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Multidisciplinary Study of Seismic Wave Amplification in the Historical Center of Rome, Italy

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MULTIDISCIPLINARY STUDY OF SEISMIC WAVE AMPLIFICATION IN THE HISTORICAL CENTER OF ROME, ITALY

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ABSTRACT

Assessment of potential strong ground motion within the city of Rome is crucial to preserve its millenary monumental heritage and protect its large urban settlements. Rome is located at a distance of some tens of kilometers from the central Apennines seismogenic zone, where earthquakes of tectonic origin and of a magnitude of up to 7.0 are expected.

The geological bedrock is mainly represented by high - consistency fine grained marine sedimentary deposits Pliocene to lower Pleistocene aged and named Monte Vaticano Unit. An upper Pleistocene – Holocene succession of fluvial deposits partially fill the paleo-valley of the Tiber river and of its tributaries formed during the last glacial period (22-18 kyr) carving the seismic bedrock. This alluvial body is composed by an heterogeneous fining-upward succession up to 60m thick.

To better quantify the expected ground shaking within the city of Rome, a multidisciplinary research activity has being carried out and: i) a detailed 3D engineering-geology model of the Tiber River alluvia was obtained based on new data from the metro lines under construction; ii) 1D and 2D numerical modeling were performed; iii) effects due to the nonlinear behavior of soil have also been taken into account.

The preliminary results show that the heterogeneity of the alluvial fill mainly controls the local seismic response. In addition, an interesting result is the fact that 1D amplification estimates are pervasively higher than the 2D ones.

INTRODUCTION

The geological setting of the historical center of Rome is characterized by a complex drainage network, related to the main Tiber river valley and filled with recent alluvial deposits and subsequently hidden by a man-made fill resulting from many centuries of urban settlement. It is worth considering that Rome is located at a distance of some tens of kilometers from the central Apennines, which is an active zone (earthquakes of tectonic origin and of a magnitude of up to 7) and where on April 6th, 2009 the Mw 6.3 L'Aquila earthquake took place (Fig.1). This event was located about 100 km NE of Rome (Blumetti et al., 2009). The mainshock of L'Aquila earthquake was felt in Rome up to V MCS intensity; nevertheless, damages to buildings, widespread located, have been denounced by inhabitants to the local authorities during the following days (personal communications to some of the Authors).

The seismogenic sources for this regional seismicity are located as close as 60-100 km from Rome; they have focal depth of about 10-15 km and can produce strong earthquakes with a magnitude up to 7. Smaller earthquakes, with a focal depth less than 6 km and maximum magnitude of 5, can be located at the Albani hills (Alban Hills in figure 1) volcanic source (Amato et al., 1994). Moreover, a local seismicity in the urban area can also produce earthquakes with magnitude not exceeding 4 (Tertulliani et al., 1996). Nonetheless, these smaller events are expected to produce a maximum I_{felt}= VI-VII in Rome.

Possible seismic inputs for the Rome urban area were derived via probabilistic and stochastic approaches, taking into account the mechanism of the seismic source and the propagation of the seismic pulse to large distances from the epicenter. Rovelli et al. (1994) obtained the spectra for the maximum expected ground motions in the city of Rome related to both the Colli Albani and the central Apennine sources. The results show that the main spectral contribution due to the Colli Albani source area is anyway at higher frequencies (higher than 5Hz) where compared to the central Apennines one. In terms of peak ground acceleration (PGA), the values expected for a M7 earthquake, at a distance of 100 km, vary from roughly 0.03g to 0.07g. These values are in agreement with the PGA probability of exceedance equal to 10% in 50 years obtained by Romeo at al. (2000).

Furthermore, previous studies reported that the 1915 earthquake caused the most severe damage to buildings located on the Holocene alluvial fill of the Tiber valley, thereby stressing the role of local geology in amplifying ground shaking (i.e. Ambrosini et al., 1986).

