Numerical modeling of nonlinear dynamic shear strains in heterogeneous soils by 1D-3C finite element SWAP_3C

F. Bozzano, S. Martino & A. C. Giacomi
Department of Earth Sciences and Research Centre for Geological Risks (CERI), University of Rome (Italy) "La Sapienza"

L. Lenti
French Institute of Sciences and Technology for Transport, Development and Networks (IFSTTAR) - Paris East University (France)

G. Martini
Italian National Agency for New Technologies Energy and Sustainable Economic Development

M. P. Santisi D'Avila
Institute Jean Le Rond D'Alembert, Université Pierre et Marie Curie (France)

SUMMARY:
The effects of nonlinearity due to seismic waves in heterogeneous soils were simulated in the time domain by the 1D-FEM code SWAP_3C and in the frequency domain by EERA. In the case of SWAP_3C, a three-component (3C) input was applied at 48 heterogeneous soil vertical profiles, obtained from the Tiber River alluvial deposits in the historical centre of Rome (Italy). The input was derived by selecting natural time-histories from the European catalogue with reference to seismological features (i.e. epicentral distance, magnitude, focal mechanism) of a M_w 7 Central Apennine seismic source, about 80km far from Rome. Compatibility between the response spectrum of the selected natural time-histories and the local expected response spectrum was obtained. Independently from the codes used, the resulting maximum shear strain values, pointed out a main role of the soil heterogeneity in conditioning their distribution along the vertical profiles and their concentration in the more plastic layers.

Keywords: nonlinearity, heterogeneous soil, numerical modelling, Rome

1. INTRODUCTION

Local seismic response in large urban areas was estimated so far via 1D and 2D numerical simulations (Rovelli *et alii*, 1994, 1995a, 1995b, Panza *et alii*, 2004b; Bozzano *et alii*, 2008; Bonilla et al., 2010; Bonilla et al., 2006; Bouden-Romdhane et al., 2003; Semblat and Pecker, 2009). These simulations were devoted to analyse possible local effects due to the modification of the input seismic wavefield in the superficial layers, both in linear and non-linear conditions. The numerical models demonstrated that local seismic response depends on many features such as soil geometry, impedance contrast, 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 is the impedance contrast between the sediments and the surrounding bedrock, the stronger is the amplification, regardless of the basin geometry; as a consequence, the amplifications resulting from 2D conditions are significantly higher than the ones obtained under 1D conditions. In particular, results by 1D and 2D numerical modelling of local seismic response highlight relevant effects due to the above mentioned heterogeneities of the alluvia, in terms of amplification functions as well as of the resulting stress-strain conditions.
Moreover, it was recently demonstrated that the heterogeneity of the Tiber's Holocene alluvial deposits - namely fine-grained plastic levels interbedded with sand horizons - can cause both amplification of the seismic signal and co-seismic maximum deformation in these plastic levels (Bonilla *et al.*, 2010; Bonilla *et al.*, 2011). In a recent study Bozzano et al. (2011) demonstrated that the damages to Rome's buildings caused by the L'Aquila seismic crisis on April 2009 were favoured

by the alluvial subsoil since their concentration was higher in correspondence with the quarters located in the Tiber River alluvial plan.
Based on a 3D engineering-geology model of the Tiber alluvia in the historical centre of Rome (i.e. Prati quarter, Castel S.Angelo and Piazza del Popolo and Trastevere, Piazza Navona and Piazza Venezia) were obtained 48 soil columns were obtained to numerical model strain effects induced by strong motions, in order to analyse effects of heterogeneity both in terms of geometry and geomechanical characteristics of the soils.

2. GEOLOGICAL SETTING

The area of Rome’s historical center was characterised by marine sedimentary conditions from Pliocene through early Pleistocene times (4.5-1.0 Myr)(Fig.1).
This Plio-Pleistocene succession consists of alternating, decimetre-thick levels of clay and sand, with an overconsolidation ratio (OCR) >5 and low compressibility (Bozzano et al., 1997). Given its lithological features, the Monte Vaticano Unit (UMV) is considered to be the geological bedrock of the area of Rome.

