Seismic microzonation of Palatine Hill, Roman Forum and Coliseum (Rome, Italy)

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SUMMARY:
The paper summarizes the results of a multidisciplinary study aimed to seismic microzonation of the Central Archeological Area of Rome including the Palatine hill, Roman Forum and Coliseum. A large amount of subsoil data, available mainly from adjacent subway lines and from the archaeological superintendence, were collected and employed to plan new investigations, carried out in 2010-2011. This survey included continuous-coring boreholes, in situ and laboratory geotechnical tests, MASW, cross and down-hole tests, ambient noise measurements, electrical resistivity tomographies, ground penetrating radar surveys. First, the paper shows the procedure employed to define an integrated subsoil model aimed to numerical modelling of site effects. Representative results of equivalent linear 2D site response analyses carried out on seven representative cross-sections are therefore presented and discussed. Ground motion amplification factors defined in terms of Housner Intensity were computed in different ranges of period to cover the entire range of fundamental vibration periods pertaining to the artefacts and monuments. The contouring of amplification factor values from all the numerical simulations, based on morphological and geological constrains, finally allowed to create microzonation maps.

Keywords: seismic microzonation, site effects, numerical modelling, archaeological area, Rome

1. INTRODUCTION

In 2009, after declaring the state of emergency for the Central Archaeological Area of Rome, the Government Commissioner and the Italian Civil Protection Department (DPC) assigned the Institute of Environmental Geology and Geoengineering (IGAG) of the Italian National Research Council (CNR) to evaluate the geohazard level affecting Palatine Hill, Roman Forum, and Coliseum (Rome, Italy). This area (Fig. 1), covering less than one square kilometer, represents one of the most relevant UNESCO World Heritage Site in the world.
As part of a larger framework agreement between CNR and DPC (UrbiSIT project 2007-2012), research activities started up involving CNR institutes and university departments, and were concluded in February 2011 (Cecchi, 2011). One of the main goals of the research activities was the seismic site effects evaluation and the seismic microzonation of the study area according to the Italian guidelines (ICMS, 2008).
A large amount of subsoil data was already available in the study area mainly from the archaeological superintendence and from the adjacent subway lines. These data were collected, validated, and processed to define a preliminary model of the area and to plan a new multidisciplinary survey carried out in 2010-2011 including continuous-coring boreholes, *in situ* and laboratory geotechnical tests, MASW, cross and down-hole tests, ambient noise measurements, electrical resistivity tomographies, ground penetrating radar surveys. A final subsoil model aimed at site response analyses was built by integrating all the available information.
After a summary of the procedure employed to define the subsoil model, representative results of equivalent linear 2D site response analyses are presented in the paper. Ground motion variations are

discussed considering the main physical phenomena involved. Some representative response spectra computed at selected sites to quantify seismic action for seismic retrofitting purposes are shown. The microzonation maps, drawn on the basis of the contouring of amplification factors defined in terms of Housner intensity, are therefore illustrated. In order to cover the entire range of fundamental vibration periods pertaining to the artefacts and monuments, the maps were drawn in three different ranges of period: 0.1-0.5 s, 0.5-1.0 s and 1.0-2.0 s.

2. INTEGRATED SUBSOIL MODEL

2.1. Morphological and geological outlines

The geological bedrock of Palatine Hill and surrounding areas is constituted by a Pliocene sandy-clayey unit of marine origin, the Monte Vaticano Formation (MVA in figure 1) whose total thickness is about 900 meters. The Quaternary complex, covering with unconformity the Monte Vaticano Formation, is composed of middle Pleistocene fluvial-palustrine and distal volcanic deposits belonging to seven superimposed formations (Fig. 1), from ancient to recent: 1) Santa Cecilia Formation (CIL); 2) Valle Giulia Formation (VGU); 3) Palatine Unit (PTI); 4) Prima Porta Unit (PPT); 5) Fosso del Torrino Formation (FTR); 6) Villa Senni Formation (VSN), with the Tufo Lionato (VSN1) and Pozzolanelle (VSN2) members; 7) Aurelia Formation (AEL). These formations show a sub-horizontal multilayered arrangement except for the Fosso del Torrino Formation (FTR), that fills a fluvial paleo-valley deeply cut into older Quaternary units in the eastern portion of the Palatine Hill (see cross-section A in figure 1). Finally, all the previous units were carved by local streams tributaries of the Tiber River during the late Quaternary sea-level fall, giving rise to deep (up to 70-80 meters) and narrow alluvial valleys, the Velabro, Labicano, and Murcia valleys (Fig. 1), confined by steep slopes joining the hilltop plateau. These valleys were filled mainly with organic rich clayey sediments in response to the Holocene sea level rise (SFTba3 in figure 1). All the area is almost entirely covered by anthropogenic deposits locally reaching the thickness of 20 m.

All the different formations recognized in the study area have been interpreted in terms of lithofacies mainly based on their sedimentological features (Moscatelli et al., 2012). In view of a mechanical characterization of materials, for each formation the lithofacies have been then grouped in lithotypes (see legend in Fig. 1) characterized by homogeneous physical properties (i.e., grain size distribution, void ratio, unit weight) deduced from laboratory geotechnical tests.

