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Seismic site effects in the Red Zone of Amatrice hill detected via the mutual sustainment of experimental and computational approaches

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Abstract

This paper presents the results of numerical analyses of ground motion in the Red Zone sector of Amatrice hill, violently struck by the 2016–2017 Central Italy seismic sequence. The methodologies used in processing the data to define the numerical model are firstly described. The results obtained from the computational analyses are then presented and discussed by comparing them with experimental data set of weak motion recordings. Computational analyses were performed via both a 2D-numerical FEM model and a pseudo-three-dimensional hybrid model (SiSeRHMap) which develops multispectral maps taking into account topographic effects. Starting from available geological data and geophysical measurements, an original and specific subsoil GIS model was developed and utilised to perform the computational analyses. The preliminary map for fundamental periods computed from the subsoil model is in good agreement with the experimental data. A restricted set of weak ground motions acquired from an accelerometric station located in a reference site was used as input for the numerical analyses, while the signals of the corresponding events recorded at the top of the hill were used as targets in the reliability evaluation analysis of the outputs. In the area of Amatrice hill, which is characterized by a complex geological and topographical context, the reliability analysis shows a good performance of the hybrid model compared to the 2D-FEM model in the prediction of seismic response. Agreement generally was also good with regards to the experimental and computational results, both in relation to the amplitude and to the shape of the spectral amplification that change depending on the hill sector. Considering the predictive reliability of the models, a high amplification, due to topographic effects, was observed for the Red Zone by performing a back-simulation of the 24th August 2016 main shock. The analysis results highlight also that the maximum amplification factors, based on the definition of the Housner intensity, occur in the interval of periods 0–0.5 s covering the fundamental period range of the buildings in this area.

Keywords Site seismic response · Topographic effect · 2D-FEM · SiSeRHMap · Metamodeling

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1 Introduction

Numerical models are used in seismic hazard analyses with the aim of predicting the ground response in the study area considering one or more expected seismic motions (input motions). These input motions stem from regional seismicity studies and they are considered as being detected at a free field site on outcropping rigid rock. Numerical models require an adequate geomorphological and geotechnical characterization of the area including the properties of the soil deposit (soil model), e.g. the depth and thickness of the soil layers, their physical and mechanical properties taking into account the non-linear dynamic stress–strain behaviour of the materials. Within this framework, a significant challenge is to find a satisfactory compromise between the ability of the numerical model to simulate realistic conditions and the computational resource deployed to reach the expected goals. A further challenge is to extend the result of the analysis to a wide and complex area, as in the case of Amatrice's Red Zone.

The numerical models adopted for local seismic response analyses commonly implement 1D, 2D or 3D wave propagation laws coupled with equivalent linear or non-linear analyses performed in the time or frequency domain. Most of these models consider only the vertical-incident shear wave propagating upward from the rigid bedrock through the soil deposit. Such a simplification and the epistemic uncertainties in the model parameterization may substantially underestimate the site effects or estimate them incorrectly. In addition, for complex conditions of topographic surface and buried morphology, the directional effects of the incoming waves may greatly influence the surface ground motion. Taking into account the limitations of the experimental approaches, mainly due to definition of the reference station (Wood and Cox 2016), some authors have highlighted unexpected substantial differences between experimental and numerical approaches in some topographically complex areas. These differences mainly regard the magnitude of the amplification function and the frequency range within which the topographic effects are greatest (Bard 1982; Bard and Tucker 1985; Geli et al. 1988; Hartzell et al. 1994; Assimaki et al. 2005; Assimaki and Jeong 2013; Chávez-García et al. 1996; Barani et al. 2014; Sánchez-Sesma et al. 1989).

Although it is extremely difficult to decouple stratigraphic effects from topographic effects (Kovacs et al. 1971; Sitar and Clough 1983; Assimaki et al. 2005; Assimaki and Jeong 2013), recent studies have tried to estimate topographic effects via an amplified/de-amplified spectral function that can also be defined by using GIS morphometric elements (Molina et al. 2019; Grelle et al. 2016; Maufroy et al. 2012; Rai et al. 2016). The main advantage of this approach is that it allows to estimate the seismic response on large areas based on a limited number of significant parameters, even though its performances have been evaluated only in a few real cases (e.g. Maufroy et al. 2015; Grelle et al. 2016; Wang et al. 2018).

Seismic site effects analyses are frequently performed for seismic risk reduction on large areas. With regards to these large areas, seismic site effects results should be spatially distributed on adequate and optimized grids and they all should be obtained with the same accuracy level. In recent times, some GIS simplified software packages have been developed to implement the seismic site effects results for the purpose of seismic risk management and prevention studies carried out for urban planning. These codes provide computational maps of topographic seismic effects using empirical solutions (Maufroy et al. 2012; Rai et al. 2016; Wang et al. 2018) or partially physical-based models such as the hybrid-model—SiSeRHMMap (Grelle et al. 2016), that takes into account both stratigraphic

and topographic effects. This latter is a modular computational methodology based on self-learning models (metamodels) trained on the results of local recurrent cases. By solving these metamodels constituted by GIS-layering-subsoil and GIS-topographic surfaces, SiSeRHMap develops maps of seismic response.

The results from computational seismic site effects analyses performed in Amatrice's Red Zone is herein presented and compared with experimental results from recordings of the 2016–2017 Central Italy seismic sequence. More specifically, seismic site effects were evaluated by combining the hybrid GIS model SiSeRHMap with a 2D finite element model. A parameterized three-dimensional model of the study area was obtained by means of the SiSeRHMap GIS-methodology and the ground seismic response was subsequently calculated on representative 2D cross sections using a Finite Element approach to ensure that both SiSeRHMap and the 2D-FEM analysis shared the same input model. Progressive computational modules of SiSeRHMap permitted checking the reliability of the input-parameterized subsoil model based on the experimental data and subsequently of the output-seismic response. The map-data provided by SiSeRHMap and results of 2D-FEM models were finally compared both with each other and with experimental analysis results. The comparison was performed on strategic cross-sections extracted from the pseudo-3D parameterized geotechnical model and the observational data were obtained from permanent seismic stations located in the study area.

2 General overview of the area

Amatrice village was heavily hit by the recent 2016–2017 seismic sequence of Central Italy (Amatrice-Visso-Norcia). During the first strong event of August 24th, 2016 (moment magnitude $M_w=6.0$), it suffered the greatest loss of human life and the most extensive damages to structures and facilities. As early as the day after the 24th August event, the extensive and widespread damage in its historic centre induced the Authorities to declare it as a “Red Zone” (off-limits area due to the high danger level).

Amatrice is located in Central Italy in the Apennine Chain sector that developed during the Oligocene-Quaternary age. It is composed of Meso-Cenozoic limestones/dolostones which are topped by syn- and post-orogenic siliciclastic marine-turbiditic deposits, named the Monti della Laga Formation (Messinian—Pliocene) consisting of sandstone with intercalations of marls and siltstones. Conglomerate/puddingstone heteropic deposits are also frequently encountered. At the top of the sequence, younger (Quaternary) deposits (colluviums, old alluvium, alluvial/debris fans and landslides deposits) fill the topographic depressed areas, and cover the gentle slopes and the ridge of the hills.