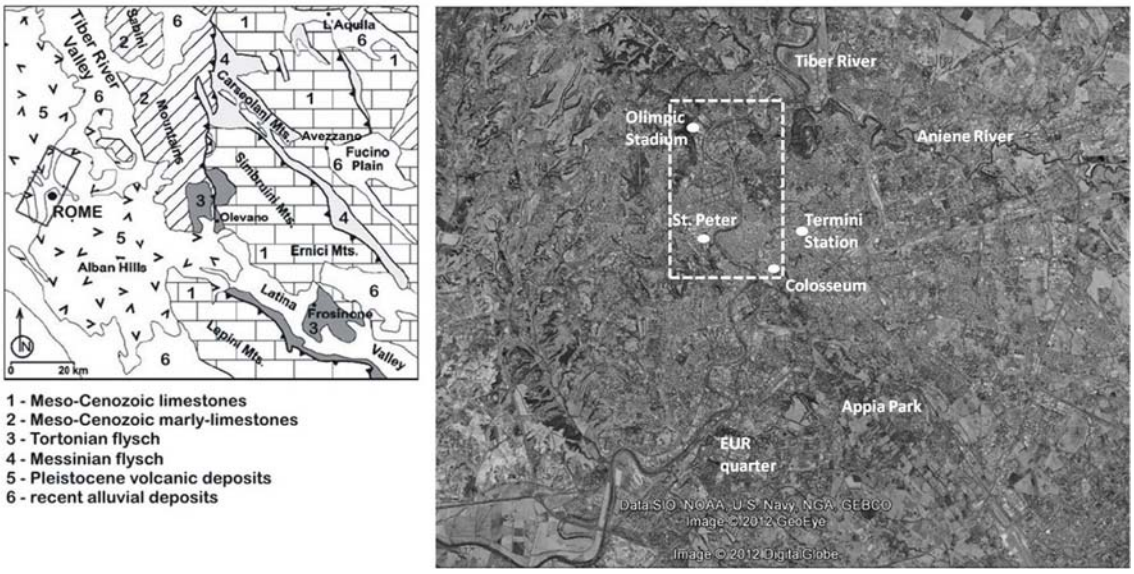


Figure 1. Location of the city of Rome in the central Apennines area. The box identifies the area of Rome’s historical center.

During middle-late Pleistocene and Holocene, the 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, this area also experienced strong volcanic activity, which caused 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, were originated from the Würm glacial period (18 kyr) and it results from re-incision and deepening of valleys heredited from the previous glacial-interglacial phases.
The sediments filling the Holocene valleys are generally characterised by a fining-upward succession, with a basal few meters thick level of gravels grading into a thick pack of sands and clays (Bozzano et al., 2000). This fine-grained portion of the deposit is represented by normally to weakly overconsolidated clayey and sandy silts, saturated in water, with low stiffness (Bozzano et al., 2000).
A 3D geological model of the Rome’s historical centre was constructed, based on data from 78 boreholes (Fig.2 and 3). The depths reached by these boreholes range from 30 up to 67 m b.g.l., across the Tiber River alluvia; many of these boreholes reach the high-consistency clays of the UMV geological substratum.

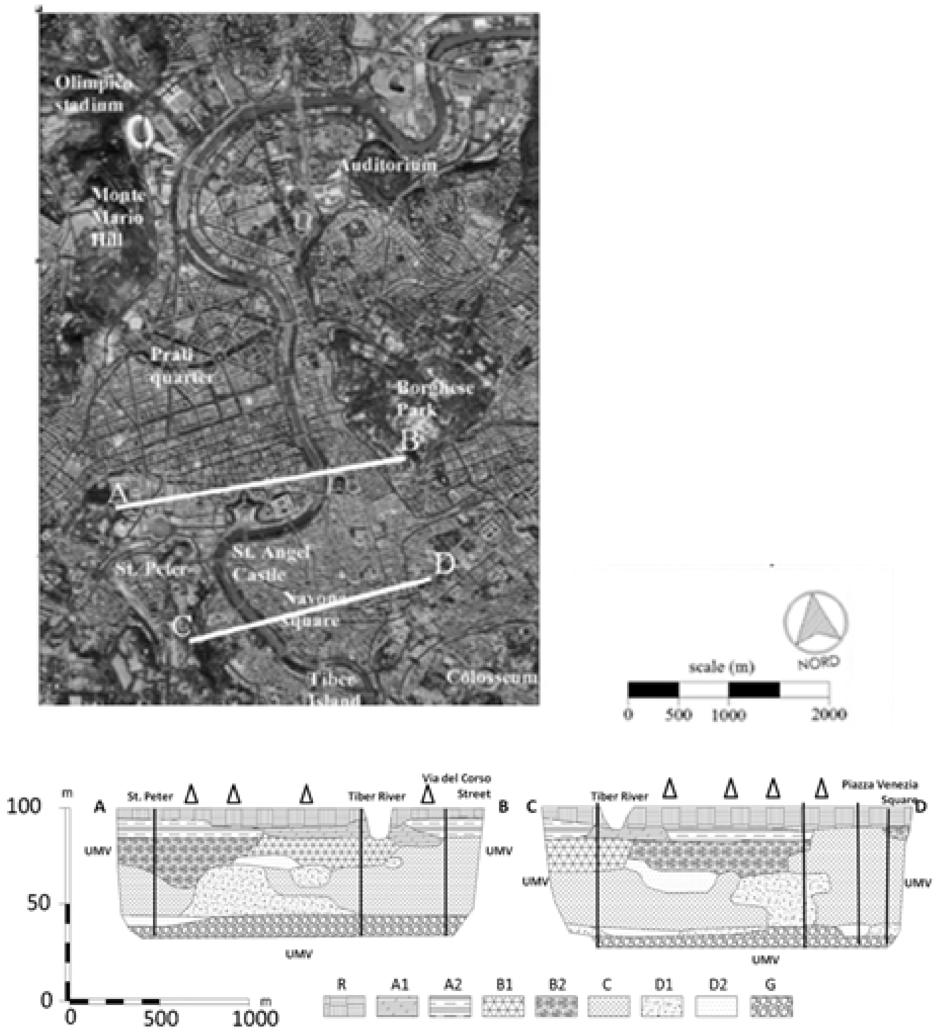


Figure 2. Engineering-geology model along traces AB and CD: the triangle symbolizes borehole (projected from 15), the black vertical line symbolizes the soil vertical profile. For legend to the lithotechnical units see the text.