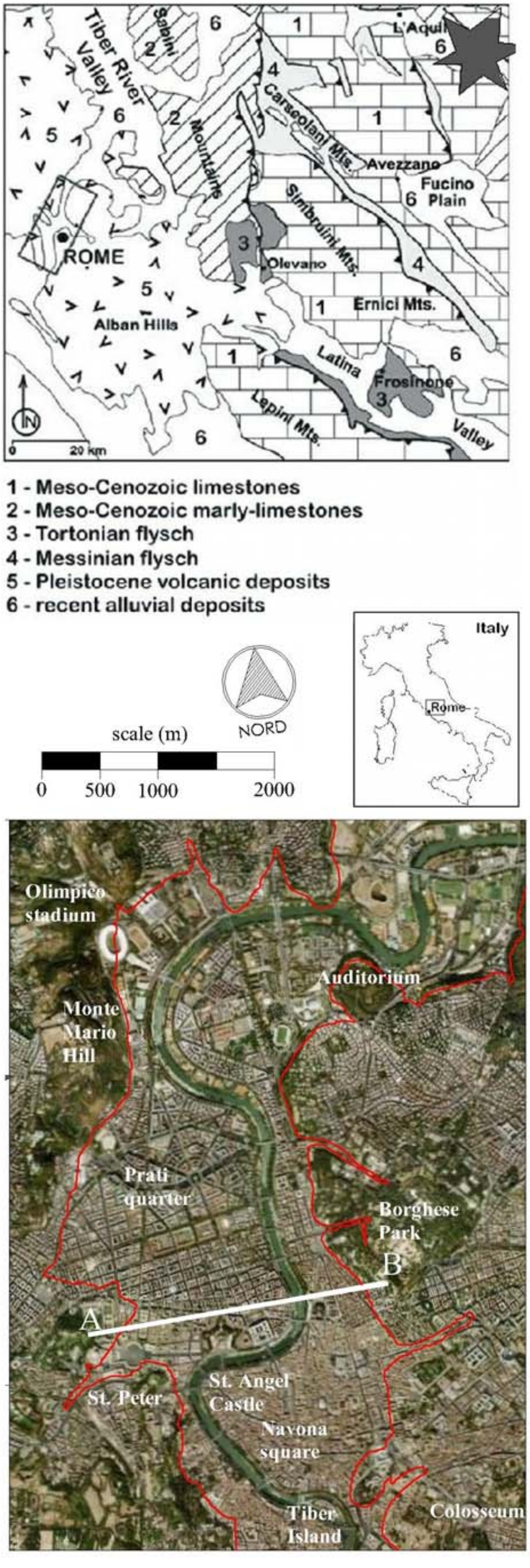

Fig. 1. Location of the city of Rome in the central Apennines area; the epicenter of the last 6th April, 2009 earthquake is also shown (up). Boundary of the alluvial deposits in correspondence with the historical center of Rome (red line) and AB trace of the geological section of Fig.2 (down).

Similarly, Boschi et al., (1995) and Funiciello et al. (1995) showed the close relationship that exists between selective damage to monuments, such as the Antonina Column and the Colosseum, and presence of soft alluvial sediments underneath.

Therefore, in the last decades, numerous studies were conducted to quantify the expected site effects within the city of Rome due to the basin-like geometry of the Tiber river valley as well as to its alluvial fill. Rovelli et al. (1994; 1995) performed 2D finite difference simulations and using a hybrid technique based on summation and finite difference proposed by Fah et al. (1993). Olsen et al. (2006) performed a 3D simulation using a homogenous model of Rome's fill. They pointed out that the alluvial fill within the main Tiber River valley has one principal mode of vibration at about 1 Hz; nevertheless, the heterogeneity of these alluvia was not taken into account.

Bozzano et al. (2000; 2008) analyzed static and dynamic geomechanical properties of the Holocene alluvial fill within the Tiber River valley. The Authors demonstrated that the silty-clay deposits (named level C), which makes the most part of the Tiber alluvial body, play a key role in the soil column deformation since it can be affected by nonlinear effects induced by the maximum expected earthquake.

Previous numerical studies of wave propagation in 1D and 2D media under linear and nonlinear conditions demonstrated that the basin response depends on many features such as site geometry, impedance contrast, material elastic and dynamic properties, as well as on the stress field induced by the seismic motion that may lead to relevant nonlinear effects. In particular, the results proved that the stronger the impedance contrast between the sediments and the surrounding bedrock, the stronger the amplification, regardless of the basin geometry; as a consequence, the amplifications resulting from 2D conditions can significantly differ from the ones obtained under 1D conditions (i.e. Bonilla et al., 2006; Bouden-Romdhane et al., 2002; Gélis et al., 2008; Semblat and Pecker, 2009).

In this paper, an engineering geology section across the historical center of Rome (i.e. southern part of Prati quarter, Castel S.Angelo and Piazza del Popolo) was obtained by analyzing boreholes logs and on new data from the tube-lines under construction. This section is used to study its local seismic response for a scenario coming from the Apennines zone taking into account the heterogeneity of the alluvial fill (Fig.2).

GEOLOGICAL SETTING OF THE CITY OF ROME

The area of Rome is characterized by marine sedimentary conditions from Pliocene through early Pleistocene times (4.5-1.0 Myr). This Pliocene-Pleistocene succession consists in alternating, decimeter-thick levels of clay and sand, the fine-grained ones with an over consolidation ratio (OCR) > 5 and low compressibility (Bozzano et al., 1997).