2.2. Identification of seismic bedrock

The MVA overconsolidated clays, geological bedrock of the whole Roman area, are characterized by an average shear wave velocity of about 500 m/s in the upper tens of meters, directly investigated by geophysical tests. This values is smaller than 800 m/s usually assumed as seismic bedrock for site response analyses. In order to identify the depth of seismic bedrock a noise measurements campaign was undertaken aimed to explore the possibility of a deep seismic bedrock. In ten selected sites covering the whole area, microtremor measurements were executed and processed according to SESAME (2004) criteria using a three-component Lennartz velocity transducer (LE3D-5 s) equipped with Marslite (20-bit A/D converter) and SL06 (24-bit A/D converter) data loggers. The HVSR curves show in the whole area a clear peak around 0.3-0.35 Hz (Fig. 2a), thus suggesting the presence of a several hundred meters deep seismic bedrock. Moreover, 1D parametric site response analyses were conducted in the Basilica of Massentius site (see BM in Fig. 1), where both microtremors measurement and 45 m-depth cross-hole test were carried out. Different V_S gradients and seismic bedrock depths were hypothesized (Fig. 2c) taking into account the following aspects: i) all noise measurements show a fundamental resonance frequency f_0 in the range 0.3-0.35 Hz; ii) a very deep borehole drilled in the Circus Maximus (see CM in Fig. 1) the entire thickness of MVA, approximately 900 m, intercepting the passage between the overlying clayey lithotype and the underlying sandy clayey lithotype at about 560 m from the surface (Signorini, 1939); iii) V_S gradient with depth showed in deep in-hole tests carried out in highly overconsolidated soils is generally limited.

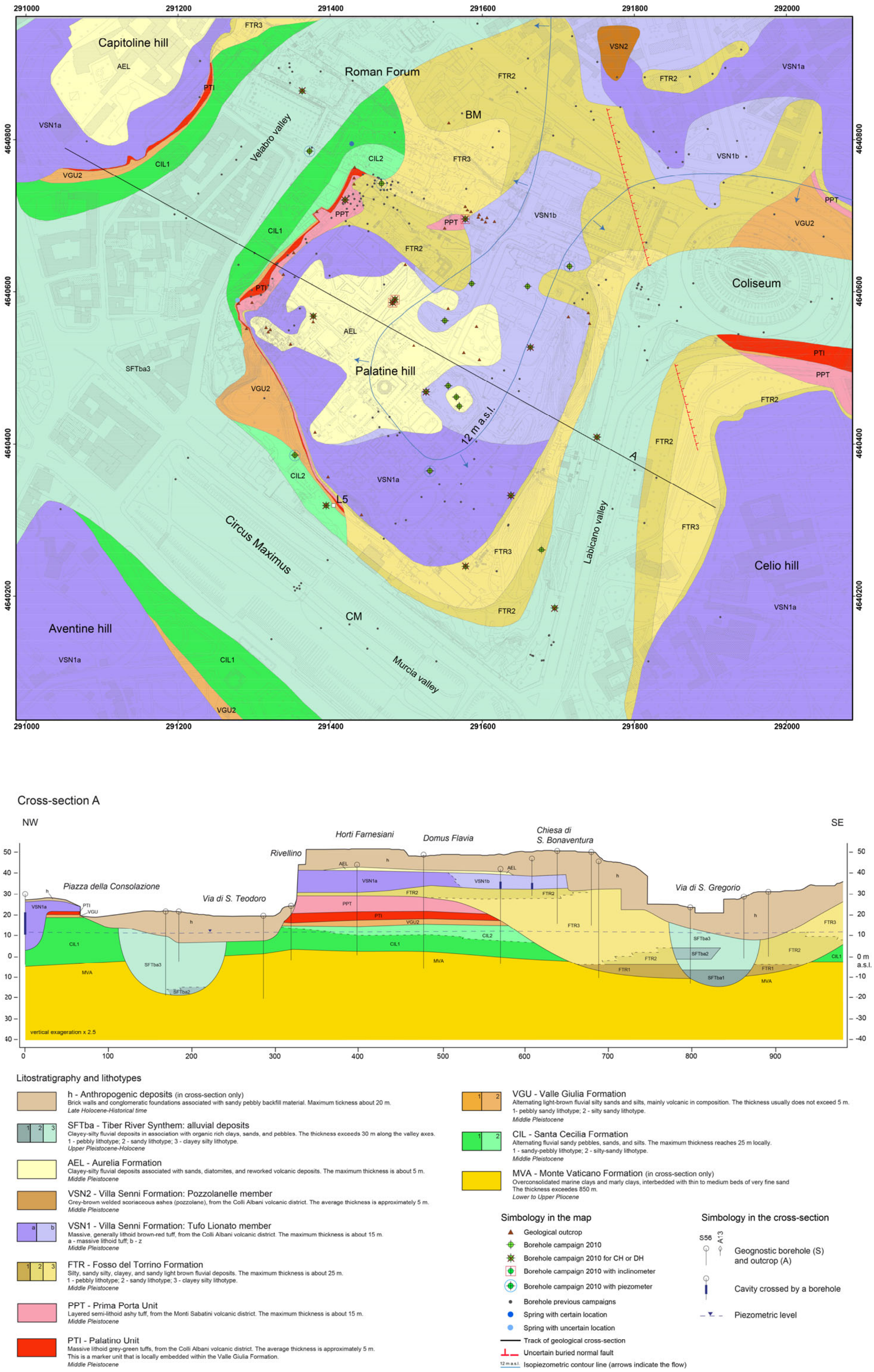


Figure 1. Geological map (above) and cross-section A (below) of the Palatine Hill and surrounding areas; BM=location of the Basilica of Massentius borehole, CM= location of the Circus Maximus borehole, L5=representative Lennartz noise measurement.