Amatrice village lies mostly on a hilly plateau which is elongated, for approximately 2 kilometres, in a Northwest – Southeast direction, in agreement with the Apennine chain alignment (Fig. 1). The more prominent sector at the NW edge of the hill is the Red Zone (Fig. 1). It is approximately 500–600 m long, 200–400 m wide. It rises up 50–70 m high from the valley and it is bordered by a steep slope (approximately 30°) to the North and to the West, and by a gentler slope (approximately 15°) to the South.

2.1 Damage

The severity of damage and its distribution coupled to the building typologies are significant markers of the role played by the seismic site effects in Amatrice (Zimmaro

Fig. 1 Amatrice hill landscape, Red Zone (reddish shaded area) and seismic recording stations (green triangles)

and Stewart 2016; Maufroy et al. 2018; Fiorentino et al. 2018). Among these, according to the results of previous studies (e.g. Hough et al. 2010; Assimaki and Jeong 2013, among others), topographic effects are certainly expected, as a consequence of the morphology of the elongated hilly plateau (promontory) on which Amatrice village lies, with the major effects at the top of the prominent zone where the Red Zone was delimited (Figs. 1, 2).

In the Red Zone, the highest level of damage was observed in the aftermath of 24th August, 2016 shock (Fig. 2) and the level of damage to the ancient masonry buildings was comparable to that on more recent buildings. In contrast, lower or negligible damage was observed for ancient masonry buildings located at the foot of the hill outside the Red Zone. Near one of these buildings (image P2 in Fig. 2), an accelerometric station of the Seismic National Network (named T1299) was installed after the 24th August event and another seismic station (named SCOI) was installed by the research team involved in this study. From Fig. 2, it should also be noted that the orientation of the row of buildings near the T1299 station is similar to that of most rows of buildings located at the top of the hill.

Despite the damage was evenly spread out across the Red Zone of Amatrice after the whole seismic sequence, resulting as the cumulative effect of the strongest events, the damage that occurred after the first shock in August 2016 was more differentiated. Aerial photos (Google Earth set on 27th August 2016; Milana et al. 2019) and remote detection performed by the European Copernicus Agency highlighted a concentration of collapsed buildings in the north and northwest hilly area, near the edge of the steep slope (Map in Fig. 2). Interestingly, the two old towers located in the central part of the hill (one of which can be seen in picture P1 of Fig. 2), were still standing at the end of the whole seismic sequence. In this regard, some Authors have highlighted how different building typologies

Fig. 2 Top left: damage map detected via remote sensing data analysis by the Copernicus Agency EU and photo shoot points at characteristic sites and there refer to situation after August 24, 2016 event. The pictures show the cumulative damage at the end of 2016–2017 seismic sequence: aggregate masonry building near T1299 station (P2); St. Catherine's monastery near the SUOR station (P3); recent reinforced concrete building near ROMA station (P4); Amatrice district hospital (P5); reinforced concrete building near the MONU station (P6); AMT station (P7). Picture P1 shows the old clock tower located in the central part of Amatrice hill that was still standing at the end of the seismic sequence

and geometries were characterized by different seismic responses during the seismic sequence in many other villages (Mollaioli et al. 2018; Iervolino et al. 2017). This effect was also evident in the Red Zone of Amatrice (Fiorentino et al. 2018).

Based on this framework, the research team involved in this study installed a network of four mobile seismic stations in many characteristic and strategic sites compatible with logistic and hazardous conditions (Map in Fig. 2). Installation and maintenance were authorized by the National Civil Protection Department upon request of the National Order of Geologists. These stations, which were added to the permanent stations of the Italian National Seismic Network, played a key role in identifying seismic site effects at Amatrice, as will be outlined in the following sections.

2.2 Geo-lithological sequence

Available geological maps and data achieved from an in-depth survey, including geological, geophysical and geotechnical in-situ and laboratory investigations, allow to identify and characterize the subsoil in the Red Zone of Amatrice at the top of the hill, and, in minor detail, in the valleys.

The complete characteristic stratigraphic sequence (Fig. 3) includes a basal rock (ML-h), beginning above a depth of 50–60 m from the top of the hill, with an average V_s of about 1100 m/s, consisting of sandstone and marly-sandstone/marly-limestone with conglomerate inclusions. This lithological unit may pass at the top in a weaker rock (ML-w) characterized by an average V_s of about 580 m/s and composed of sandstone and siltstone, and subordinately of very dense sandy material. The shear velocity of this member is comparable with that of the altered portion of ML-h member when it is outcropping or near-surface. Both ML deposits are members of the “Monti della Laga” Units. Soft covering materials follow moving upwards in the sequence and characterize the top of Amatrice hill and the bottom valleys. These soft materials vary within the area in composition and thickness. A layer of an ancient coarse sandy alluvial deposits (AD) extends down to 15–20 m in depth with an average V_s value of about 380 m/s. Near the ground surface, colluvium, and/or anthropogenic deposits (CD), with an average V_s value of 220 m/s, may be found almost everywhere at the top of the stratigraphic succession, and slope debris of similar materials covers the slopes of the plateau with the exception of the steeper zones. In addition, the CD geo-lithological unit is frequently mixed with recent alluvial deposits (SD). These latter, which are characterized by an average V_s of about 300 m/s, are the depositional filling materials of the valleys and they also fill a topographic depression in the southern-west sector of the hill.

Geo-lithological sequence, thickness and shear wave velocity of each unit vary within the study area. Based on the complete characteristic stratigraphic sequence, the original

Fig. 3 Typical transversal cross-section of Amatrice hill (it refers to DD' section line in Fig. 6)

procedure included in SiSeRHMap package (Grelle et al. 2016) was applied to identify zones characterized by the same lithological 1D-sequence in a pseudo-three-dimensional subsoil model as described in Sect. 4. A detailed dynamic characterization was also performed for all the above mentioned geo-lithological units, including the definition of the curves of normalized shear modulus and damping ratio versus shear strain, as detailed in Sect. 4. Such data were then processed by SiSeRHMap in order to develop quantitative maps representing the subsoil geophysical model that was assumed to perform numerical 2D-FEM and 3D-hybrid ground response analyses.