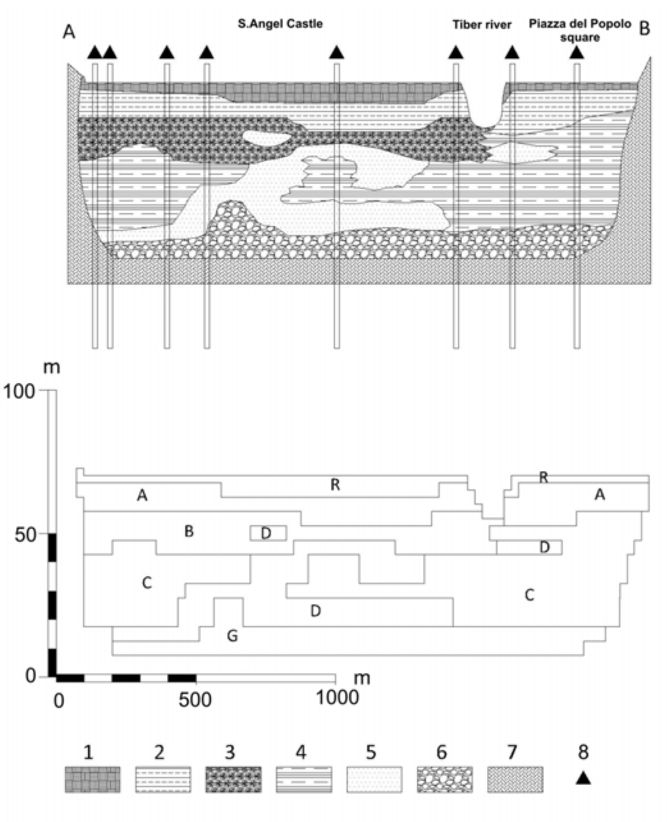

Fig. 2. Geological section along trace AB of Fig.1 (up) and related engineering-geology model (down): 1) man-made fills (level R); 2) level A; 3) level B; 4) level C; 5) level D; 6) level G; 7) Marne Vaticane clays (UMV); 8) borehole (projected from 15m).

During middle-late Pleistocene and Holocene times, sedimentary processes were confined to fluvial channels and coastal plains and strongly controlled by glacio-eustatic sea-level changes (Karner and Renne, 1998; Karner and Marra, 1998, Marra et al., 1998). In the same time interval, the region also experienced strong volcanic activity, causing the emplacement of a thick pyroclastic cover that became intercalated into the continental sedimentary deposits.

The present-day hydrographic network of the Tiber valley and its tributaries had been originated in the Würm glacial (22-18 kyr) period as re-incision and deepening of the valleys formed during the previous glacial-interglacial phases.

The sediments filling the upper Pleistocene valley are characterized by a fining-upward succession, with a relatively thin level of gravel at the base grading into a thick pack of sand and clay (Bozzano et al., 2000). This fine-grained portion of the deposit is represented by normally to weakly over consolidated clayey and sandy silt, saturated in water, with low rigidity moduli (Bozzano et al., 2000).

The selected section AB (Fig.2), almost W-E oriented, about 2 km long and almost perpendicular to the Tiber River valley, is obtained across the historical center of Rome, starting from Prati and Reinassaisment quarter, on the left bank of the Tiber river and reaching Piazza del Popolo square, on the right bank of the Tiber river. The stratigraphy reconstruction of the alluvial deposits shows that the Tiber palaeo-valley in Rome's historical center has a depth about 60 m to the North to about 70 m to the South below the present-day ground level. The valley, which is enclosed by steep slopes, has a flat floor slightly dipping southwards (Fig. 2).

According to Bozzano et al. (2000), the alluvial deposits were distinguished into 6 lithotypes which can be noticed along the AB selected section of Fig.2.

Basal gravels (level G) cover the ancient Pliocenic high consistency clays (UMV) with a thickness ranging between 5 and 10 m: they are mainly composed of limestone gravel in a grey sandy-silty matrix and can be related to a braided depositional system by the Tiber river.

The alluvial deposits belonging to levels C and D are associated to the sea level rising-up, and indicate a progressive lowering of the energy related to the depositional system. In particular, the D level is composed by grey colored silty-sands passing to clayey-silts. The C level is composed by grey clays passing to silty clays with a variable organic content which is responsible for the local dark-brown color. The C level is prevalent close to the boundary of the valley and, in particular, on its right side, where it reaches a maximum thickness of about 50 m (see section of Fig.2).

Moving upward within the alluvial succession, the C level results to be locally eroded in its upper part by high energy streams and subsequently filled by the alluvial deposits referred to level B,. It is composed by brown to yellow colored medium-coarse sands laterally passing to silty sands and clays close to the middle of the valley. The deposits referred to level B can be related also to the presence of the ancient tributaries of the Tiber river, as along the considered section AB, where the Gianicolo creek junction is intersected. The geometry of this body varies from lenticular to tabular. Level B is not found on the right side of the Tiber.