Two different geological cross-sections (AB and CD of Fig. 2) were obtained across the Tiber valley from the 3D engineering-geology model , almost W-E oriented and about 2 km long. Section AB starts from the Prati and Rinascimento quarters, located on the left side of the Tiber and reaches Piazza del Popolo square, located on the right side of the Tiber River; section CD starts from Trastevere quarter, located on the left side of Tiber river and reaches Piazza Venezia square, located on the right side of the Tiber.

The 3D stratigrafic reconstruction of the alluvial deposits shows that the Tiber palaeo-valley in the Rome's historical centre has a thickness varying southward from 60 up to 70 m (Fig. 2).

According to Bozzano et al. (2000) and Giacomi (2011), the alluvial deposits were distinguished in 7 lithotypes which can be recognized along the AB and CD selected sections of Fig.2.

Basal gravels (level G) cover the UMV with a thickness up to10 m and composed of limestone gravel in a grey sandy-silty matrix.

The D level is composed by grey coloured silty-sands passing to clayey-silts; this level can be distinguished in the two sub-levels: D1 sub-level characterised by a prevalent sandy grain size, D2 sub-level characterized by a prevalent silty-clay grain size. . The C level is composed by grey clays passing to silty clays with a variable organic content which is responsible for local dark colour; this level is mainly located close to the boundary of the valley and, in particular, on its right side, where reaches a maximum thickness of about 50 m (see section AB of Fig.2).

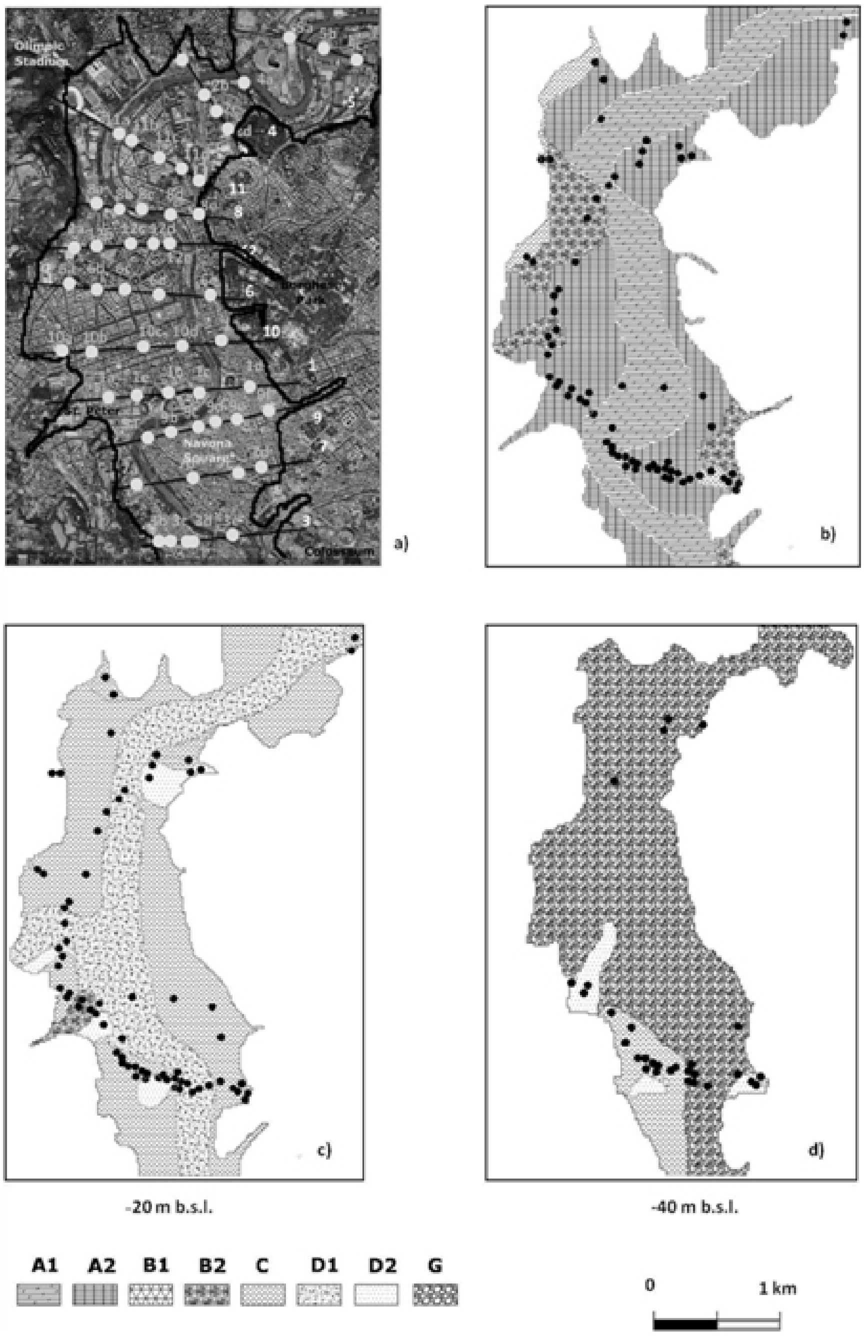


Figure 3. a) Location of soil vertical profiles simulated; b)-c)-d) distribution of alluvia in Rome's historical centre at different elevations. Black point symbol the boreholes. For legend to the lithotechnical units see the text.

The clayey level C is locally eroded by the level B, which is generally composed by brown to yellow coloured sands (B1) and locally passes to to silty sands and clays (B2).