3 Computational models

3.1 SiSeRHMap

SiSeRHMap methodology (Simulation of Seismic Response via a Hybrid Model, Grelle et al. 2016) is based on a Geographic Information System (GIS) data-layered and a meta-modeling procedure. It provides multispectral maps of damped acceleration response and other derived parameters. The methodology is implemented via a Python Computer Code (<https://www.geosmartapp.it>) composed of five sequential modules (Fig. 4). The “lithodynamic units”, LU, (sensu Grelle et al. 2014) provide the key elements of the modelling, i.e. the layer sequence of the soil deposit and zones obtained via their combination. The subsoil is modelled through a physical and geometrical multilayer information framework, named as “GIS Cubic Model” (GCM), which is completed by morphometric information derived from the Digital Elevation Model (DEM). The base general model takes into account coupled stratigraphic and topographic effects (Grelle et al. 2018), that is the stratigraphic acceleration response spectra are upscaled non-linearly in the frequency domain by using a Topographic Aggravation Factor (TAF) function. It is a dedicated heuristic model that depends on the morphometric shape of the relief and on the equivalent uniform shear wave velocity of the materials composing the relief. SiSeRHMap was conceived for having a good compromise between the typology and accuracy of results in terms of maps, accuracy versus 2D modelling, easy GIS treating of data and mainly the computational and input model building time saving compared to a rigorous 3D-model. To date, it has been validated by the comparison with 3D numerical analysis on a real relief constituted by uniform material (Grelle et al. 2016) and 2D numerical models of non-uniform reliefs and experimental results (Grelle et al. 2018). However, since the hybrid model is not based on a rigorous physical approach, SiSeRHMap still requires continuous validations and improvements.

Figure 4 shows the computational steps of the SiSeRHMap model. Additional and more detailed information is reported in Grelle et al. (2016), while the complete flow chart of the methodology is available on the website: <https://www.geosmartapp.it>. In the GIS Cubic Model, the shear wave velocity, V_s , for each layer of the soil deposit is assumed increasing with depth following a log-linear law:

$$V_s(z) = V_0 + \alpha \ln(1 + z) \quad (1)$$

V_s is assumed constant ($\alpha=0$) for the intact bedrock; for the overlying degraded bedrock, V_s is assumed to have a linear depth-depending law until it reaches a given value that defines the intact bedrock.

Fig. 4 Flow data of SiSeRHMap computational methodology processing: Module 0 is the preparatory module for combining the litho-dynamic units in zones (optional tool); Module 1, Vs-depth characterization of the litho-dynamic units; Module 2, GIS Cubic Model building and random Vs profiles selection for 1D seismic response computation; Module 3, 1D seismic response computation producing the target seismic response spectra; Module 4, training of the metamodel on target spectra; Module 5; (1) grid metamodeling solving to produce the map set of stratigraphic response, (2) solving TAF model for developing the map set of topographic aggravation factors, (3) developing maps-set of seismic response, (4) developing Housner Intensity maps

An assigned number of 1D Vs-depth profiles is selected in each different zone of the study area by using the uniform probability technique and response spectra are computed by applying the equivalent linear approach in a total stress condition. The normalized shear modulus (G/G_0) and damping ratio (D) curves versus shear strain (γ) were derived from laboratory experimental data for each lithodynamic unit. The fitting process is performed by using the robust nonlinear least squares regression algorithm of Levenberg–Marquardt (Levenberg 1944; Marquardt 1963). The convergence solution is obtained by iteratively solving the following equations, introduced by Yokota et al. (1981), for normalized shear modulus and damping ratio, respectively:

$$\frac{G}{G_0} = \frac{1}{1 + \alpha \gamma^\beta} \quad (2)$$

$$D[\%] = D \exp\left(-\lambda \frac{G}{G_0}\right)_{\max} \quad (3)$$

where G_0 is the initial shear modulus; α , β , $D_{\max}$ and λ are the material constants obtained from the best fit of the experimental data-target.

The response spectra computed by assuming one or more input motions become the targets used in the metamodel training process. This is performed by means of an evolutionary algorithm based on the elitist proliferation of solutions up to converging at the best minimum error. Subsequently, a final best optimization is also performed by using the Levenberg–Marquardt algorithm (Levenberg 1944; Marquardt 1963). After the training processes, multi-spectral maps are drawn up over the whole area, by resolving the trained metamodel in the GCM using discretized periods. A number of discretized periods T defines the number of spectral maps starting from the PGA map ($T=0.001$ s). Significant additional information regarding the linear-equivalent model and computation of the acceleration response spectra as well as the dedicated evolutionary algorithm for the metamodel training process are provided in Grelle et al. (2016)—Appendix A and B.

With regards to the topographic effect, the Topographic Aggravation Factor map values are computed by resolving a “grey box model”, which is frequency and Digital Elevation Model (DEM) parameter dependent. The model is defined by two non-linear functions that are composed to fit the solution of the theoretical bi-dimensional Geli’s half relief, which is regular in shape and uniform in the constituting material. The two functions are respectively solved on the slope and on the ridge sector by using as inputs the DEM and its derived parameters: slope and curvature digital map values.

The curvature is the key parameter; it takes into account the influence of the whole 3D-surface of the reliefs. The curvature values are considered as the enveloping parameters of the topographic surface so that their smoothing is related to the discretized wavelength values λ of the harmonic wave series (Maufroy et al. 2012). Therefore, the TAF maps are computed for each period (frequency) by assuming the shear wave value V_{SR} associated with the uniform relief model (Grelle et al. 2018). At present, the model takes into account only positive values of the curvature. Hence, it is capable of detecting only $TAF \geq 1.0$.

Since the 3D surface curvature values always refer to the smallest radius (greatest curvature), the computed TAF value is the largest possible at each point of the map and for each vibration period and it refers to the direction along which the topographic surface has the greatest slope. The TAF model was tested and calibrated on the 3D-numerical results presented in Maufroy et al. (2012) and regarding the complex Albion mountain area (France). The 3D numerical model presented in the paper is constituted by

uniform material with different seismic sources at the base and, consequently, different incident angles of the seismic rays respect to the topographic surface. Following the calibration, the TAF values computed by SiSeRHMap fall into the third quartile of the distribution of the numerical results. Validation analyses were also performed on the cases of the Narni hill (Italy) (Grelle et al. 2016) here a better performance of the model on experimental data is shown respect the 2D, East Mountain (Utah, USA) and Port Au Prince (Haiti) (Grelle et al. 2018). This latter suggests that the best performance of the model occurs when the equivalent shear wave velocity of the relief, V_{S_R} , is defined as follows:

$$V_{S_R} = \frac{\sum_{i=1}^n h_i}{\sum_{i=1}^n \frac{h_i}{V_{S_i}}} \quad (4)$$

where h_i and V_{S_i} are respectively the thickness and the shear wave velocity of a generic i -layer in the subsoil series.

In addition, the new version of the code provides at each point of the map the amplification factor, $F_a(\Delta T, \xi)$, based on the definition of the Housner intensity (Housner 1952) and calculated for a certain interval of the vibration period ($\Delta T = T_2 - T_1$). It is defined as follows:

$$F_a(\Delta T, \xi) = \frac{\int_{T_1}^{T_2} PSV(T, \xi)_{OUT} dT}{\int_{T_1}^{T_2} PSV(T, \xi)_{IN} dT} \quad (5)$$

where subscripts 'IN' and 'OUT' refer to input and output respectively, PSV is the damped pseudo-velocity response spectrum, T is the period and ξ is the damping ratio.

INPUT and OUTPUT data set and data-maps regarding the SiSeRHMap analyses are stored following the order of the computational modules shown in Fig. 4 in two folders (named as Step1-reliability and Step2-simulation) available at the following link: <https://www.geosmartapp.it/siserhmap-analyzed-cases/> or in supplementary files that accompany this paper.