Analyses were carried out with the computer code Proshake (EduPro Civil System, 1998) assuming for the soil a linear visco-elastic behaviour. The damping was set equal to 2% for cover lithotypes (h, FTR1, FTR2) and equal to 1.5% for MVA clays according to available cyclic tests. For the cover lithotypes the V_S values were deduced from cross-hole tests. The numerical transfer function best matching the experimental fundamental frequency f_0 (0.30-0.35 Hz) is represented as bold line in figure 2b. The corresponding MVA V_S profile is also shown in figure 2c as bold line. According to this gradient, assumed in the subsoil model for the site response analyses, the V_S attains an average values of 550 m/s in the upper 200 m, 600 m/s in the following 200 m and 650 m/s in the lower 100 m of MVA; the value ≥ 800 m/s is achieved at 500 m from the top of MVA, about -530 m a.s.l.

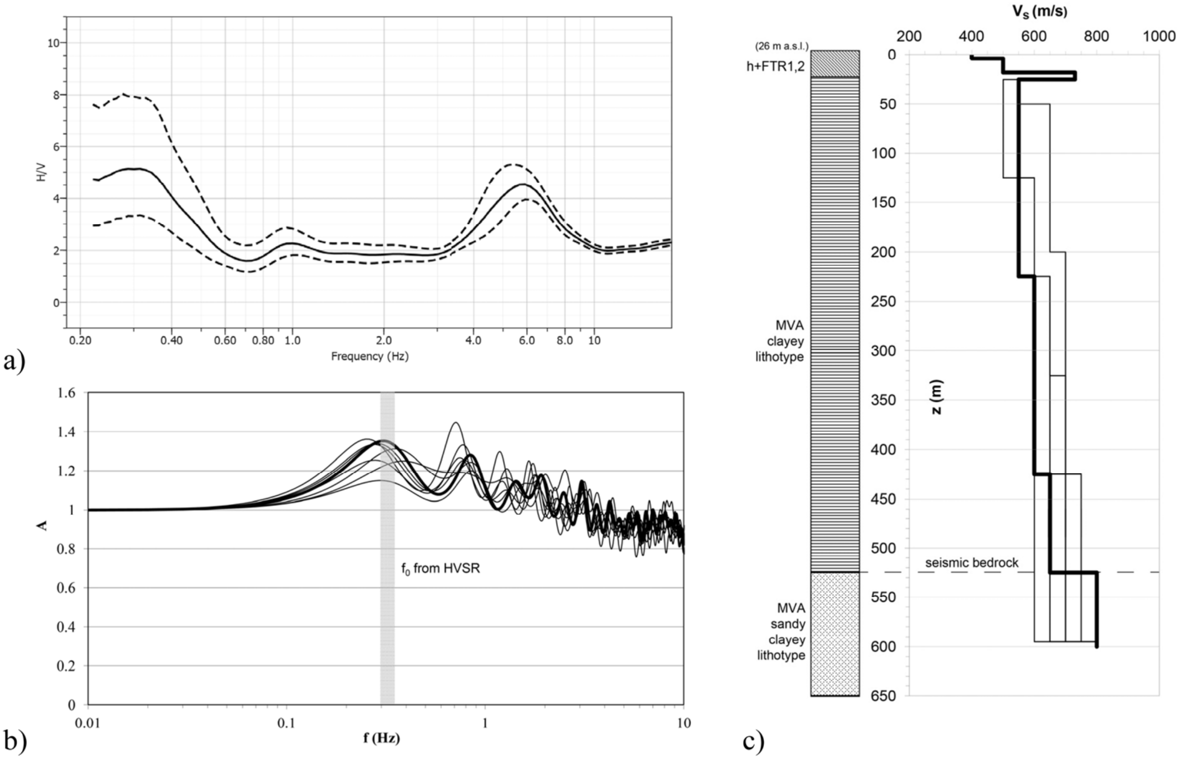


Figure 2. a) Representative HVSR measurement, see L5 on figure 1 for location; b) comparison between amplification function from 1D parametric analyses and experimental f_0, c) V_S gradients and seismic bedrock depths assumed in the MVA Formation for 1D parametric analyses at the Basilica of Massentius site

2.3. Geophysical and geotechnical characterization

The seismic response analyses adopt the traditional visco-elastic linear-equivalent approach; therefore, the subsoil numerical model requires the characterization of each unit in terms of unit weight (γ), shear wave velocity (V_S), compression wave velocity (V_P) or, similarly, Poisson ratio (ν) and the variation of normalized shear modulus (G/G_0) and damping ratio (D) with shear strain amplitude (γ_c). The S-wave velocity were determined from a total of 17 cross-hole tests, 11 down-hole tests, 3 seismic dilatometer tests and 20 MASW tests available from previous and 2010 surveys. In general, the results of geophysical tests showed that the area is characterized by substantial spatial uniformity of the geophysical parameters related to the same lithotype (Pagliaroli et al. 2011a). Each lithotype was characterized by averaging V_S and ν throughout the different depth ranges explored. A constant value of the geophysical parameters with depth was assumed with exception of the anthropogenic layer (h) and the MVA for which a V_S gradient with depth was defined. For h the gradient was derived by interpolating all available measurement points while for MVA a V_S trend was deduced by reproducing with 1D analyses the experimental site fundamental frequency as described in the previous paragraph.
The normalized shear modulus $G(\gamma_c)/G_0$ and damping ratio $D(\gamma_c)$ curves were measured from a total of 20 resonant column and 2 cyclic torsional shear tests available from previous surveys, integrated with