The recent alluvia of the Tiber (level A) complete the sedimentary succession. These alluvia are mainly composed of silty-sands locally passing to clayey silts up to 15 m thick in correspondence to the left side of the valley.

Finally, man-made fills of level R, represent the most recent deposits which overly the Tiber alluvia; this fills are characterised by abundant, variously sized brick fragments and blocks of tuff embedded in a brown-green silty-sandy matrix, also including ceramic and mortar fragments; the thickness of the level R close to the Rome's historical centre reaches 8 m.

2. ENGINEERING-GEOLOGY MODEL OF THE TIBER RIVER ALLUVIA AND SEISMIC REFERENCE INPUT

To perform 1D numerical modeling rheological models and geomechanical properties were attributed to the aforementioned Tiber River alluvial deposits as shown in Fig. 4, according to Bozzano et al. (2008) and Caserta et al. (2012).
Based on the geomechanical characterisation by Bozzano et al. (2000; 2008), C level is classified as inorganic silty clay of average-high compressibility, whereas the UMV and A and D levels are defined as silty-clays with low to middle compressibility.

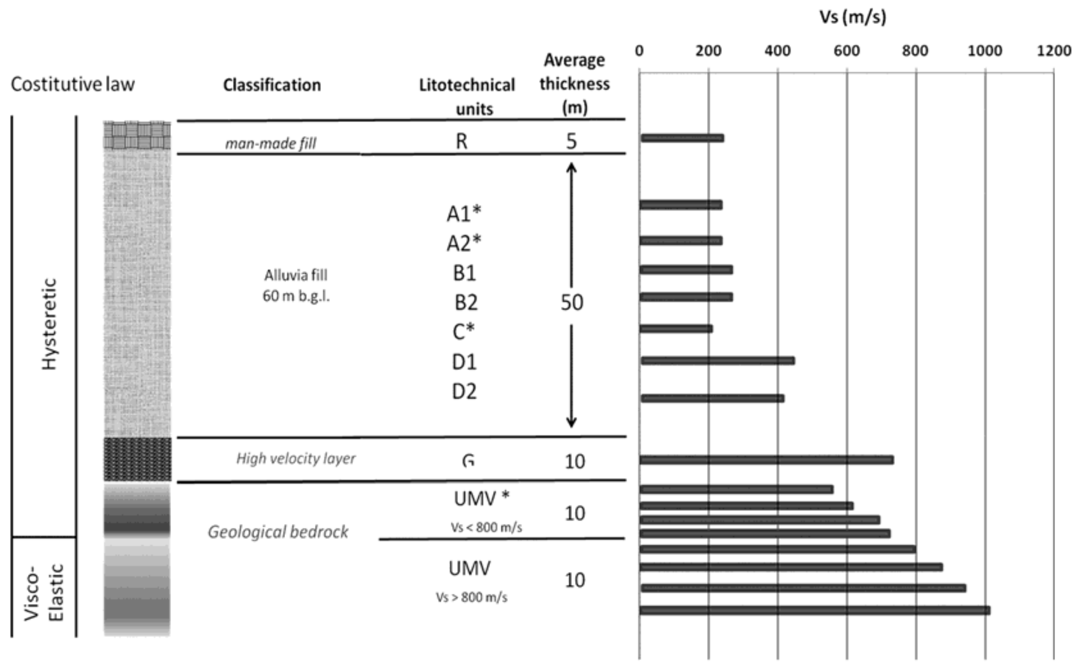


Figure 4. Schematic column representing the composition of the Tiber Rover alluvial deposits in the historical centre of Rome; values of Vs velocity and rheological behaviours are also reported.

Site and laboratory testing of the Tiber alluvial deposits (Bozzano et al., 2008), demonstrated that a significant difference exists between sandy or silty–clayey deposits (levels A, B, C, D) and the basal sandy gravels (level G). In terms of S-wave velocity (Vs) the above mentioned difference corresponds to a ΔVs of about 300 m/s. In this regard, the G level can be considered as the local seismic bedrock, since it is characterised by Vs > 700 m/s (Bozzano et al., 2008). Relatively low Vs values (<600 m/s) were measured within the first 10 m of UMV; this finding is consistent with a softening related to the stress release caused by the fluvial erosion (Bozzano et al., 2006). As a consequence, linearly increasing Vs values (e.g., from 540 up to 1000 m/s) have been assumed in the numerical models for the first 20 meters within the UMV.
The dynamic properties of the Tiber alluvial deposits were derived by resonant column and cyclical torsional shear tests; at low strain levels (i.e., for strain levels where no significant reduction of shear moduli are observed, strain level < 10^{-6}) these tests output a difference between the stiffness related to the Tiber alluvia and the high consistency UMV clays of the bedrock equal to about 100 MPa. On the contrary, the difference of stiffness at low strain levels measured within the alluvial deposits (levels A, B, C, D) ranges referred to the bedrock stiffness between 50 and 100 MPa. The decay curves deduced from the same tests put in evidence that the linearity threshold for the shear strains is of about 0.005% for the UMV and in the range 0.01%-0.02% for the alluvial deposits, while the plasticity threshold for the alluvia ranges from 0.02% to 0.04%.
According to the resonant column laboratory tests , an hysteretic constitutive low was attributed to layers with Vs< 800 m/s; whereas a viscoelastic constitutive low was attributed to the other UMV layers (Fig.4).