3.2 D-FEM

2D ground response analyses were performed in the study area by means of the LSR2D (STACEC 2017) computer program. It implements the Finite Element Method and performs total stress analyses in the time domain by applying the equivalent linear approach. The analysis domain was subdivided into triangular elements to better define morphological and topographic irregularities and boundaries. To allow the transfer of the highest frequency, f_{max} , of the input motion that can be considered significant (usually 20 Hz), the maximum dimension Δh of the triangular finite elements within each soil layer was assumed according to the following relationship (Kuhlemeyer and Lysmer 1973):

$$\Delta h = \frac{V_S}{8 \cdot f_{max}} \quad (7)$$

where V_S is the S-wave velocity within the layer. By way of example, Fig. 5 shows the finite element mesh for a portion of the analyzed cross section CC' (Fig. 6).

Fig. 5 FEM mesh for a portion of DD' cross section (Fig. 3). The different filling colours relate to the quality of meshing (red for poor quality to dark green for excellent quality). The red box highlights the free-field conditions imposed at the lateral boundaries

The LSR2D (STACEC 2017) code takes into account the same physical and mechanical properties for all the elements within the same layer and performs the analysis by solving the equation system:

$$[M] \cdot \{\ddot{u}\} + [C] \cdot \{\dot{u}\} + [K] \cdot \{u\} = \{R(t)\} \quad (8)$$

where $[M]$ is the mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, $\{R(t)\}$ is the seismic input motion vector and $\{\ddot{u}\}$, $\{\dot{u}\}$, $\{u\}$ are acceleration, velocity and displacement vectors, respectively.

The non-linear hysteretic behaviour of soils is modelled by using an equivalent-linear approach. The seismic input motion consisting of vertically incident SV shear waves and P compression waves is applied simultaneously to all the nodes at the base boundary of the analysis domain and the equation system is solved in the time domain using the constant average acceleration (CAA) method. Different constraint conditions can be assumed at the side boundary nodes.

In this study, free-field conditions were chosen at the side boundary nodes by connecting them to a free-field soil column by means of normal and tangential viscous dampers (Fig. 5). This permitted avoiding the presence of waves reflected from the side boundaries within the analysis domain.

4 Geotechnical modelling and processing

The multilayering geotechnical model (Fig. 6) of the subsoil sequence involved a regular area of 594×705 m (about 0.42 km^2) centred on the Red Zone of Amatrice. This model was built in a semi-automatic way by using the pre-processing module used to combine spatially the litho-dynamic units (LU) in SiSeRHMap. The module allowed to obtain the GIS Cubic Model (GCM) (Grelle et al. 2014) for the study area from the spatial interpolation of the thickness layer values associated to point and linear geo-information features. These features contain both data from direct measurements as well as data inferred from the geological interpretation. The former mainly relate to feature points and were derived from inversion analyses to achieve the V_s -thickness profile, while the latter concern linear elements representing the extension limits of the different LUs. These limits match the structural and depositional borders deriving from site

Fig. 6 Multilayer representation from the GIS Cubic Model of SiSeRHMap: raster-maps on the left and bottom show the thickness distributions of the lithodynamic units; the top right raster-map shows the Zone distribution obtained combining the LU-maps and the traces of the cross sections analysed by FEM (the lithodynamic sequence characterizing each zone is shown below the map)

findings and/or via coherent geological interpretations. Thus, a GCM composed of four zones was developed where each zone was characterized by a specific sequence of lithodynamic units detected in the study area (Fig. 6).

As described in Sect. 2.2, the subsoil material sequence in the Red Zone of Amatrice, is composed of four covering litho-dynamic units (ML-w, AD, SD, CD) overlying a seismic bedrock, ML-h. Stratigraphic features and unit sequences on the five cross sections traced on the map of Fig. 6 are shown in Fig. 15. For the above mentioned units, the shear wave velocity values were measured by means of geophysical surveys; for the coarse sandy alluvial deposits (AD unit) V_s was also estimated by means of empirical correlations (Otha and Goto 1978) from normalized Standard Penetration Test (SPT) measurements (the values can be found in the folder “INPUTVsZ” of the supplementary electronic material provided with this paper).

Figure 7a shows for each lithological unit the experimental V_s values versus depth and the corresponding best fitting curve defined by Eq. (1). The root mean square error (RMSE) is lower than 20% for the covering materials. The shear wave velocity of 1100 m/s associated to the bedrock (ML-h) is close to the average value detected at the base of the seismo-stratigraphic sequence in the HVSr-MASW inversion analyses.

From the topographic profile and from the depth grid-values of the lithodynamic units provided by the GIS Cubic Model of the Red Zone, five bi-dimensional models (AA', BB', CC', DD' and EE' cross sections) were obtained assuming a linear sampling value of 10 m (Fig. 6). They were used for the comparative analyses performed with both SiSeRHMap and 2D-FEM models. For this purpose, each lithological unit was characterized in terms of density (ρ), shear waves velocity (V_s), Poisson ratio (ν), damping ratio (D) and normalized shear modulus (G/G_0) curves versus shear strain (γ). The main physical and mechanical properties assumed in the computational analyses are summarized in Table 1.

Fig. 7 a V_s -depth distribution attributed to each Lithodynamic Unit and corresponding calibrated regression law. b Strain depending curves of normalized shear modulus and damping ratio assumed for each LU

Table 1 Average physical and mechanical soil properties of the Lithodynamic Units (LU) considered for the computational analyses

L.U	ρ (kg/m ³)	V_s (m/s)	V_p (m/s)	ν (–)	D_0 (%)
SD	1800	250	520	0.35	2.20
CD	1800	260	485	0.30	2.14
AD	2000	380	710	0.30	1.00
ML-w	2100	580	1085	0.30	0.50
ML-h	2300	1100	1905	0.25	0.50

The normalized shear modulus and damping ratio curves are shown in Fig. 7b. The curves of CD and SD Units were obtained from Resonant Column (RC) tests, which were performed by the Geotechnical Laboratory of the University of Florence on three undisturbed soil samples (two from the CD units and one from the SD Units). These samples were taken from boreholes at two sites located in the hamlets of Saletta and Sommati within the municipality of Amatrice where the same Units were encountered. The curves $G(\gamma)/G_0$ and $D(\gamma)$ proposed by Modoni and Gazzellone (2010) were assumed for the lithological Unit AD, while the curve proposed for Yellow and Green Tuff (de Silva et al. 2015) was assumed for ML-w and ML-h lithological Units.

5 Analyses

5.1 Input motions and analysis steps

In order to evaluate the seismic site effects on Amatrice hill, two main steps were followed: first, the reliability of the input model adopted was evaluated, and secondly, the ability of the two computational methods selected for predicting the seismic effects on Amatrice hill were tested and compared. A preliminary comparison analysis was performed to check the congruence of the 1D fundamental frequency vibration distribution of the pseudo-3D parameterized subsoil model obtained by using SiSeRHMap with the experimental data.