the results of 12 cyclic simple shear tests carried out with DSDSS apparatus (D'Elia et al., 2003; Pagliaroli et al. 2011a) in 2010-2011 aimed at the characterization of all lithotypes, with particular attention to those not investigated by previous surveys (mainly organic clays SFTb3 and tuffs PTI-PPT-VSN1a). For gravelly soils (CIL1, FTR1 and SFTba1) for which undisturbed sampling was not possible, reference was made to literature data obtained on similar materials. In particular, the results obtained by Hatanaka et al. (1988), which refer to gravels characterized by a granulometric distribution similar to the soils under exam here, were considered. The same curves have been used for the anthropogenic layer (h), given the prevalence of coarse material. Where multiple laboratory determinations for the same lithotype were available, the average $G(\gamma_c)/G_0$ and $D(\gamma_c)$ curves have been selected. Only for MVA clay, considering the high thickness of the formation, the curves obtained with the DSDSS for the highest confining pressure applicable (σ'_v=1600 kPa) were preferred.
Finally the lithotypes were grouped into sets characterized by homogeneous values of the properties relevant for site response analyses: γ, V_S, ν and $G(\gamma_c)/G_0$ and $D(\gamma_c)$ curves (Table 2 and Fig. 3).

Table 2. Integrated subsoil model for site response analyses (* gradient with depth)

Lithotype	**γ (kN/m^3)**	**V_S (m/s)**	**ν(-)**
h	18.0	VS=185z0.31	0.42
hm	19.0	530	0.40
SFTba2,3	18.5	270	0.49
SFTba1	20.0	590	0.46
VSN1a	16.0	600	0.40
PTI-PPT	16.0	650	0.39
FTR2,3-VGU2-VSN1b-CIL2	19.7	340	0.48
VGU1	20.0	390	0.42
FTR1	20.5	680	0.45
CIL1	20.5	620	0.39
MVA	20.5	550-650*	0.48
Seismic bedrock	22.0	800	0.46

3. SELECTION OF INPUT MOTION

At least six times the macroseismic intensity in Rome reached VII MCS (Galli and Molin, 2012). Rome is affected by earthquakes associated to three different seismogenic districts: 1) the seismogenetic structures of the Central Apennine mountain chain (about 90-130 km east of Rome) responsible for magnitude M up to 6.7-7.0; 2) the Colli Albani volcanic area 20 km south (M=5.5); 3) the Roman area (inside the beltway, i.e. the *Grande Raccordo Anulare*) characterized by shallow rare low magnitude events (Fig. 4a). Historical sources indicate that Roman monumental buildings have been damaged almost exclusively by Apennine seismic events (Galli and Molin, 2012).
In order to evaluate the seismic input for site response analyses aimed at the microzonation of the Palatine Hill, Roman Forum and Coliseum Archeological Area, two approaches were followed: probabilistic and deterministic seismic hazard assessments. For the probabilistic approach, different uniform hazard spectra (UHS) were considered, among which the one from the 2004 INGV hazard map for a return period of 475 years and rock site condition. It should be remarked that this spectrum correspond to the Italian National Code spectrum, being the *Norme Tecniche per le Costruzioni* (NTC-08, i.e. the Italian Building Code) based on the INGV hazard assessment. The INGV UHS spectrum was used to simulate a spectrum-compatible time-history acceleration.
For the deterministic approach, two earthquake scenario were selected: 1) an earthquake representative of the moderate seismicity of the Colli Albani volcanic complex, with Mw=5.5 and epicentral distance R=20 km; 2) an earthquake representative of the high seismicity of the Fucino basin source (Mw=7.0, R=85 km). The acceleration response spectra of these earthquake scenarios were calculated with the Sabetta and Pugliese (1996) (SP96) ground motion prediction equation (Fig. 4) with reference to outcropping rock. Non-stationary accelerograms were therefore simulated for the two earthquake scenarios to be compatible with the reference spectra. Moreover, following the deterministic approach, the accelerograms recorded at Torre del Greco (1980 Irpinia earthquake) and at Assisi (1997 Umbria-Marche earthquake) were selected for Fucino and Colli Albani scenarios, respectively (Fig. 4).

