. We have to point out that the ridge investigated is a 3D configuration and 2D analysis slightly underestimate the higher pick, failing in the attempt to reach intensity of the amplification, nevertheless perfectly matching the frequency in which it occurs. Regarding Fig. 4b, a satisfactory agreement is observed between differently computed results. In particular, 2D amplification function shows a pick with a maximum amplification of about 4 at 6 Hz, whereas 1D and GIT reveal a pick of less amplitude, about 3 at 5 Hz. However, it is to be noted that GIT function for Borgo has been obtained as a geometric mean of the two EW and NS horizontal components (Laurenzano et al., 2018), whereas the 2D numerical analysis has been computed perpendicularly to the valley axis, where we expected the maximum level of amplification as consequence of possible valley effect.

Numerical modelling of August 24th mainshock

After the calibration of the subsoil model, numerical analyses were carried out for the three sections drown along Arquata del Tronto, San Francesco and Borgo hamlets by using a seismic input representative of the August 24th 2016 mainshock. In particular, a set of 7 accelerograms was selected in order to be compatible on average, in the 0.1-1.1 s period range, with the target spectrum computed by the application of Akkar and Bommer (2014) attenuation relationship, assuming Mw 6. and a Rjb = 9, to reproduce 24th August 2016 expected ground motion at outcropping flat seismic bedrock.

The 2D numerical analyses were carried out with QUAD4M adopting a linear equivalent strategy to model material nonlinearity. The results are reported in Fig. 4c) and d) for three nodes representative of the centre of the investigated villages (see Fig. 3 for location) in terms of nonlinear amplification functions and acceleration response spectra, respectively.

The three sites show a quite different seismic response especially in the 1-3 Hz frequency range. Highest amplification can be noticed at San Francesco where a peak of about 5 is attained at about 3 Hz and amplifications as high as 2-3 characterize the 0.8-1.5 Hz range. Amplifications ranging between 2 and 3 are also computed at Arquata del Tronto while a substantial deamplification of ground motion is observed at Borgo. For frequencies higher than 3 the seismic response is more homogeneous among the three sites, being Borgo characterized by higher amplifications although somewhat moderate (about 2 around 5-6 Hz).

The villages consist mainly of unreinforced masonry structures 2–3 stories in height. Very few structures were retrofitted with through-going iron bars. Isolate relatively modern reinforced concrete structures can be found (essentially in Borgo and San Francesco). Noise measurements carried out by Pagliaroli et al. (2015) in Castelvecchio Subequo village (Abruzzi region in Central Italy) with reference to typical 2-3 stories masonry buildings like those located in the study area, showed that first vibration modes are in the range 4–6 Hz.