2. NUMERICAL MODELING

2.1 Reference seismic input

A 3 component time history has been produced, taking into account the maximum PGA expected in the historical centre of Rome. As a first step, as a reference recorded time history for Rome was not yet available, an historical analysis of the felt seismicity was performed by considering the last 2000 years, to obtain a couple of values (Magnitude-distance) representative for the maximum seismic scenario expected in Rome. The so-obtained parameters allowed selecting from the European Strong-motion Database (ESD) a first set of 3-components time histories as to representative for the maximum expected ground motion. As second step, the response spectra (5% inelastic damping) related to these time histories were calculated and compared to the reference response spectrum expected for Rome, this last one already available and defined in the framework of the national project UHS INGV, Cluster 6, Central Italy (Convenzione INGV-DPC 2004-2006). The best fit allowed selecting only one 3-components time history among the whole set of data selected starting from the ESD. The horizontal component with the maximum ground acceleration value was scaled to the PGA value characteristic for the historical centre of Rome (i.e.Ag0=0.1258 at 475 years) (Convenzione INGV-DPC 2004-2006). The other components were then scaled taking into account the ratios between the PGA values associated to the 3 not-yet scaled components of the timehistory. This procedure allowed obtaining 3 acceleration timehistories representative for the maximum ground motion expected in Rome and which were used in the numerical modelling.

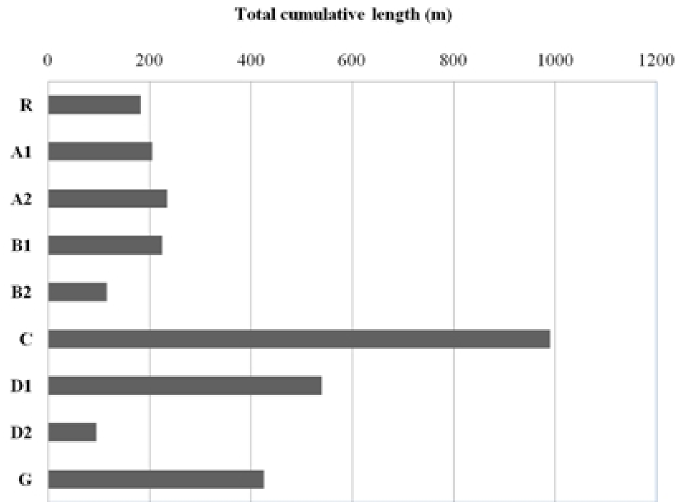


Figure 5. Total cumulative length (m) of the lithotechnical units ascribable to the Tiber River alluvial deposits in the Rome's historical centre.

2.2 Numerical codes

The seismically-induced strain effects are investigated in forty-eight 1D soil profiles (Fig. 3), using two numerical 1D wave propagation models, EERA and SWAP_3C, and considering the time histories obtained by the above described procedure. In particular, EERA (Bardet et al., 2000) allows evaluating the local seismic response of horizontally stratified soil considering the equivalent linear approach in the frequency domain to solve the 1D propagation of vertically incident seismic waves. SWAP_3C, despite EERA, (Santisi d'Avila et al., 2010; 2012) can evaluate the seismic response of a soil column considering at the same time the three components of the ground motion; more in details, SWAP_3C solves the 1D propagation in the time domain adopting the finite element scheme and the three-dimensional Iwan's constitutive model (Iwan, 1967; Joyner, 1975; Joyner and Chen, 1975). Iwan's procedure, defined as a Masing-Prandtl-Ishlinskii-Iwan (MPII) type model by Segalman and Starr (2008), has been selected because few parameters are necessary to characterize the soil hysteretic behaviour. The MPII formulation of soil hysteretic behaviour can be used to evaluate the seismic wave propagation in well physically and mechanically constrained case studies as well as to investigate the role of critical parameters affecting the soil response.

3. ANALYSIS OF NUMERICAL DATA

48 soil columns have been selected from the three-dimensional geological model of the Tiber alluvia in the Rome's historical centre (Fig.3). Based on the 3D engineering-geology model, the C level results the mostly represented one within the Tiber alluvial fill (Fig.5). The results obtained by EERA and SWAP_3C codes are compared in Fig. 6. Generally speaking, SWAP_3C provides higher values of the shear strain respect to the values obtained with the linear equivalent approach, up to relative differences of about 300%.