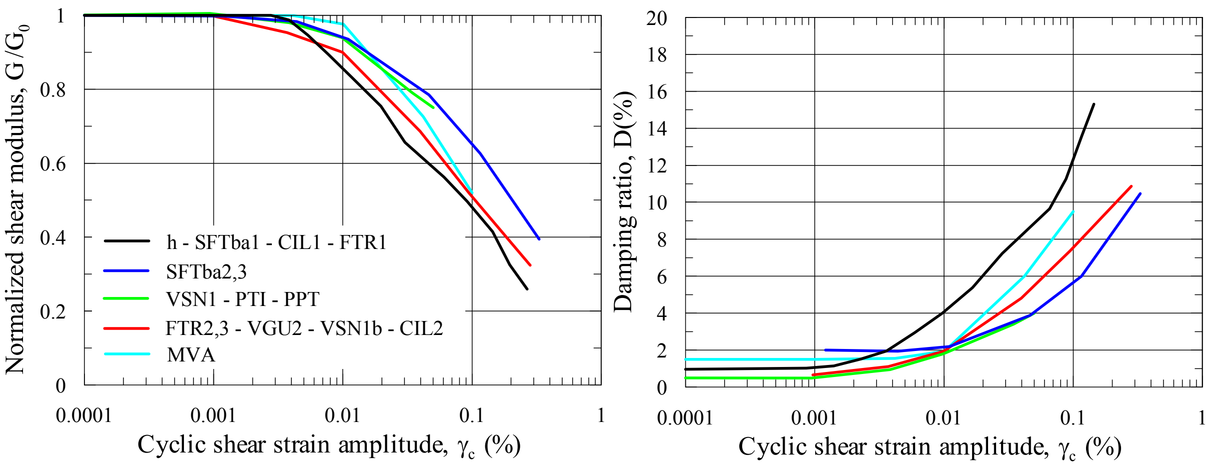
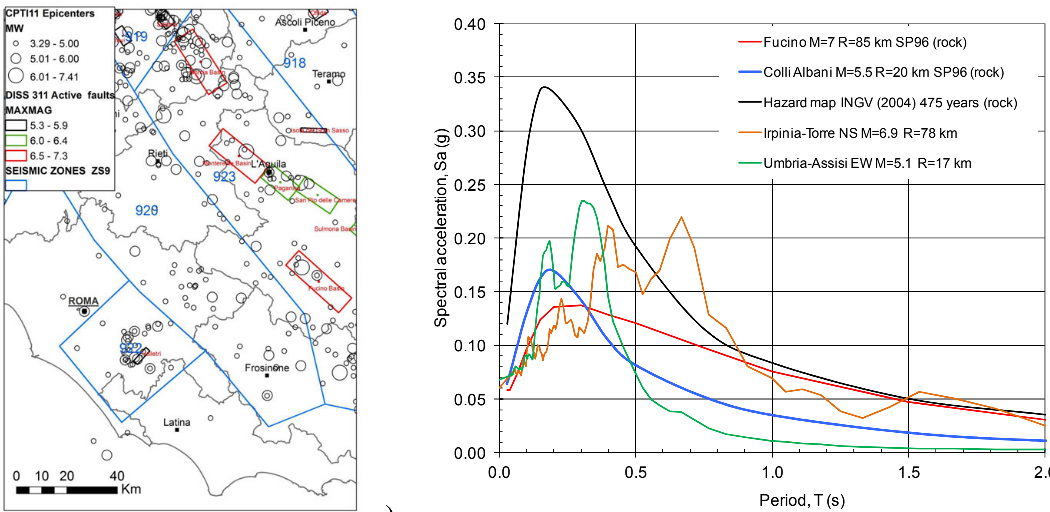


Figure 3. $G(\gamma_c)/G_0$ and $D(\gamma_c)$ curves selected for each lithotype and assumed for site response analyses.

Ultimately, five acceleration time histories were selected as input motion: three artificial signal compatible with INGV 2004, Fucino basin and Colli Albani spectra respectively, and two natural accelerograms. As microzonation is a planning tool focused at the prevention of damage that can occur due to future earthquakes having different magnitudes and/or distance from site, the probabilistic approach allowing to reconstruction of an equi-probable spectrum combining a series of earthquakes that can affect, to different degrees, the study site, is preferable. Moreover, the reference to a specific value of the return period is particular useful as the analyses were also aimed at computing response spectra to be employed for seismic retrofitting of monuments and artefacts. The INGV 2004 UHS was therefore employed as reference spectrum.

4. REPRESENTATIVE SITE RESPONSE ANALYSES

In order to define a seismic microzonation map of the Palatine hill and surroundings, 2D numerical analyses were executed with the equivalent linear finite element code QUAD4M (Hudson et al. 1994) on seven cross-sections representative of the geological and morphological settings of the area. Numerical results were processed in terms of Peak Ground Acceleration (PGA) and Housner Intensity (HI), computed at cross-section surface with reference to horizontal component. In order to cover all the range of fundamental vibration periods pertaining to the monuments present in the archaeological area, HI was computed in 3 ranges of period: 0.1-0.5 s, 0.5-1.0 s e 1.0-2.0 s. The corresponding amplification factors profiles ($FH_{0.1\text{-}0.5s}$, $FH_{0.5\text{-}1.0s}$ and $FH_{1.0\text{-}2.0s}$) were therefore calculated by taking the ratio between HI computed at surface and the corresponding HI of the input motion.



a) b)

Figure 4. Seismicity affecting Rome (a) and reference spectra selected for the microzonation (b)