The historical alluvia of the Tiber (Lithotype A) complete the sedimentary succession. The grain size of these deposits is finer with respect to the level B; in particular, they are represented by silty and sandy deposits with brick fragments. Finally, the man-made fill, composing the R level, represents the most recent deposits which overlie the historical alluvia of the Tiber (level A). They are characterized by abundant, variously sized brick fragments and blocks of tuff embedded in a brown-green silty-sandy matrix. This horizon also contains ceramic and mortar fragments. The thickness of the R level close to the historical centre of Rome ranges between 7 and 8 m; nevertheless, along the considered section AB, the higher values are reached on the right side of the valley, in correspondence with the Prati quarter. The total thickness of levels A and R) is comparable on both banks.

ENGINEERING-GEOLOGY MODEL OF THE TIBER RIVER ALLUVIA

The 2D numerical model along the geological section of Fig.2, makes use of relationships among the different lithotypes in terms of both geometries and geomechanical properties.

The values of the physical properties and the index parameters are attributed according to Bozzano et al. (2008), (Table 1).

Table 1. Dynamic parameters for levels of Fig.3

Level	Vs (m/s)	ρ (kg/m^3)	v	G_0 (MPa)	ξ %	Lithology
R	220	1830	0.36	87	5	silty-sand
A	239	1875	0.37	105	5	silty-sand
B	260	1865	0.48	124	5	silty-sand
C	212	1865	0.48	83.5	5	clayey-silt
D	417	1957	0.47	334	5	sand
G	713	2141	0.46	1068	5	gravel
UMV	480	2039	0.46	461	1	clayey-silt

Level C is classified as inorganic silty clay of medium-high compressibility, whereas the Marne Vaticane and lithotypes A and D are defined as silty clays with medium-low compressibility.

Based on odometer tests, the silty clays belonging to level C are normally–consolidated, whereas level A clayey silts are over consolidated in their upper part (OCR up to 10), probably due to changes on the water table position. Conversely, the Marne Vaticane (Pliocene bedrock) high consistency clays result to be over consolidated (OCR > 2).

Site and laboratory testing of the Tiber alluvial deposits (Bozzano et al., 2008), prove that a significant stiffness contrast occurs between sands or silty–clayey alluvia (levels A, B, C, D) and basal sandy gravels (level G); these last ones overly the Marne Vaticane unit (UMV) which can be regarded as the geological substratum of the Tiber alluvia in Rome.

In terms of S-wave velocity, the above mentioned contrast is equal to about 300 m/s, while the basal gravels, characterised by Vs > 700 m/s, can be considered as the local seismic bedrock.

Moreover, relatively low values of Vs (<500 m/s) were measured within the first 10 m of Marne Vaticane; this finding is consistent with a softening related to the stress release caused by the fluvial erosion (Bozzano et al., 2006).

The dynamic mechanical properties of the Tiber alluvial deposits were derived by resonant column (RC) and cyclical torsional shear tests; they proved a stiffness contrast between the alluvia and the high consistency UMV clays clay bedrock, of about 100 MPa. On the contrary, the same contrast measured within the alluvial deposits ranges between 50 and 100 MPa.

The derived linearity threshold for the shear strains corresponds to about 0.005% for the UMV and to 0.01%-0.02% for the alluvial deposits, while the plasticity threshold for the alluvia ranges from 0.02% to 0.04%.

In the analysed section AB (Fig.2), the stiff level D is located in the middle portion of the Tiber valley and is imbedded in the soft and ductile level C. On the right side of the valley the B and A levels overly the C level which, as a consequence, results to be imbedded between the B and G levels. On the contrary, in the left side of the valley, level C results to be imbedded between the A and G levels. Moreover, in the first 25 m below ground level, some thin layers of the level D are overlapped by the C level.

NUMERICAL MODEL OF THE BASIN

1D and 2D numerical simulations have been performed along the section AB of Fig.2 by using the corresponding engineering-geology model, under linear and nonlinear conditions. A laterally homogeneous layer is added all along the 2D profile to simulate an increase of seismic velocities with depth. The gradient ranges from 480 m/s just below the G level bottom to 1000 m/s 20 m below the G level bottom for Vs and from 1880 m/s to 2500 m/s for Vp. The density is kept constant to 2040 kg/m3 in this layer. Below this gradient layer, seismic velocities and density are kept constant. We use the finite difference method (FDM) to propagate seismic waves from the homogeneous bottom layer into the previously described velocity gradient layer and Tiber alluvia.

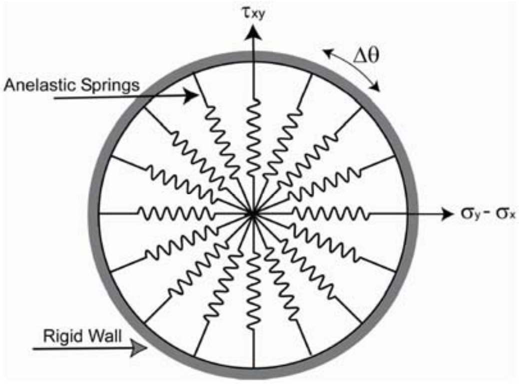

Fig. 3. Schematic figure for the multiple simple shear mechanism.