This comparative analysis was aimed to evaluate the reliability of the input parameterization model as well as the simulate/predictive ability of the two computational methods used. For this purpose, two ground motion sets were used both as inputs and comparison targets. They include the strongest events among the weak-earthquakes (Table 2) that were recorded simultaneously at different accelerometric station: T1299 station of the Italian Strong Motion Network installed by National Civil Protection Department (DPC) and the mobile stations SUOR, ROMA, MONU installed permanently at the top of the hill during the Round 1 and Round 2 time periods (Table 3).

By using the subsoil input model tested in the first step, the simulation performed in the second step had the aim to estimate the seismic site effects that may have occurred during the 24th August earthquake. With regards to this last analysis, other strong motions of the 2016–2017 seismic sequence recorded at the permanent AMT station of the DPC network (Fig. 6) were considered for the validation (Table 3).

Once the pseudo-3D parameterized subsoil model was defined according to the GCM model, two different subsequent simulation steps were performed by using both SiSeRHMap and LSR2D software. Hereinafter, they will be referred as “Model Reliability” and “Simulation of 24th August event”, respectively. The input motions used for the two

Table 2 Main parameters of the seismic events used in the simulation analyses; the first set refers to the strong motions, the second and third sets refer to the weak motions

Earthquake ID	Type	Station	M_w	PGA_{NS} (m/s ²)	PGA_{EW} (m/s ²)
M1-EMSC-20160824_0000006	SM (strong motion)	AMT	6.0	3.68	8.53
M2-EMSC-20161026_0000077	SM	AMT	5.4	0.60	0.89
M3-EMSC-20161026_0000095	SM	AMT	5.9	0.59	0.91
M4-EMSC-20161030_0000029	SM	AMT	6.5	3.94	5.24
M4-EMSC-20161030_0000029	SM	T1299	6.5	4.37	4.45
M5-EMSC-20170118_0000027	SM	AMT	5.1	3.56	1.97
M6-EMSC-20170118_0000034	SM	AMT	5.5	3.20	3.07
M7-EMSC-20170118_0000037	SM	AMT	5.4	1.15	1.56
M8-EMSC-20170118_0000119	SM	AMT	5.0	0.49	0.57
088	WM1 (weak-motion of Round 1)	T1299	3.2	0.06	0.04
088	WM1	SUOR	3.2	0.10	0.05
089	WM1	T1299	3.2	0.16	0.11
089	WM1	SUOR	3.2	0.26	0.12
092	WM1	T1299	3.4	0.03	0.02
092	WM1	SUOR	3.4	0.08	0.06
094	WM1	T1299	3.4	0.28	0.21
094	WM1	SUOR	3.4	0.43	0.70
106	WM1	T1299	3.9	0.04	0.04
106	WM1	SUOR	3.9	0.18	0.15
110	WM1	T1299	3.5	0.02	0.03
110	WM1	SUOR	3.5	0.08	0.05
111	WM1	T1299	3.5	0.01	0.02
111	WM1	SUOR	3.5	0.06	0.03
113	WM1	T1299	3.2	0.08	0.07
113	WM1	SUOR	3.2	0.22	0.36
116	WM1	T1299	3.2	0.02	0.02
116	WM1	SUOR	3.2	0.04	0.02
004	WM2 (weak-motion of Round 2)	T1299	3.3	0.01	0.01
004	WM2	ROMA	3.3	0.04	0.02
004	WM2	MONU	3.3	0.01	0.02
011	WM2	T1299	3.3	0.01	0.01
011	WM2	ROMA	3.3	0.05	0.04
011	WM2	MONU	3.3	0.02	0.02
022	WM2	T1299	3.8	0.03	0.03
022	WM2	ROMA	3.8	0.12	0.09
022	WM2	MONU	3.8	0.06	0.05
027	WM2	T1299	3.2	0.01	0.01
027	WM2	ROMA	3.2	0.01	0.01
027	WM2	MONU	3.2	0.01	0.01
030	WM2	T1299	3.5	0.13	0.05
030	WM2	ROMA	3.5	0.18	0.17
030	WM2	MONU	3.5	0.09	0.08

Table 2 (continued)

Earthquake ID	Type	Station	M_w	PGA_{NS} (m/s ²)	PGA_{EW} (m/s ²)
031	WM2	T1299	3.8	0.42	0.16
031	WM2	ROMA	3.8	0.97	0.67
031	WM2	MONU	3.8	0.39	0.32
032	WM2	T1299	3.6	0.81	0.37
032	WM2	ROMA	3.6	1.36	1.10
032	WM2	MONU	3.6	0.52	0.91
034	WM2	T1299	3.2	0.02	0.01
034	WM2	ROMA	3.2	0.05	0.04
034	WM2	MONU	3.2	0.02	0.02

Table 3 Type of use of the earthquake recordings (rows), with regards to the two steps of the computational analyses (columns): “Input” means “used as input data in the simulation”, “Comparison” means “used in post-processing comparison analysis”, “X” marks the usage

Station	Computational analysis by SiSeRHMap and LSR2D					
	Step 1: Model reliability				Step 2: Simulation of 24th August event	
	Round1		Round 2		Input	Comparison
	Input	Comparison	Input	Comparison		
<i>Experimental analysis</i>						
AMT	–	–	–	–	X	X
T1299	X	X	X	X	–	X
SUOR	–	X	–	–	–	–
ROMA	–	–	–	X	–	–
MONU	–	–	–	X	–	–

simulation steps are different while the geometrical model and the parametrization data are the same. In this regard, it is worth mentioning that SiSeRHMap and 2D-FEM use different V_s distributions. Specifically, 2D-FEM assumes a uniform shear wave velocity value within each subsoil layer while the V_s values vary in SiSeRHMap according to the calibrated regression law shown in Fig. 7a for each lithodynamic unit of the GIS Cubic Model. In addition, in the hybrid model, the bedrock motion varies in each point at the top of the bedrock since the deconvolved motion depends both on the bedrock depth and on soil that lies above it; on the contrary, a uniform motion is assigned at the base of the analysis domain in the 2D-FEM.

Figure 8a shows the locations of the epicentres of the weak earthquakes used both as input motion and as spectral target in the comparison analysis. These events were recorded by T1299 and SUOR stations during Round 1 (nine events), and by T1299, ROMA and MONU stations during Round 2 (eight recordings). With regards to the Round 1 and Round 2 events, the events with the highest moment magnitude, $3.2 < M_w < 3.9$, were selected as input for the analyses of the first step. The other strong ground-motions were recorded at AMT (eight recordings) and T1299 (one recording) sites; they refer to the

Fig. 8 **a** Epicentral distribution of the seismic events summarized in Table 3 (the small and large stars refer to T1299 and AMT station respectively; the red and green stars refer to events of moment magnitude $M_W \geq 3.5$ and $M_W \leq 3.5$, respectively). **b** Location of AMT station (top) and acceleration response spectra of the 24th August 2016 event recorded at AMT (bottom) [the black line is the spectrum of NS waveform obtained on outcropping rock (ML-h) by means of 1D numerical deconvolution analysis for the 1D sequence extracted from GCM falling into zone 4 (Fig. 6)]

strongest earthquakes with moment magnitude $5.0 < M_W < 6.5$ and they were adopted for the analyses of the second step. The epicentre distribution of the weak-earthquakes overlaps the distribution of the strongest earthquakes, and thus they are characterised by similar paths of seismic waves. In this way, it is reasonable to suppose that the regional anisotropic subsoil effects influence the weak- and strong-motions in the same manner, during the wave propagation.