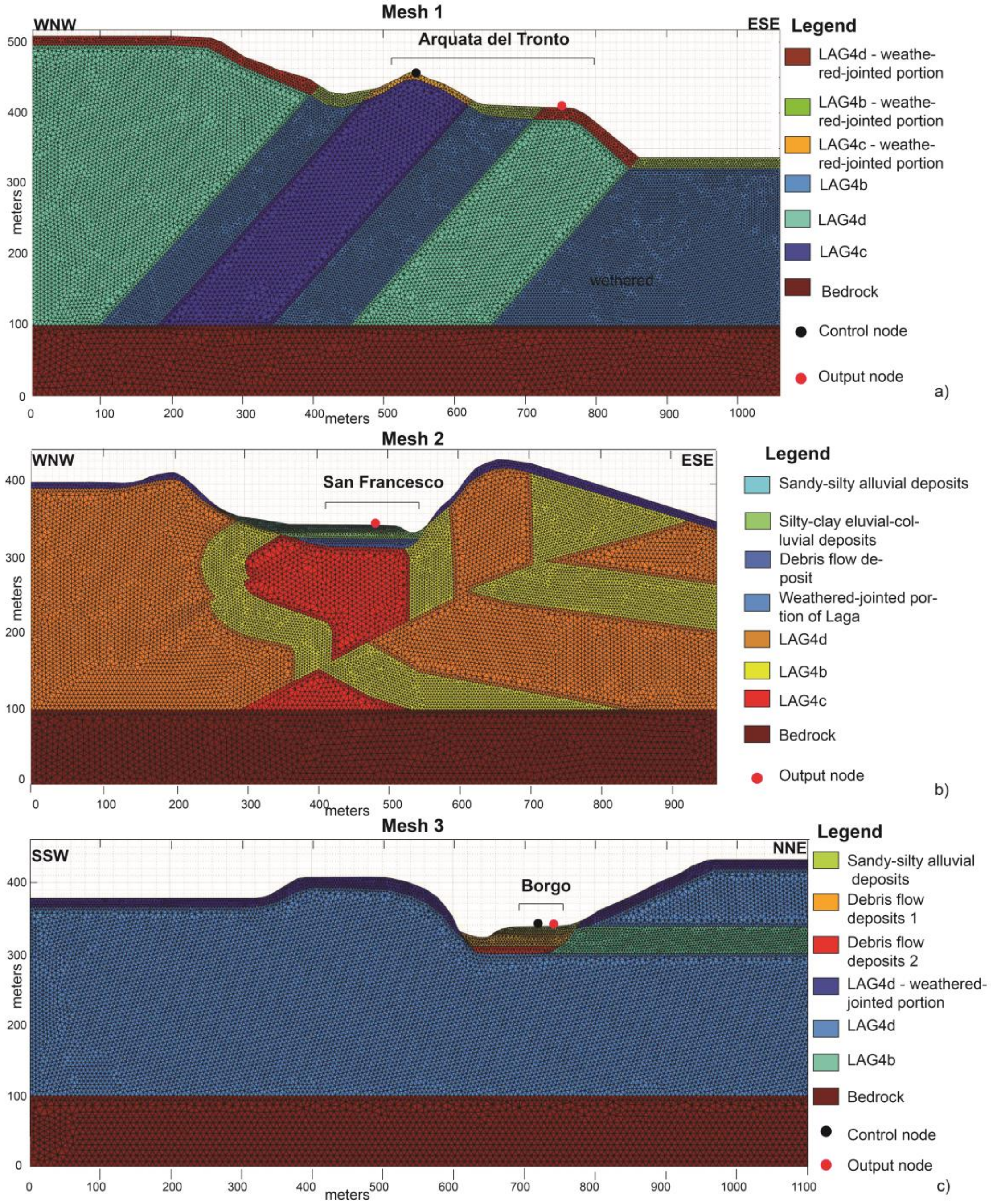

Figure 3. Finite element mesh adopted respectively for Section 1 a), Section 2 b) and Section 3 c); the labels identify the lithological units briefly described within the text, whose physical and mechanical properties are presented in Table 1. In a) and c) control nodes (black ball) represent MZ80 and MZ85 OGS seismological station location, respectively named Rocca di Arquata and Borgo; in a) b) and c) output node (red ball) represent the hamlet centre; it is the node where we extracted 2D nonlinear results.

These frequencies, estimated from ambient vibrations, characterise the building behaviour in the linear range. A reduction up to 50 % of the vibration frequencies can take place during earthquakes because of the nonlinear behaviour of masonry structures and development of cracking for severe shaking (Michel et al. 2011). This reduction, therefore, suggests that fundamental frequencies lies around 2-3 Hz during the most severe part of the shaking.

section	material	γ (kN/m³)	Vs (m/s)	ν (-)	Nonlinear curves
1	LAG4b	22	700	0.4	Linear D 1%
	LAG4c	23	1200	0.38	Linear D 0.5%
	LAG4d	23	1000	0.4	Linear D 1 %
	LAG4c Weathered – Jointed portion	22	900	0.4	Linear 1%
	LAG4b Weathered – Jointed portion	21	650	0.42	Linear 1%
	LAG4d Weathered – Jointed portion	22	750	0.4	Linear%
	Bedrock	24	1500	0.36	Linear 0.5%
2	LAG4b	22	700	0.4	Linear D 1%
	LAG4c	23	1200	0.38	Linear D 0.5%
	LAG4d	23	1000	0.4	Linear D 1 %
	Weathered – Jointed portion	22	750	0.4	Linear D1%
	Sandy -Silty alluvial deposit	18	400	0.42	Rollins et al., (1998)
	Silty clay eluvial – colluvial deposit	19	550	0.42	Rollins et al., (1998)
	Debris flow deposit	21	700	0.4	Rollins et al., (1998)
	Bedrock	24	1500	0.36	Linear D 0.5%
3	LAG4b	22	700	0.4	Linear D 1%
	LAG4d	23	1000	0.4	Linear D 1 %
	LAG4d Weathered – Jointed portion	22	750	0.4	Linear D 1%
	Sandy -Silty alluvial deposit	19	400	0.42	Rollins et al., (1998)
	Debris flow deposit 1	21	600	0.4	Rollins et al., (1998)
	Debris flow deposit 2	21	820	0.4	Rollins et al., (1998)
	Bedrock	24	1500	0.36	Linear D 0.5%

Table 1. Selected parameters for subsoil models used for site response analyses of Section 1, 2, and 3