The stencil proposed by Saenger et al. (2000) was used to model 2D P-SV wave propagation. This stencil allows computing all components of the stress-strain tensor in one point of the numerical mesh, simplifying the implementation of the computation of the nonlinear soil rheology and avoiding spatial averaging of physical parameters such as Lamé coefficient. Furthermore, the free surface is easily introduced by zeroing Lamé parameters and surface waves can be modeled more accurately (Gélis et al., 2005) than with traditional staggered-grid methods (i.e. Virieux, 1986). The total size of the model is 90 m depth and almost 4 km length because the domain corresponding to the basin of AB profile was laterally extended in order to have a numerical reference in the model so that rock outcropping motions can be obtained.

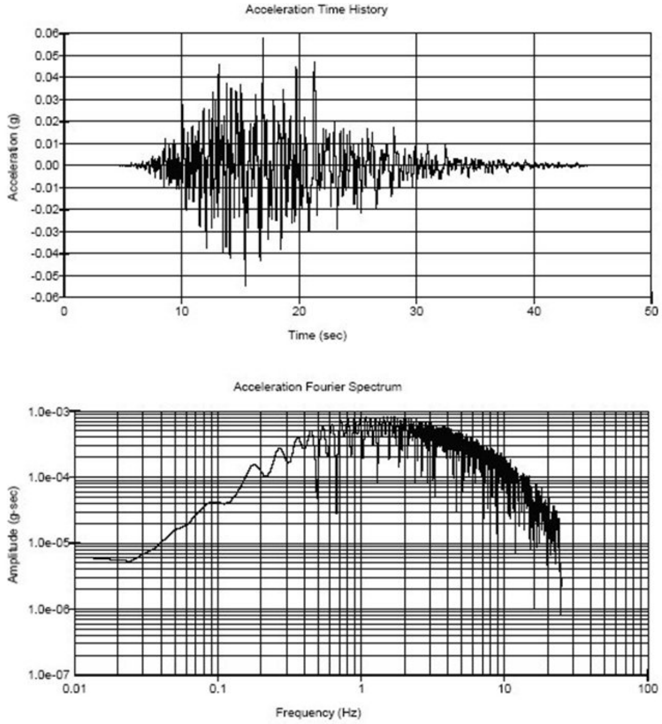

Fig. 4. Acceleration time history used for the numerical modeling and related Fourier spectrum (after Rovelli et al., 1994).

The minimum and maximum shear wave velocities in linear conditions are 210 and 1000 m/s for the alluvial deposits and the bedrock respectively (Bozzano et al., 2008). The P wave velocities are then deduced on the basis of the measured geomechanical properties (Table 1). The minimum quality factors Qs, corresponding to the quality factor for S waves, are computed, when possible, from the experimental values of the damping, measured by RC tests at small deformations. In the other cases, Qs is directly derived from the shear modulus G_0. Moreover, the values for Qp are assumed equal to 2Qs. The numerical spatial and time steps were 1 m and 1.0e-4 s which permit to have reliable results for both linear and nonlinear simulations up to 8.5 Hz. In this study, we introduce anelastic attenuation for all linear simulations by using the method proposed by Day and Bradley (2001).

The strain-stress relation, governing the nonlinear behavior modeling and used at each time step, is based on the multishear mechanism model by Towhata and Ishihara (1985). The multishear mechanism model is a plane strain formulation to simulate pore pressure generation in sands under cyclic loading and undrained conditions. After the work by Iai at al. (1990ab), the model was modified to account for the cyclic mobility and dilatancy of sands.

However, in its basic form, this formulation also models soil nonlinearity without taking into account any contribution from co-seismic water pore pressures.

The multiple mechanism model relates the stress (σ) and strain (ε) through the following incremental equation,

$$\{d\sigma'\} = [D]\,(\{d\varepsilon\} - \{d\varepsilon_p\}) \qquad (1)$$

where the curly brackets represent the vector notation; $\{\varepsilon_p\}$ is the volumetric strain produced by the pore pressure, and [D] is the tangential stiffness matrix. This matrix is composed by the volumetric and shear mechanisms, which are represented by the bulk and tangential shear moduli, respectively. The latter is idealized as a collection of *I* springs separated by $\Delta\theta = \pi / I$ (Fig.3). Each spring follows the hyperbolic stress-strain model (Konder and Zelasko, 1963) and the generalized Masing rules for the hysteresis process. For more details on the nonlinear stress-strain rheology, the reader may see the papers by Iai et al. (1990ab).