M1, that is the 24th August 2016 event ($M_W = 6.0$, Epicentre = 10 km), was recorded only by the AMT station in the study area. Thus, the input motion on outcropping rock used in the back analyses (Fig. 8b) was obtained by means of 1D numerical deconvolution analysis from the N–S component of the free surface motion recorded at AMT station during the M1 event. In a similar way, other strong events recorded at AMT were used in the subsequent validation analyses. The N–S component was selected as input in order to minimize the influence of the topographic effects prevailing in E–W direction due to the longitudinal elongation in the N–S direction of the small hilly relief. 1D numerical deconvolution analyses were performed using the linear equivalent analysis using the STRADA frequency-domain code (Kottke and Rathje 2008) and assuming the V_s -depth profile extracted from the GCM at the AMT site, where geophysical data used for the GCM developing was also available.

For the sake of brevity, the final results of the first step of the analyses provided by the two computational models are reported with reference only to the hill station sites that were assumed as comparative targets. Concerning the second step of the analyses, the results from numerical ground response performed by 2D-FEM modelling as well as the multispectral maps computed by SiSeRHMap are shown for the whole area under study.

5.2 Preliminary validation by processing

The set of preparatory maps (supplementary files are in the folder: OUTPUT\GISout) includes the fundamental period T_f computed at any x, y point by considering the average shear wave velocity, V_{Si} , associated to each i -layer, L_i , having thickness h_i as follows:

$$T_{f(x,y)} = \frac{4 \sum_{i=1}^n h_{i(x,y)}}{\sum_{i=1}^n h_{i(x,y)} / \sum_{i=1}^n \left(h_{i(x,y)} / V_{Si(x,y)} \right)} \quad (9)$$

The map of the fundamental period T_f (Fig. 9) shows different frequency distribution values at the top of the hill with a shift at the higher frequencies moving towards the edge. In the area close to the middle of the valley, the frequency values tend to decrease.

The fundamental periods obtained from SiSeRHMap by using the low-magnitude events from Round 1 and 2 were compared with the frequency distribution curves obtained from the seismic experimental analysis performed at the temporary and permanent station sites where noise signals were recorded by the velocimetric stations used for Standard (SSR) and Horizontal to Vertical (HVSr) Spectral Ratio analyses.

With regard to the weak earthquakes recorded at the permanent stations T1299, AMT, SUOR, ROMA, and MONU (Fig. 9), the spectral peaks which resulted from SSR and HVSr analyses, show a good agreement with the computed values extracted from the T_f map at SUOR (3.2 Hz) and MONU (2.3 Hz) stations. Conversely, the matching is not very good for ROMA station where the experimental SSR and HVSr curves show peaks in a large spectral interval. However, the computed T_f value equal to 3.5 Hz falls into this interval.

A better performance is highlighted by the comparison between the calculated periods and those obtained from HVSr analyses on noise data acquired by the temporary network seismic station. Particularly, it is possible to observe (Fig. 9) that the computed T_f values show a good agreement with all the experimental peak values detected on the different sites at the top of the hill. Therefore, the site-spectral distribution analysis confirms that a lower frequency of approximately 2 Hz can be attributed to the central portion of the plateau, with a progressive increase up to 3.5–4.0 Hz at the ridge of the steep slopes. In addition, a good agreement is also shown for the HVSr peak of approximately 6.3 Hz at BUCC station close to AMT, where the modelling highlights a thin layer that covers the weak-rock substratum (ML-w) (Zone 4 in Fig. 6).

5.3 Step one: model reliability check

The first step of the procedure consisted of a model reliability check (Fig. 10) that was performed by comparing the results of the computational analysis performed by SiSeRHMap and 2D-FEM with the experimental data obtained from N-S and E-W horizontal components of motion at the hill station sites SUOR, ROMA, and MONU (hereinafter

Fig. 9 **a** Map of the stratigraphic fundamental period computed by SiSeRHMap; **b** HVSR curves obtained at the reference station T1299 (red star in the map) used for the SSR analyses; comparison between T_f values extracted from the map (orange vertical bar) and SSR and HVSR curves obtained at the stations: SUOR (c), ROMA (d), MONU (e) and comparison between T_f values (green vertical bar) extracted from the map and HVSR curves obtained from the stations of a temporary network (yellow labels in the map) (f)

called “control sites”) both expressed in terms of Seismic Response Ratio, SRR, that is the ratio between the pseudo-velocity elastic response spectrum ($\xi=5\%$ of critical damping) calculated at the hill station site and the corresponding spectrum calculated at the site of T1299 station that was assumed as reference station. This assumption was based both on the flat shape of the HVSR curves determined from the recordings and on the low seismic soil impedance contrast detected through the MASW surveys performed at a site close to the station.

Fig. 10 Comparison of seismic response ratio from numerical (SRR) 2D-FEM and SiSeRHMap analyses and from experimental data for both the horizontal components of motion (e-SRR) (graphs in each row). The graph in the bottom row shows decoupled stratigraphic and topographic amplification from SiSeRHMap analyses

At each control site, the computational output data were extracted from the multi-spectral map set developed from the SiSeRHMap analysis and from the results obtained on the cross-sections, which include the control site, analysed by the numerical 2D-FEM

approach. The seismic response is calculated at 1.0-meter depth where the 3D ground motion sensor of the permanent stations was located.

The SRR values calculated from SiSeRHMap and 2D-FEM results are reported in terms of average values computed on nine weak earthquakes. These events have a moment magnitude M_w between 3.2 and 3.9 and were recorded at the T1299 and SUOR stations (Tables 2, 3).

The low values of PGA detected at the control sites, suggest that the strain-induced values computed by the numerical models lie within the strain linear domain. In fact, G/G_0 is always greater than 0.98 in the SiSeRHMap analysis (the reports are in the supplementary files: Step1-reliability\OUTPT\mod3_Seismic_Response\Motionx\Report GGo-D).

With regards to the experimental SRR values (Fig. 10), the different shape between the average spectra of the N–S and E–W components point out directional topographic effects. The difference is greater at the hill edge sites, SUOR and ROMA, than at the hill centre site, MONU. However, both the horizontal components recorded at all the control site stations show peaks at periods 0.3–0.5 s, while peaks at lower periods, around 0.1 s, are also identified at SUOR station with spectral amplitudes from the E–W component greater than those from the N–S component. Moreover, the greatest SRR values derive from recordings at ROMA station. Anyway, both the computational methods show an underestimation at the periods higher than 0.5 s.