In the following the analyses are showed for INGV 475 years input motion with reference to section A (Fig. 1) considered as representative of the main geomorphological features of the area.
PGA and FH amplification factors for section A are reported in figure 5a,b. On Palatine hilltop plateau, PGA profile shows minor fluctuations indicating limited two-dimensional effects, slightly increasing proceeding towards the SE (on average from 0.12 to 0.14g). On the contrary, in correspondence of the hill toe and Labicano and Velabro alluvial valleys (SFTba2,3), 2D effects associated to topography and buried morphology, respectively, give rise to significant spatial variations of the PGA: at the valley centre PGA reaches values up to 0.16g while at the hill toe PGA values less than 0.1g are attained. Ground motion amplification in the alluvial valleys is related to the impedance contrast between the soft layer constituted by alluvial clays and sands (SFTba2,3) and anthropogenic deposit (h) and the underlying stiff soils (MVA overconsolidated clays and CIL1-FTR1 gravels). The 2D amplification function computed at Velabro Valley centre (node 2A in Fig. 5c) shows two clear amplification peaks at 2 Hz and 3.6 Hz. The first one corresponds to the 1D fundamental frequency (f_{01D}) of the entire SFTba2,3-h layer while the second one satisfactorily matches the 2D alluvial valley resonance frequency computed according to the formula proposed by Bard and Bouchon (1985) for SV wave incidence as function of geometric (shape ratio) and mechanical properties of the valley. The 3.6 Hz peak is not present in Labicano Valley (nodes 2F and 2G in Fig. 5c) characterised by an essentially 1D response (f_{01D}=2 H, see Fig. 5c). This is because the 2D resonance probably does not occur for this valley which is characterised by a smaller impendence contrast with respect to the Velabro one (CIL1 gravels are missing, see Fig 1). The low PGA values computed at the hill toe can be ascribed to deamplification topographic effects as usually observed in many experimental and numerical studies (Pagliaroli et al., 2011b).
The amplification factor $FH_{0.1\text{-}0.5s}$ is almost constant on Palatine hilltop plateau (1.15 on average). No appreciable differences can be observed between NW (multilayered deposit) and SE (FTR paleo-valley) sectors. Higher values (1.4-1.6) are reached in correspondence of Labicano and Velabro valleys while significant deamplification does occur at hill toe especially on NW sector (San Teodoro street). Since this factor quantifies the amplifications occurring mainly in the medium to high frequency range (2-10 Hz), the causes of ground motion modification can be essentially ascribed to the same physical phenomena responsible for changes in the PGA and previously discussed.
The amplification factor $FH_{0.5\text{-}1.0s}$ (frequency range 1-2 Hz) is characterized by a maximum (1.6-1.7) reached in correspondence of FTR paleo-valley. The thickness of fluvial filling deposit together with the overlying anthropogenic layer reaches more than 50 m. Considering an average V_S of about 300 m/s, a fundamental 1D resonance frequency f_{01D}=1.4 Hz can be estimated (see node 2E in Fig. 5c). Moreover, at the NW valley edge the ground motion is probably further increased in amplitude and/or duration by 2D effects (interference by direct SV waves and diffracted Rayleigh waves). Considering the valley shape ratio together with the mechanical properties, 2D resonance can be excluded. Lower values of $FH_{0.5\text{-}1.0s}$ are achieved in the alluvial valleys that enhance higher frequencies.
Finally, the factor $FH_{1.0\text{-}2.0s}$ shows minor fluctuations in all the area with limited amplification phenomena (1.2) only in the NW portion of the FTR paleo-valley.
As stated in the introduction, acceleration response spectra were computed in about 50 selected sites and monuments in order to quantify seismic action for seismic retrofitting. Response spectra computed at nodes 2A-2G along section A surface are shown in Fig. 5d together with the Italian code spectra (NTC-08) associated to the corresponding subsoil conditions: class A (outcropping rock input motion), class B (nodes 2B and 2C) and class C (nodes 2A, 2D, 2E, 2F and 2G). The numerical analyses generally lead to a reduction of seismic action with respect to NTC-08.

5. MICROZONATION MAPS

As said before, 2D numerical analyses were carried out on seven cross-sections, three oriented NW-SE, three SW-NE and one in correspondence of Coliseum. For each period range a microzonation map in terms of FH amplification factor was produced according to the following methodology: i) the range of FH was divided into windows of fixed amplitude (0.2 for $FH_{0.1\text{-}0.5s}$ and $FH_{0.5\text{-}1.0s}$, 0.1 for $FH_{1.0\text{-}2.0s}$); ii) for each cross-section, points at which limiting values of FH windows are reached were identified on section trace; iii) contours of FH limiting values were manually identified taking into account the buried and surficial morphological features responsible for site effects.