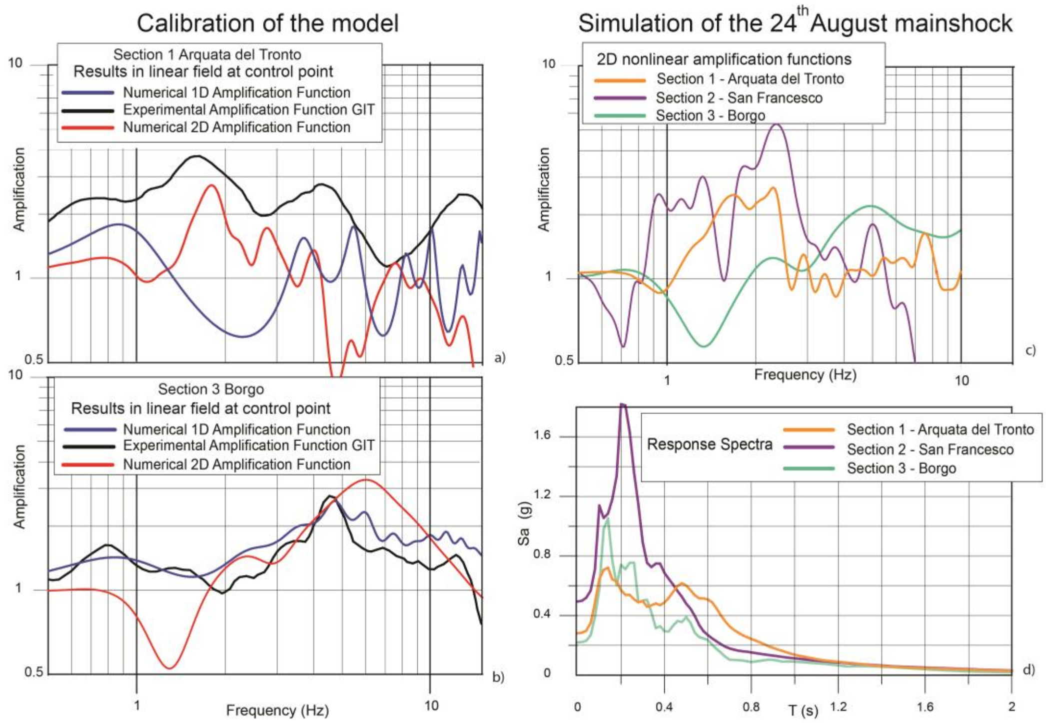

Figure 4. a, b) Calibration of the model: Comparisons between experimental results (black curve) and numerical modelling (blue curve for 1D; red curve for 2D) in linear field at the control nodes located along Section 1 and 3; c, d) Simulation of the 24th August mainshock: 2D numerical results in nodes representative (output node) of the most damaged location in Arquata del Tronto, San Francesco and Borgo nonlinear amplification functions (c) and response spectra (d). See Fig. 3 for the location of control and output nodes.

Then, the high amplification in this range computed at Arquata del Tronto and San Francesco could explain the high damage observed in the two villages with respect to Borgo after the August 24th mainshock (Fig. 1). Moreover, it should be noticed that major damage occurred at Arquata del Tronto can be partially related to the vulnerability of buildings, which is slightly higher than in Borgo and San Francesco: no reinforced masonry structures were identified in the Arquata del Tronto village. In fact, iron bar-reinforced buildings, isolated concrete structures, and more recent masonry buildings were noticed only in Borgo and San Francesco. The combination of ground motion amplification and vulnerability could have played a relevant role on the significant difference in damage level observed in the three hamlets, as shown in Fig. 1. In addition, Arquata del Tronto is probably affected by 3D effects not captured by the 2D model: the real amplification is therefore quite higher than calculated by the numerical analyses (Fig. 4a) and comparable with or higher than San Francesco.

Conclusions

Local seismic response analyses were performed by using numerical and experimental methods in the Arquata del Tronto area, following the heterogeneous damage pattern observed in the aftermath of the 24th August 2016 Central Italy event. In fact, despite their proximity (less than 500 meters) Arquata del Tronto, San Francesco and Borgo villages experimented a different degree of damage (D4-5; D2-3; D1-2, respectively).

Coherently with the observed damage pattern, major amplifications do occur at San Francesco and Arquata del Tronto sites. However, we noticed the highest amplification peak of about 5 at San Francesco, whereas Arquata del Tronto exhibits a peak of 2.8, in the same frequencies range of 2-3 Hz. We explained this result by considering that Arquata del Tronto is probably affected by 3D effects, therefore the 2D numerical analysis may lead to underestimate the real amplification.

Regarding the results obtained at Borgo, the numerical analysis shows lower amplification, slightly greater than 2, at 5-6 Hz. Although this frequencies range is typical of masonry building similar to those located in the investigated villages, we invoke the reduction of the vibration frequencies for the nonlinear behaviour of the masonry structures as reason of the lower damage observed at Borgo than in Arquata del Tronto and San Francesco villages.

Regarding the physical phenomena responsible for site effects, Arquata del Tronto suffered a ground motion amplification induced by ‘‘atypical topographic effects’’, which are linked to the presence of a ridge characterised by a 3D shape and the alternation of highly dipping different rocky materials and of a weathered-jointed upper layer.

On the other hand, the higher amplification observed in San Francesco rather than Borgo, as lying on valleys characterised by similar morphology, may be ascribed to the different thicknesses and physical properties of the Quaternary covers, as well as the different stiffness of lithotypes representing the local seismic bedrock, resulting in a higher impedance contrast at San Francesco.

The case study here presented shows that in complex geological and morphological configurations the numerical model could be successfully calibrated by adopting a multidisciplinary approach, taking into account information coming from both geological, geomechanical, geophysical surveys and experimental methods. In particular, H/V from noise measurements provided encouraging results in the catching fundamental frequency, also in such complex configurations. Moreover, this work shows the importance of a seismological network, whose recordings could be used to obtain experimental amplification functions to apply in the calibration of reliable numerical models. This alternative may appear expensive but it is encouraged in the case of microzonation studies in regions characterised by such a complex geological, morphological, and structural setting.

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