The discretized values of SRR extracted at all the control sites from the spectral maps computed by SiSeRHMap show a greater agreement with the experimental values than those computed by the 2D-FEM model. The best agreement between experimental and numerical SRR values occurs at the MONU and SUOR stations. Conversely, at ROMA site, a good agreement can still be found in terms of spectral shape, while SRR values from experimental data, for both the horizontal components, are higher than those from numerical approaches. Particularly, the best performance of SiSeRHMap in capturing the topographic effects is performed for the EW component in SUOR at high frequency (0.1–0.5 s). In this direction, the 2D ground-model is oriented in the manner to define tight secondary relief (cross-section BB' represented in Fig. 15) respect wide hilly promontory (e.g. represented by the cross-section DD'). This effect is also detected by the 2D numerical model with minor performance.

The absolute best performance, on all the investigated spectral interval, is obtained for both the two computational models in comparison to the EW component of MONU (central hilly station). However, for this site control, a high overestimation is shown by all the computation models for the NS component at very low periods (<0.2 s). This seems to be a statistical anomaly encountered in such periods range. The stratigraphic and topographic decoupled analyses of SiSeRHMap (at the bottom of Fig. 10) show a substantial agreement between the peaks and the corresponding vibration periods. Specifically, the best agreement is at the ROMA site with amplitude of approximately 3.5 and a vibration period of approximately 3.0 s. A similar agreement is observed at the edge site of SUOR where the greater TAF values occur at 0.2–0.3 s with SRR aggregate values over 4.0. Conversely, at the central site MONU, a wide TAF peak centred at 0.5 s is observed with a slow decrease at highest periods. Due to the greater thickness of the soft covering material at this site, the maximum stratigraphic amplification shifts to 0.4 s, with a SRR-max value of 2.8. In addition, the minor agreement of SSR from 2D analyses with experimental ratios cannot be explained by the improper orientation of cross-sections with respect to buried and surficial morphological features driving site response. With this regard, the two different cross-sections AA' (longitudinal) and BB' (transversal) considered in SUOR do not show a particular increment in the performance of the 2D numerical model in periods over 0.1 s.

5.4 Step two: response spectral simulation of the 24th August event

By using the parametrized GIS three-dimensional layering model (GCM) validated in step 1 of the procedure, the simulation of the 24th August event was computed using the hybrid model, and the metamodeling process. The emulating performance of the meta-model (Fig. 11) is defined in terms of the Root Mean Squared Error (RMSE) computed on the Seismic Response Ratio within the interval $\approx 0.0\text{--}1.4$ s and it varies from 0.012 (Zone 4) to 0.053 (Zone 2) (reports are in the supplementary files: Step1-reliability\OUTPUT\mod4_Metamodel\Parameters_metamodels\Errorx). The outputs are recomposed in terms of 5% damped spectral acceleration response, S_a (g), at a 2.0 m depth from the topographic surface that can be considered the mean foundation depth in the Red Zone of Amatrice.

Multi-spectral map-sets, each consisting of 15 maps, providing stratigraphic acceleration response spectra (5% of critical damping) and TAF, respectively, were obtained by solving the trained metamodel on the vibration period interval of $\approx 0.0\text{--}1.4$ s discretized by using a sampling interval of 0.1 s. Figure 12 shows maps of stratigraphic seismic response and TAF maps extracted from the broader map-sets. It can be observed that the maximum spectral acceleration values for stratigraphic effects (1D Maps)

Fig. 11. 24th August event simulation analysis—SiSeRHMap training process: Vs-depth (n.20) profiles virtually sampled in each zone by means of computational Module 2 (upper aligned graphs); derived PSA ($\xi=5\%$) (the black spectra are the input motions computed by using a 1D linear equivalent approach by means of the computational Module 3 (middle aligned graphs); performance of the metamodel training on target SRR spectra (bottom aligned graphs)

Fig. 12 SiSerHMap maps for the 24th August event: maps of stratigraphic seismic response (top row) and TAF maps (bottom row). Both sets were extracted from the respective broader map-sets that are composed of 15 maps covering a period range from 0 to 1.4 s with a sampling interval of 0.1 s. Below the TAF maps, the relative average wavelength for the investigated period is shown

are found in zone 1 (Fig. 6) at a vibration frequency of approximately 2.5 Hz (period 0.4 s). The greatest values of TAF fall into the edge ridge sector at a frequency range of 3.0–5.0 Hz (periods 0.2–0.3 s). Diversely, in the lower frequency range, 1.5–2.0 Hz (periods 0.5–0.7 s), the greatest TAF values move towards the central portion of the plateau.

Therefore, the maps of the seismic response, $Sa(g)$, were developed by the convolution of the stratigraphic spectral acceleration map-set and TAF map-set in the same vibration periods (Fig. 13).

The Sa map-set highlights that the greatest values of the spectral accelerations are distributed over the edge-ridge sectors of the hilly promontory. Here, they are defined at low vibration periods, short wavelengths, and with maximums of PGA values. Specifically, values greater than 0.90 g are computed at the SUOR station site and at other sites close to the Hospital building (see companion paper). In addition, significant PGA values are expected at the ridge sector up to the steep slope where the ROMA station is located, as well as at the AMT station. The lowest computed values of PGA (0.33 g) occurred along the foothills of the steep slopes to the west and north of the hill. Higher spectral acceleration values occur moving towards the central portion of the plateau, as the vibration period increases. The maximum spectral value of 2.96 g occurs at a period of 0.4 s and it falls within the sector where the church of St. Francis is located.

Maps of the amplification factor Fa (Eq. 5) relating to three different spectral intervals: 0.1–0.5 s, 0.4–0.8 s, 0.7–1.1 s which commonly include the fundamental periods of different building typologies, are plotted in Fig. 14. It should be noted that most of the buildings in Amatrice's Red Zone fall into the first spectral range (Masi et al. 2016). On the contrary, the ancient towers that were still standing after the 24th August event (see companion paper) fall into the second/third range of the considered range of periods.

Fa maps show that the greatest amplification values (in the range 2.5–3.0) were obtained at the interval period 0.1–0.5 s and they largely occurred at the top of the hill.

Fig. 13 SiSeRHMap maps for the 24th August event: Seismic Response maps (S_a) from combined stratigraphic and topographic effects (5% of the critical damping ratio). Note that a different colour scale is used for the PGA map (top left)

Fig. 14 SiSeRHMap maps for the 24th August event: maps of the amplification factor based on the definition of the Housner intensity (Eq. 5) computed for three different spectral intervals

High values were observed also in the second period range (0.4–0.8 s) in the central zone of the hill, with a maximum of around 2.0 that decreases to 1.5 when the spectral interval of 0.7–1.1 s is considered.