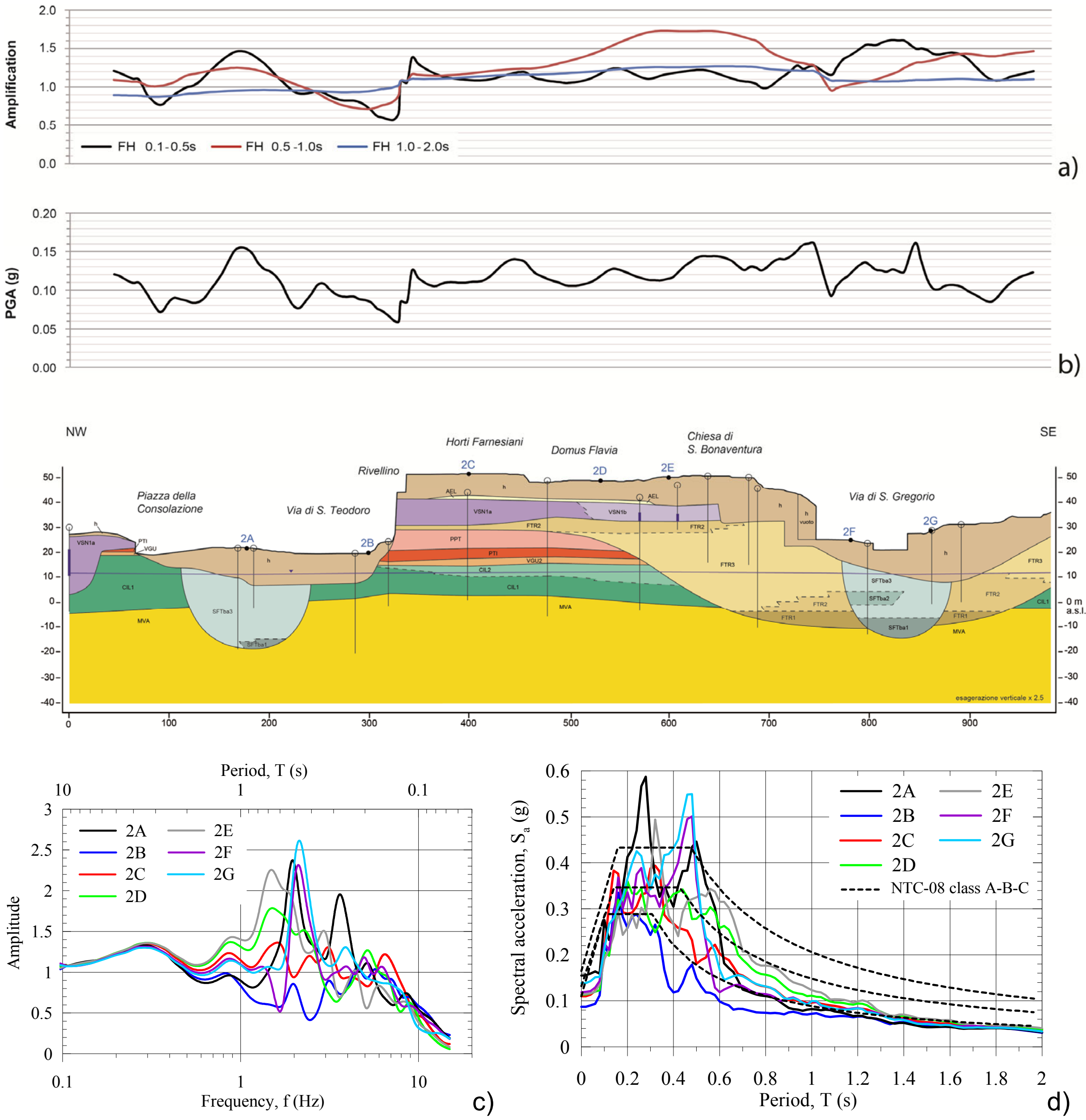


Figure 5. Section A: FH (a) and PGA (b) profiles; amplification functions (c) and response spectra (d) in selected superficial nodes

Each microzone therefore identifies an area with fairly constant amplification value and homogeneous stratigraphic, topographic and paleo-morphologic conditions.

$FH_{0.1\text{-}0.5\ s}$ map. High amplification values are concentrated along Labicano and Velabro valleys, especially in the areas characterized by elevated shape ratio, where FH higher than 1.4 is reached with a peak of 1.6-1.8 in the southern portion of Coliseum (Fig. 6a). As previously observed with reference to section A, this amplification can be related to 1D resonance of anthropogenic and alluvial layers superimposed to 2D resonance of SFTba valleys.

Major amplification is also found along the western flank of the FTR paleo-valley (Fig. 6a) where FH as high as 1.4-1.6 is reached. Such amplification can be ascribed to focusing of the seismic waves at the valley edge and/or interaction between the direct waves and diffracted surface waves. Similar amplification values (FH =1,4-1,6) are also attained in the Horti Farnesiani and Aula Regia area (Fig. 1 and 6a) probably for the 1D resonance of layer h overlying the stiffer VSN1a lithoid tuff.

Ground motion deamplification (FH 0,8-1,0) can be observed at the toe of Palatine, Aventino and Celio hills for topographic effects.

$\underline{FH_{0.5\text{-}1.0\ s}\ map}$. The maximum amplification factors (FH = 1.6-1.8) do correspond to the areas of maximum thickness of FTR paleo-valley and SFTba alluvial valleys (Fig. 6b). FH values as high as 1.4-1.6 in Circus Maximus area are associated to the 1D resonance of the anthropogenic cover and the clays filling the Murcia valley that is wider than Velabro and Labicano valley and therefore has a smaller shape ratio. Lower amplification phenomena (FH = 1.2-1.4) reached at Palatine hilltop (Horti Farnesiani) are related to topographic effects. Ground motion deamplification (FH = 0.8-1.0) is observed in the area comprised between the Roman Forum and S. Anastasia church (western flank of Palatine hill) characterized by a reduced thickness of anthropogenic layer and sub-outcropping gravels.

$\underline{FH_{1.0\text{-}2.0\ s}\ map}$. As observed for the previous map, amplification zones (FH=1.1-1.3) are associated to essentially 1D seismic response of the layer constituted by the high-thickness filling of FTR paleo-valley and SFTba valley and the anthropogenic unit (Fig. 6c). Deamplification zones (FH=0.9-1.0) are in the NW portion of the area (area between Roman Forum and S. Gregorio church). It should be emphasized that in this period range amplification factors are significantly lower than those computed in the other ranges.