The input acceleration time histories (Fig. 4) was applied as a vertical incident SV plane wave, located within the 2D stratigraphy, at a depth of 90 m from the surface, and at the base of the soil columns for the 1D simulations. The source we used is a synthetic waveform simulating a M 7 earthquake with an epicentral distance in the range 80-100 km referred to the Apennines seismogenic zone and with a corresponding PGA of 0.06g on outcropping bedrock (Rovelli et al., 1994). The input accelerogram was divided by 2 to take into account the free surface effect before propagating at the base of the model.

NUMERICAL RESULTS

The results from the 2D numerical modeling along section AB of Fig. 2 were analyzed in terms of amplification functions (A(f)) (Fig.5) as well as of maximum shear stress and strains within the Tiber alluvia (Figs.6 and 7). The A(f) values obtained under linear conditions reach 3.0 at frequencies varying from 5-6 Hz to 3-4 Hz, moving from west to east, i.e. from the Prati Quarter towards Piazza del Popolo square. Conversely, in the frequency range 1-2 Hz, the A(f) values reach 3 but the 2D amplifications show some lateral discontinuities due to laterally propagating waves or diffracted waves at the basin and layer edges (Semblat et al., 2005).

By comparing the A(f) values resulting from 1D and 2D linear modeling, the following considerations can be deduced (Fig.5). Amplification values from 1D results are generally higher than the 2D ones at all frequencies. Both 1D and 2D models reveal the similar resonance frequencies. However, the 2D results show some discontinuity in the amplification values.

The amplification at about 1Hz can be related to the first resonance mode of the alluvial deposits as pointed out by Rovelli et al (1994, 1995), Fah et al (1993) and Olsen et al (2006).

Moreover, both 1D and the 2D linear models point out relevant amplifications in a frequency range greater than 4Hz; nevertheless, these frequencies vary from west to east along the section. A possible reason for justifying this effect can be considered the increasing depth of the silty-sandy layer A in the same direction.

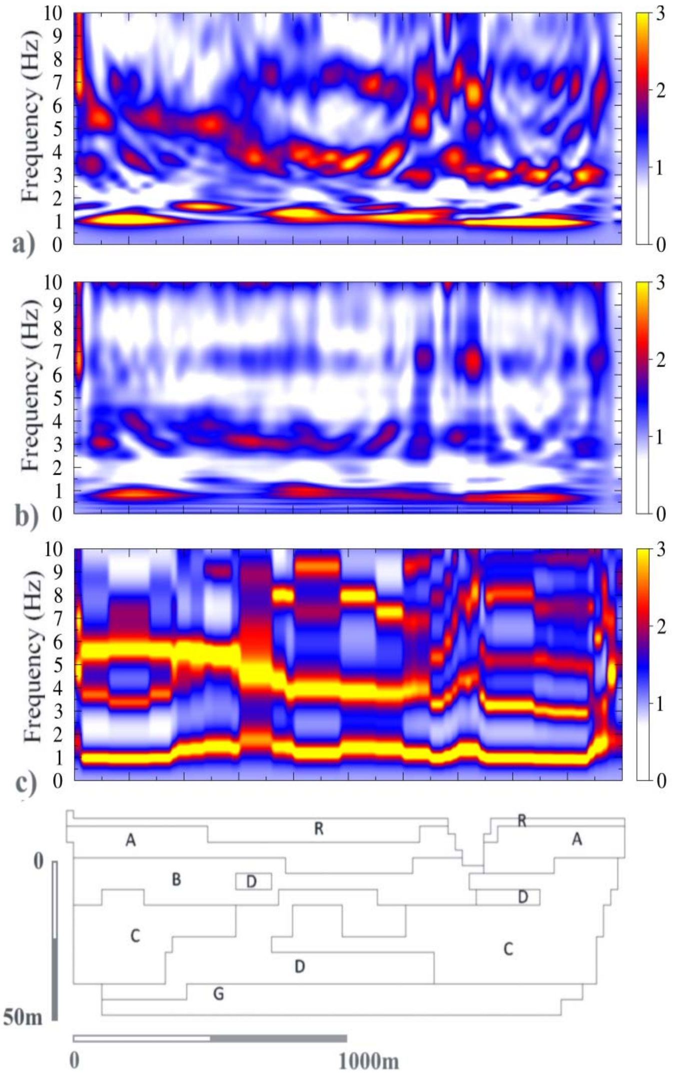

Fig. 5. Comparison between amplification functions computed numerically under linear-2D (a), nonlinear-2D (b) and linear-1D (c) conditions; the reference engineering-geology section is also reported.

Otherwise, the case of the 2D nonlinear solution (Fig.5) points out a general decrease of the values of the amplification for all the amplified frequencies. Moreover, a shift of all the amplified frequencies towards lower values is a consequence of the nonlinear rheology of sediments: the first mode of resonance shifts down to about 0.5Hz and the amplified band of frequencies in the range 4-6Hz shifts down to 3-4Hz. Furthermore, no significant variations are observed in the distribution of A(f) values along the studied cross-section.