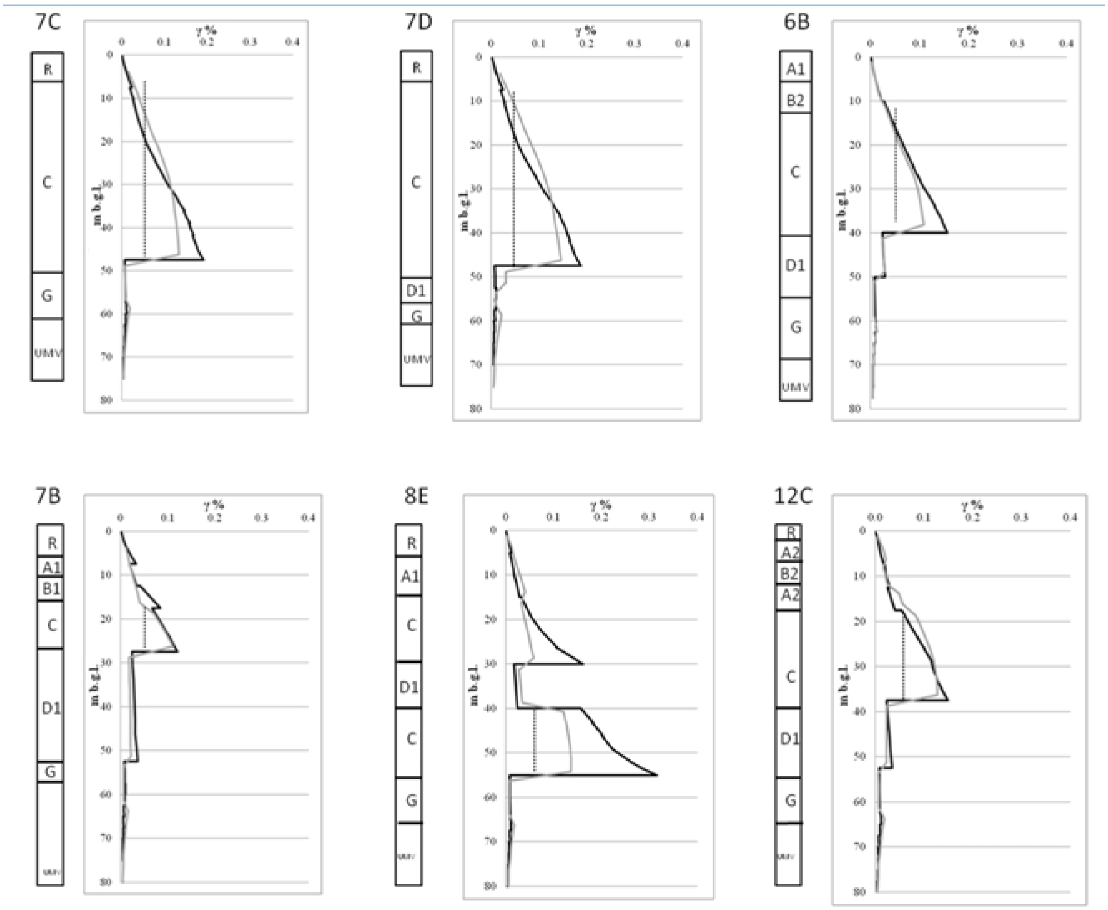
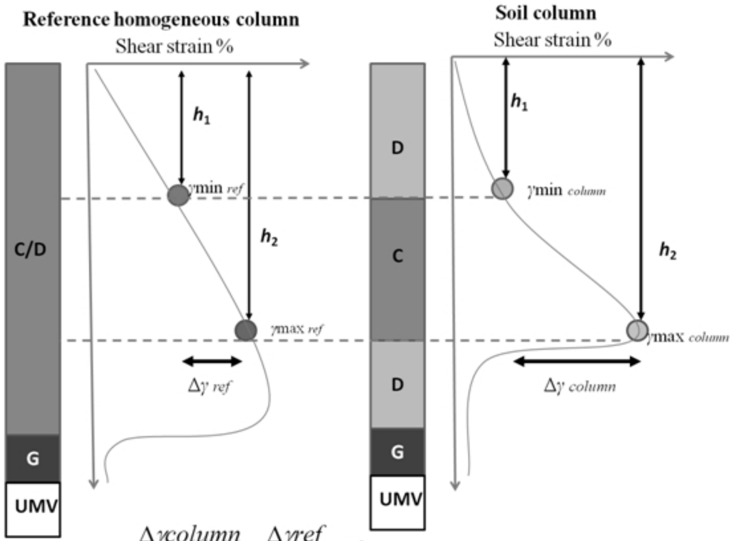


Figure 6. Example of comparison between the shear strain outputs obtained via numerical modelling by EERA (grey line) and SWAP-3C (black line). The dashed vertical line indicates the plasticity threshold lab-measured for the level C.

The numerical modelling performed by the use of both EERA and SWAP_3C numerical codes evidences the highest shear strain levels within the plastic layers, above all when "boxed" between two stiffer layers. In particular, the highest strains appear in correspondence with the interface between the lithotype C and the adjacent layers, i.e. where seismic waves encounter high seismic impedance drops along the soil column. The induced shear strain level exceed the volumetric threshold in the C level; the maximum levels of the shear strain decrease with the thickness of the soft layer boxed between stiffer layers.

3.1. Analysis of shear strain concentration

To point out the role of the heterogeneity characterising the profiles considered in this study, the shear strain values obtained by applying the 2 seismic wave propagation models, are compared with the corresponding values obtained for homogeneous soil profiles. This comparison was carried out in order to understand the role of the geometrical and mechanical conditions (i.e thickness and impedance contrast between adjacent layers) by taking into account the effect due to the position along the soil column.



$$\frac{\Delta\gamma column}{\Delta h} - \frac{\Delta\gamma ref}{\Delta h} > 0$$

Figure 7. Sketch illustrating the here proposed definition of the SSCI index.