Fig. 15. 2D-color plots for the cross-sections sketched in Fig. 5: computed from 2D-FEM analyses (above colour plot) and extracted from the SiSeRHMap computational maps (below colour plot)

Figure 15 shows the comparison between the seismic ground response assessed by the hybrid and 2D-FEM computational approaches. The comparison highlights that S_a values calculated by the hybrid model are generally greater than those provided by the 2D-FEM approach (approximately 30%) and the differences are greater on the ridge edge sectors rather than on the central area of the hill. Indeed, the greatest S_a values obtained at short vibration periods are mainly due to the topographic effect computed by the hybrid model close to the ridge edges. Conversely, in the central portion of the plateau, the S_a values of both computational models are similar and the maximum values correspond to a period of about 0.4 s. The greatest difference between the two computational models is found along

the longitudinal cross-section AA'. Specifically, the 2D-FEM analysis does not detect high amplification conditions far from the ridge, e.g. at the MONU site. In contrast, the same 2D-FEM model predicts a substantial increase of the S_a values along the transversal sections (e.g. CC' and EE'). The same inconsistency is not revealed by SiSeRHMap which is based on a pseudo-three-dimensional model (GCM) that doesn't depend on an assumed direction. TAF spectral maps are computed in terms of maximum possible values based on the smallest curvature radius of the ground surface, regardless of their local orientation. Consequently, on the two-dimensional longitudinal section AA' of SiSeRHMap maps, the 3D-topographic effect is also included, unlike with regards to the 2D FEM analysis.

5.5 On the observational and computational results at AMT site

The 24th August earthquake and the subsequent strong-motion events recorded at the AMT station allowed to perform a comparative back-analysis between the seismic response predicted by both the hybrid SiSeRHMap method and the 2D-FEM method, and the strong-motion recordings (Fig. 16). Concerning the strong-motion set (Table 2, first set), the 24th August event shows the greatest difference between the PGA values of the two components. This peculiarity was also observed for other recorded strong-motion events coming from north of AMT station, and so it can be attributable to extra-site effects probably due to the combination of source and propagation effects. These aspects and others captured by experimental analysis will be the object of further future studies. Therefore, the comparative analysis focused on the topographic effect considering the average of the strong motions coming from both north and south of AMT. Since it is located on an elongated ridge having a high length/width ratio (approximately six), the topographic effect mostly influences the seismic response in the direction of the transversal axis of the relief that is approximately the EW direction. Thus, it was possible to identify the horizontal topographic effect by evaluating the spectral ratios between the observed EW and NS components and by assuming the topographic effects on the NS component of the motion of minor or no significance. In this way, a better agreement between observational and computational seismic response can be expected in terms of topographic effects at the AMT site. Figure 16 shows a good agreement between the spectral ratios obtained from measurements and numerical results. For this latter, the spectral ratios were computed in terms

Fig. 16 Comparison between EW/NS mean spectral response ratios calculated from the strong motion events (M1 to M8) recorded at the AMT station and the Topographic Aggravation Factor computed via 2D-FEM and SiSeRHMap

of Topographic Aggravation Factor values both from SiSeRHMap and 2D-FEM computational models. Due to the nature of the two computational models, the TAF values were directly computed by SiSeRHMap without taking into account the possible nonlinear effect on the TAF spectral function. In contrast, by using the 2D-FEM analysis, the TAF average value was computed on the EE' section, crossing the site of AMT station, assuming as input the outcropping rock motions obtained by a deconvolution process from the NS components of M1 to M8 strong motions recorded at AMT accelerometric station.

6 Discussion and conclusions

A study of the seismic site effects at the Red Zone of Amatrice village during the 2016–2017 Central Italy seismic sequence was carried out by using experimental and computational approaches. In the comparison analyses, the observational data played a crucial role in reducing the epistemic uncertainties of the input model for numerical analyses as well as in evaluating the reliability and the prediction accuracy of two different computational approaches: a total physical-based two-dimensional finite element method, 2D-FEM, and a new generation three-dimensional model, SiSeRHMap, that is partially physical-based (hybrid) and produces multispectral maps by means of metamodeling processes by using GIS data to build a geometrical model.

A consistent geological and geotechnical subsoil model assumed in the simulation analyses was at first obtained from the computation of several preparatory maps and by the comparison with the observational data in terms of the fundamental period of vibration. Thus, simulation analyses were performed using a set of weak motion recordings as seismic inputs.

The results from the two computational approaches are in agreement with those obtained by means of Standard Spectral Ratio analyses taking T1299 station as reference site. These results confirm the significant role played by the topographic effects on Amatrice hill that were also pointed out by the greater damage to the buildings on the top of Amatrice hill than those located in the valley. Particularly significant is the integrity of the masonry building located near to T1299 station in the valley compared with the severe damage to the building on the top of the hill characterized by the same construction features and age. Moreover, geophysical investigations performed at this site have revealed a rigid subsoil and a substantial absence of spectral amplification/de-amplification peaks.

With regard to computational analyses, the hybrid model showed a higher performance than 2D-FEM in predicting the seismic response of the topographically complex site of Amatrice. This capability prevails on the edge and at the end of the promontory, rather than in the central area of the hill. In addition, the de-coupled stratigraphic and topographic effects computed by the hybrid model allow to observe a significant influence of the 3D-topographic effect on the spectral peaks distributed on the hill. In this regard, although the seismic response maps were obtained following a non-rigorous physical approach, they highlight some important issues regarding the evaluation of the local seismic response. These issues involve the importance of: (1) providing uniform accuracy in the spatial computation (e.g. in contrast with the spatial interpolation of point data results); (2) taking into account the topographic effects (that are not considered by the 1D analyses) and (3) evaluating these effects, regardless of the direction, in complex topographic settings (as does not usually occur in 2D analyses).

Calculated amplification values are maximum in the range of the periods 0.3–0.5 s and they rapidly decrease at higher vibration periods, while the experimental data show significant amplification values also at high periods. This effect could be due to an additional deeper rigid bedrock, although it was not detected by the geophysical surveys.

Regarding the back-simulation of the 24th August event using the validated parameterized subsoil model, the spectral acceleration maps from SiSeRHMap show maximum S_a values of 2.6 g at 0.4 s. Instead, a maximum value of about 2.0 g was obtained from the 2D-FEM analyses, on five cross-sections.

Moreover, the maps of the amplification factor, based on the definition of the Housner intensity, are in agreement with the observed damage distribution. Particularly, the greatest amplification values were distributed throughout the study area and correspond to the interval of low periods, 0.1–0.5 s, which include the fundamental periods of vibration of most of the collapsed structures in the Red Zone of Amatrice. In this regard, severe damages affected also more recent buildings of two and three floors, highlight that the high amplifications occurred in agreement with the aforesaid spectral interval. However, amplification decreases by approximately 50% with reference to the interval of 0.4–0.8 s in the central area of the hill. In this area, the two old municipal towers, which are presumably characterized by a fundamental period falling in this range, suffered minor damage. Finally, the topographic aggravation factor (TAF), computed by both the hybrid and the 2D finite element numerical models at the AMT station site, is in good agreement with the average spectral ratio between the components of the horizontal NS and EW recordings. This ratio, has proved to be a valuable tool for defining the experimental amplitude of the topographic effects for this case study and, consequently, for validating the predictive performance of the two computational models with regard to these effects. However, further comparison showed a significant underestimation of the numerical predicted effects with respect to those observed after the 24th August main shock. Thus, they confirmed the peculiar characteristics of the ground motion induced by this event, especially in the high-frequency interval and along the EW direction.

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