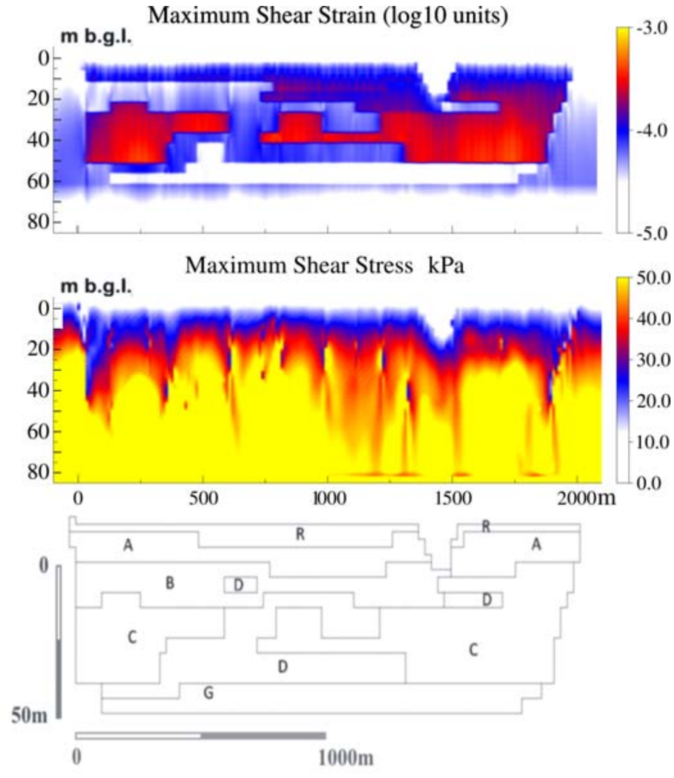

Fig. 6. Maximum shear strains and stresses obtained by 2D linear numerical modeling; the reference engineering-geology section is also reported.

The related maximum shear strain distribution, obtained along the analyzed section under linear conditions (Fig.5), proves that the highest values are reached within the high compressibility clayey deposits (C level) especially where they are overlapped with stiffer soils, such as sands or gravels (i.e. B, D and G levels). In particular, where the thickness of the C level is strongly reduced, down to some meters, a high concentration of shear strains can be observed. Conversely, the maximum shear stress distribution highlights a nearly uniform distribution of the resulting values within the alluvial deposits.

For the nonlinear case, the maximum shear strain distribution, obtained along the analyzed section, proves that the highest values are reached within the high compressibility clayey deposits (level C) especially where they are imbedded with stiffer soils, such as sands or gravels (i.e. B, D and G levels) (Fig.7). This is consistent with the results of Bozzano et al. (2000, 2008) who expected that the C level plays a key role in the soil deformation because of its potential nonlinear behavior. Moreover, the maximum shear stress distribution highlights decreasing values in correspondence with the sandy deposits of the D level.

The maximum shear strain values are higher in the nonlinear modeling, whereas maximum shear stress values are higher in the linear modeling. This is a consequence of the nonlinear behavior of alluvia in the Tiber basin.

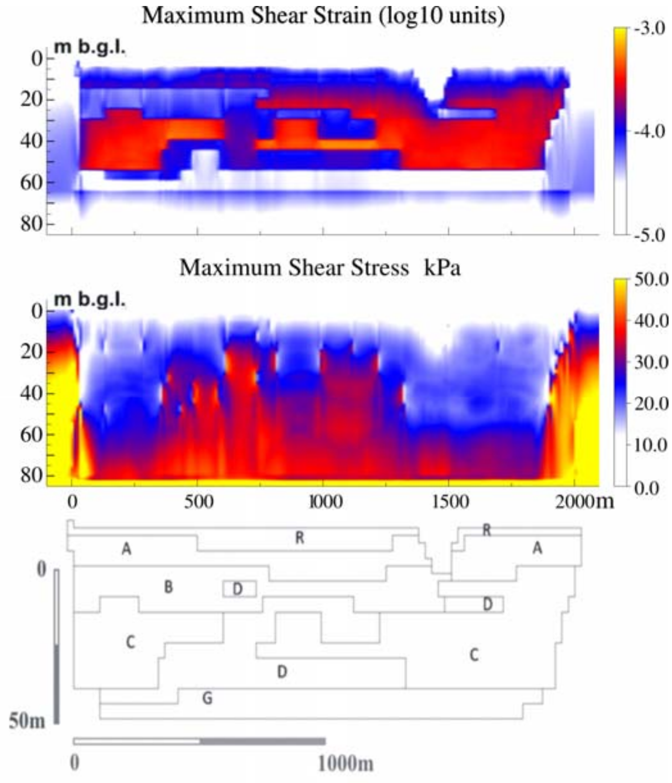

Fig. 7. Maximum shear strains and stresses obtained by 2D nonlinear numerical modeling; the reference engineering-geology section is also reported.