For that reason, the results for each column were compared with the corresponding results obtained for a "reference column", this last one, characterized by the same total thickness but it is constituted by the clayey C level only or by the sandy D level only, depending on which between these two different kinds of soils was prevalent along the considered soil column.
To perform this comparison for each heterogeneous profile a Shear Strain Concentration Index (SSCI) was calculated according to the following definition:

$$SSCI = \frac{\Delta\gamma column}{\Delta h} = \frac{(\gamma \max column - \gamma \min column)}{h\max - h\min}$$

where:

γ max is the maximum shear strain within the C level in the considered column;
γ min is the minimum shear strain within the C level in the considered column;
(h max- h min) *is* the difference between the two depths at which the minimum and maximum values of the shear strain are obtained within the C level; this difference generally coincides with the thickness of the level C (Fig.7)
The same index was also calculated for the each corresponding reference column by the formula:

$$SSCI_r = \frac{\Delta\gamma reference}{\Delta h} = \frac{(\gamma \max reference - \gamma \min reference)}{h\max - h\min}$$

Using the above reported equations, it was possible to define the differential strain rate $\Delta\Gamma$ in the form:

$$\Delta\Gamma = SSCI - SSCI_r$$

A synthesis of the results obtained by the numerical modelling performed by both EERA and SWAP_3C is given in terms of ΔΓ vs. the thickness of the level C in Fig. 8. In particular, the comparison shows that higher values of ΔΓ are obtained by EERA and that, in any case, the ΔΓ generally increases with decreasing thickness of the C level. This increasing is much more evident for C level thickness lower than 15 m. Moreover, it is worth noticing that also the variation of the obtained results increases with the decreasing thickness of the C level; this output can be explained due to the increasing heterogeneity of the soil columns for decreasing thickness of the C level.
The different outputs obtained by the two codes can be related to the 3 component input which is applied at the bottom of the soil columns in the case of SWAP_3C as it causes the maximum shear strain not necessary to result in the same direction than in EERA. Nevertheless, since in the present study the results of the numerical models were compared in the same direction, further numerical simulations have been performing to compare the maximum shear strain levels without a selected direction (i.e., octahedral strain according to Santisi D'Avila et al. 2010)

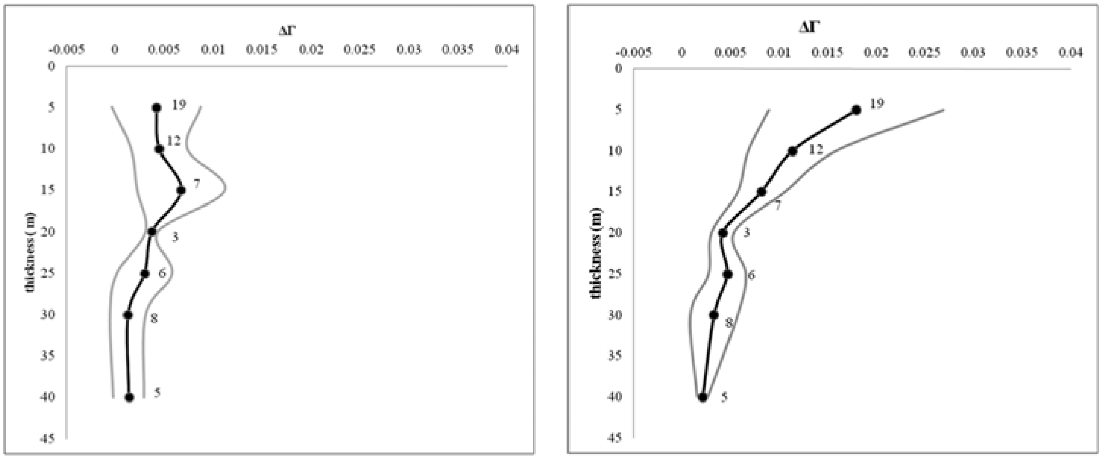


Figure 8. ΔΓ vs. the thickness of the level C resulting by the numerical modelling performed by EERA (right) and SWAP-3C (left). The gray lines indicates the standard deviation respect to the average shear strain (black), the numbers indicate how many samples were considered for each thickness class.

4. CONCLUSION

This study shows the role of the geometrical and mechanical heterogeneity within the alluvium deposits in determining the shear strain curves vs. depth related to 48 soil columns extracted from the 3D engineering-geology model of the Tiber alluvial deposits in the Rome's historical centre.
The numerical results obtained by both the two different numerical approaches (i.e., the linear equivalent approach by EERA and the finite element approach by SWAP_3C) highlight a main role of the plastic level C in increasing the co-seismic shear strain concentration within the considered soil column. The results in terms of computed maximum shear strains for the layers C obtained by the 2 codes present non-negligible relative differences that can reach a value of 300%.
These differences can be referred to the rheological models implemented in the two used codes. More in particular, SWAP_3C uses a 3D rheology which causes the maximum shear strain to not necessary result in a constant direction along the soil column; as a consequence, the here presented comparison between EERA and SWAP_3C strain outputs is not reliable because it is performed in a unique direction. The role of the heterogeneity and of the thickness of the plastic C level within the Tiber alluvial fill was here analyzed by introducing a Shear Strain Concentration Index (SSCI) for both the heterogeneous soil columns and for the reference homogeneous ones. These reference soil columns avoid considering the strain effect due to the soil location within the column. The differences between the SSCI index computed for the heterogeneous and the corresponding homogeneous columns (ΔΓ) were averaged for class of stiffness of the C level within the soil column.