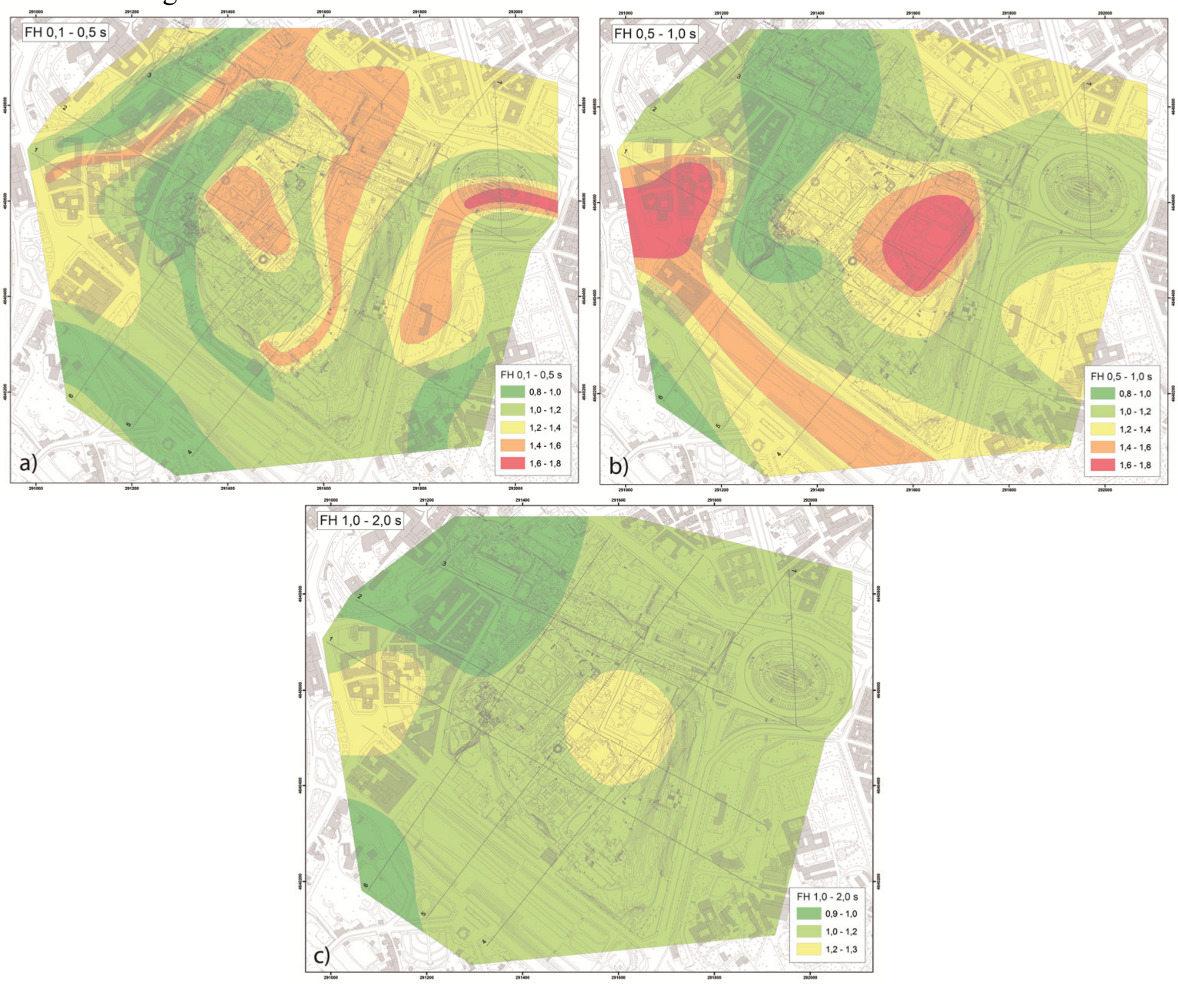


Figure 6. Microzonation maps for 0.1-0.5 s (a), 0.5-1.0 s (b) and 1.0-2.0 s (c); the traces of the seven cross-sections subjected to numerical modelling are also shown

6. CONCLUSIONS

The results of a multidisciplinary study aimed to seismic microzonation of the Central Archeological Area of Rome including the Palatine Hill, Roman Forum and Coliseum is presented. A large amount of data, collected from previous investigation and derived from *ad hoc* multidisciplinary survey, allowed to define an integrate subsoil model for site response numerical modelling. For the definition of the subsoil model particular efforts were devoted to the identification of deep seismic bedrock, the characterization of the buried morphology and the measurements of cyclic properties of soils and soft

rocks. The subsoil complexity of the archaeological site required an integrated action among various research units with capabilities in geology, geotechnical engineering, geophysics and archaeology.
An uniform hazard spectrum with return period of 475 years was selected as reference spectrum for input motion selection. Bi-dimensional numerical analyses were then carried out for seven representative cross-sections. The results show that ground motion distribution is mainly controlled by 1D resonance phenomena and 2D effects associated to recent soft alluvial valleys bordering Palatine Hill, a large and deep paleo-valley and, to a less extent, topography.
The microzonation maps were drawn bounding zones with homogeneous stratigraphic and morphologic features and expected values of amplification factors in terms of Housner Intensity (FH) computed in three different ranges of period (0.1-0.5 s, 0.5-1.0 s and 1.0-2.0 s). The maps show limited changes in ground motion amplitude (maximum amplification as high as 1.4-1.8 in the range 0.1-1.0 s are expected) the importance of which, however, can be significant for the monumental and archaeological heritage generally characterised by high vulnerability.
In addition to the microzonation maps, response spectra were computed in about 50 selected sites and monuments in order to quantify seismic action for eventual seismic retrofitting works.
The methodology described in this paper represents a useful reference for local seismic hazard assessment in ancient urban centers and archaeological areas.

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