Deposits belonging to the D level are mainly located in the middle portion of the valley, they split the clayey deposits of level C in two main portions: the first one located in the southern area of the Prati Quarter and the second one corresponding to the historical center of Rome, close to Piazza del Popolo square, and eastward respect to the Tiber River.

Based on the numerical results, the two portions of the deposits ascribable to the C level along section AB of Fig.1, result to be strongly confined by both the high consistency clays of UMV formation (which represent the geological bedrock of the valley) and the sandy deposits of the D level, located in the middle portion of the valley (Fig.2). This effect is empathized in nonlinear conditions, where the shear modulus has a stronger decay for the clayey deposits (level C) with respect to the sandy ones (level D).

The output in terms of maximum shear stress ratio between 2D linear vs 2D nonlinear conditions is shown in Fig.8. This result confirms that the highest decay of the stiffness is within C level (i.e. from 40 to 60 m b.g.l.).

Generally speaking, both the geometry and the deposit dynamic properties are responsible, in the frequency band of 1-2Hz, for a spatial variability of A(f). Surprisingly, 2D amplification values are lower than the ones obtained from 1D computations.

CONCLUSIONS

Log-data from boreholes have been collected and previously lithographical description (Bozzano et al., 2000; Bozzano et al., 2008) were used to derive a detailed geological and geotechnical model along a WE oriented section across the historical center of Rome (from south of Prati Quarter to Piazza del Popolo square).

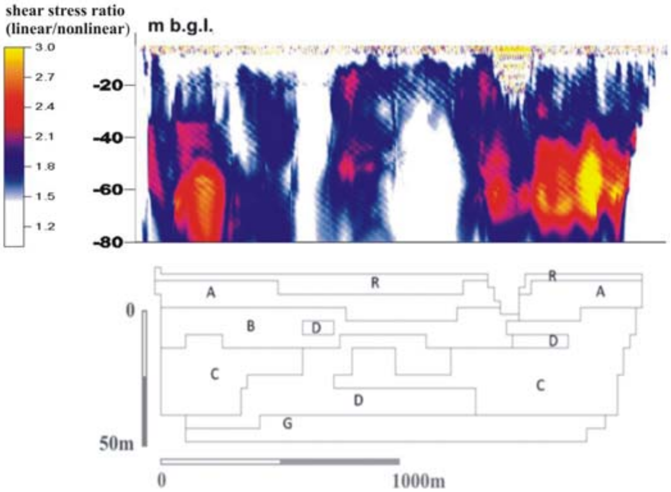

Fig. 8. Maximum shear stress ratio between 2D linear vs 2D nonlinear conditions.

The alluvial fill of the Tiber river analyzed in this section is composed of plastic deposits (i.e. silty clays), which are in contact with stiffer ones (i.e. sands and gravels) with a strong spatial variability in both vertical and lateral directions. In particular, the above mentioned plastic deposits belong to a thick level of inorganic middle to high compressibility clays whose dynamic properties (i.e. in terms of shear modulus decay) show some nonlinear behavior.

This preliminary study represents a first step in evaluating the local seismic response in the historical center of Rome, taking into account both the heterogeneity of the alluvial fill and possible nonlinear effects. In particular, the results obtained by the present 1D and 2D numerical modeling highlight relevant effects due to the above mentioned heterogeneities of the alluvia, in terms of amplification functions as well as related stress-strain distribution. Since the shape ratio of the valley, along the analyzed section, is higher that the one requested for a proper 2D resonance (Bard and Bouchon 1985; Rovelli et al., 1994; Semblat et al., 2003) the heterogeneity of the alluvial fill mainly controls the local seismic response. 1D modeling shows that the first mode of resonance is at 1-2 Hz all along the considered section. Conversely, 2D linear modeling shows a lateral variation of such resonance frequency. The reason is probably due to laterally propagating waves or diffracted waves on the layer corners and edges. In addition, an interesting result is the fact that 1D amplification estimates are higher than the 2D ones.

The results from the nonlinear computations show a shift of the resonance frequencies and a clear deamplification of the valley response. However, more research is needed to better understand the role of the weaker layer and the combination of softer and stiffer materials on the wave propagation. Moreover, effects due to seismic wave directivity as well as to a higher degree of complexity due to lateral and vertical heterogeneities will be considered using the full 3D reconstructed model of Rome basin.

This study highlight the importance of a multidisciplinary study that makes possible to give new insights on the local seismic response in very complex basin-like systems, by combining geological and engineering contributions to perform highly detailed numerical models.

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