The so-computed values were the considered as a function of the C level thickness and the averaged $\Delta\Gamma$ suggests a concentration of high shear strain within C level thinner than 15 m with an associated high variability of the resulting values. In this regard, it is worth noticing that the increasing dispersion can be explained due to an increasing heterogeneity along the soil column with decreasing thickness of the C level.

REFERENCES

Bonilla F., Bozzano F., Gelis C., Giacomi A.C, Lenti L., Martino S. & Semblat J.F. (2010). Multidisciplinary Study Of Seismic Amplification In The Historical Center Of Rome, Italy, Atti Del *5th Int. Conf. On Recent Advances In Geotech. Earthq. Engin. And Soil Dynamics*, May 24-29 2010, San Diego, California.

Bonilla F., Bozzano F., Gelis C., Giacomi A.C, Lenti L., Martino S. & Semblat J.F. (2011). Numerical modeling of shaking effects due to strong motions on the Tiber alluvial deposits in Rome (Italy).*4^{th} IASPEI/IAEE International Symposium: Effects of Surface Geology on Seismic Motion*, August 23-26, 2011, University of California Santa Barbara.

Bonilla, L.F., Liu, P.C. and Nielsen S. (2006). 1D and 2D linear and nonlinear site response in the Grenoble area. *Third International Symposium on the Effects of Surface Geology on Seismic Motion Grenoble*, France, 30 August - 1 September 2006. Paper Number: 082/S02

Bouden-Romdhane, N., Kham, M., Semblat, J.F. and Mechler, P. (2003). 1D and 2D response analysis vs experimental data from Tunis city. Beşinci Ulusal Deprem Mühendisliği Konferansı, 26-30 Mayıs 2003, *İstanbul Fifth National Conference on Earthquake Engineering*, 26-30 May 2003, Istanbul, Turkey, Paper No: AE-051

Bozzano, F., Andreucci, A., Gaeta, M. and Salucci R. (2000). A geological model of the buried Tiber River valley beneath the historical centre of Rome. *Bull. Eng. Geol. Env.*, **59**, 1-21.

Bozzano, F., Caserta, A., Govoni, A., Marra, F. and Martino, S. (2008). Static and dynamic characterization of alluvial deposits in the Tiber River Valley: new data for assessing potential ground motion in the city of Rome. *Journal of Geophysical Research*, **113**, B01303, doi: 10.1029/2006JB004873.

Bozzano, F., Funiciello, R., Gaeta, M., Marra, F., Rosa, C. and Valentini G. (1997). Recent alluvial deposit in Rome (Italy): morpho-stratigrafic, mineralogical and geomechanical characterisation. In the *Proceedings of the International Symposium of Egineering Geology and Environment*, Publ 1, 1193-1198.

Caserta A., Martino S., Bozzano F, Govoni A., Marra F. (2012). Dynamic properties of low velocity alluvial deposits influencing seismically-induced shear strains: the Grottaperfetta valley test-site (Rome - Italy). *Bull. Earth. Eng*. DOI 10.1007/s10518-012-9349-8.

Giacomi A.C. (2011), Implications of river system on recent Tiber river alluvium, *Il Quaternario*, **24**, p.110-112.

Karner, D.B. and Marra F. (1998). Correlation of Fluviodeltaic Aggradational Sections with Glacial Climate History: A Revision of the Classical Pleistocene Stratigraphy of Rome. *Geol. Soc. Am. Bull*., 110, 748-758.

Karner, D.B. and Renne P.R. (1998). 40Ar/39Ar Geochronology of Roman Volcanic Province Tephra in the Tiber River Valley: Age Calibration of Middle Pleistocene Sea-Level Changes, *Bull. Seis. Soc. Am*., 110, 740-747.

Marra, F., Florindo, F. and Karner D.B. (1998). Paleomagnetism and geochronology of early Middle Pleistocene depositional sequences near Rome: comparison with the deep sea □18O climate record. *Earth and Planetary Science Letters*, 159, 147-164.

Multidisciplinary Study Of Seismic Amplification In The Historical Center Of Rome, Italy, Atti Del *5th Int. Conf. On Recent Advances In Geotech. Earthq. Engin. And Soil Dynamics*, May 24-29 2010, San Diego, California.

Panza G., Romanelli F., Vaccari F., Decanini L. & Mollaioli F. (2004). Seismic Ground Motion Modelling And Damage Earthquake Scenarios; A Possible Bridge Between Seismologists And Seismic Engineers. *23rd General Assembly Of The International Union Of Geodesy And Geophysics*, Sapporo, Japan, 2003.

Rovelli, A., Caserta, A., Malagnini, L. and Marra F. (1994). Assessment of potential strong motions in the city of Rome. *Annali di Geofisica*, **37**, 1745-1769.

Rovelli, A., Malagnini, L., Caserta, A. and F. Marra (1995). Using 1-D and 2-D modelling of ground motion for seismic zonation criteria: results for the city of Rome. *Annali di Geofisica*, **38**(5-6), 591-605.

Santisi d'Avila M. P., Gandomzadeh A., Lenti L., Semblat J-F., Bonilla F., Martino S. (2010). Nonlinear site effects: interest of one directional –tree component (1C-3D) formulation . *5th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, proceeding May 24-29 in 2010, ISBN 1-887009-15-9, S. Diego (California).

Semblat, J.F. and Pecker, A. (2009). Waves and vibrations in soils: earthquakes, traffic, shocks, construction works". IUSS Press (Pavia, Italy), 49