ENGINEERING-GEOLOGICAL AND NUMERICAL MODELING FOR THE EVALUATION OF THE VIBRATIONAL INTERACTION BETWEEN THE CITY AGGLOMERATE AND HETEROGENEOUS GEOLOGICAL SYSTEM: PRELIMINARY RESULTS

C. Varone¹, L. Lenti², S. Martino¹

¹ Department of Earth Sciences and Research Center for the Geological Risks (CERI), University «Sapienza», Rome, Italy ² Université Paris-Est, Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux, Champs sur Marne, France

Introduction. This paper is focused on the evaluation of the Site-City Interaction [SCI: Kham *et al.* (2006); Semblat *et al.* (2008)] due to the influence of buildings on the local seismic response and on the seismically-induced effects of alluvial fills. The study is part of a PhD research of the University of Rome "Sapienza", which has been carrying on in co-operation with the IFSTTAR (Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux) of Paris. The Fosso di Vallerano valley (Rome, Italy) was selected as case study due to the fact that it is characterized by a highly heterogeneous geological setting and it is one of the most recent urbanized areas in Rome. More in particular, the Fosso di Vallerano valley hosts the "Europarco Business Park" i.e. the highest buildings (120 m) in Rome. A first phase of the study was focused on the reconstruction of the engineering-geological model of the valley through geological maps and cross-sections and a second phase is consisting in 2D numerical modeling of the seismic response in free field conditions as well as by considering the system city agglomerate according to a SCI approach. Some preliminary results of this research are here presented.

Engineering-geological model. The Rome urban area is located in a peculiar geodynamic context on the Tyrrhenian Sea Margin, at the transition between northern and central Apennines, that results from combined glacio-eustatic, sedimentary, tectonic and volcanic processes from the Pliocene to present (Karner and Marra, 1998; Marra *et al.*, 2008; Milli *et al.*, 2008; Sottili *et al.*, 2010). To reconstruct the complex geological setting of the valley, 250 log stratigraphies from boreholes were considered as well as in-site geomechanical investigations, available from technical reports and official documents (Bozzano *et al.*, 2000; Ventriglia, 2002; Marra F. Personal database). Based on such data four main lithotechnical units were distinguished in the Fosso di Vallerano valley:

- Plio-Pleistocene Marine deposits (Marne Vaticane Formation) composed by high consistency clays with silty-sandy levels;
- Pleistocene alluvial deposits of the Paleo Tiber 4 River (650-600 ky) composed by soils including graves, sands and clays;
- Volcanic deposits of the Alban Hills and of the Monti Sabatini Volcanic Districts (561-360 ky) consisting of highly heterogeneous tuffs;
- Recent alluvial deposits that filled the valley incisions since the end of the Würmian regression (18 ky-Present), characterized by a basal gravel level and including by different soft soils from sands to inorganic or peaty clays.

In particular, the Plio-Pleistocene Marine deposits represent the local geological bedrock. Mechanical and dynamic properties were attributed at each lithotechnical unit according to literature data (Bozzano et al., 2008; Caserta et al., 2012). The geological model was integrated by a geophysical dataset available from field survey in order to provide an engineering-geological model of the valley. In the June-October 2009, 3 ambient noise surveys were carried out in the Fosso di Vallerano Valley, using a 4Hz digital data-logger TROMINO (Micromed) set to a 128 Hz sampling rate; in the June – July 2014 an additional campaign of ambient noise records was carried out in the valley, using a Lennartz seismometer LE-3D/5s set to a 250 Hz sampling rate. The ambient noise analysis, performed according to the HVSR (H/V spectral ratio) Nakamura technique (Nakamura, 1989), pointed out a stratigraphic seismic response of the valley with a fundamental resonance frequency of 0.8-0.1 Hz. On the other hand, no amplification resulted in the surrounding volcanic hills. From June to July 2009 a free-field velocimetric array operated in STA/LTA (Short Time Average to Long Time Average) acquisition mode in the Fosso di Vallerano Valley, in order to record weak-motion events during the tail of the L'Aquila seismic sequence. The computed receiver functions (Lermo et al., 1993) of the recorded events confirm the results obtained from the HVSRs derived by the noise measurements.

Numerical modeling. In the last decades great efforts were aimed at seismic response numerical modeling since it represents a powerful tool for validation and prediction of physical phenomena related to the seismic wave propagation in problems of civil engineering and earthquake geotechnical engineering. A lot of numerical codes based on different mathematical approaches, i.e. Boundary Element Method (BEM), Finite Element Method (FEM) and Discrete Element Method (DEM), were implemented in both the time and the frequency domain. The numerical modeling actually represents the main tool to estimate the local seismic response and the seismically-induced effects, particularly in the urban area (Rovelli *et al.*, 1994, 1995; Bouden-Romdhane *et al.*, 2003; Panza *et al.*, 2004; Semblat and Pecker, 2009; Bonilla *et al.*, 2010) where the geophysical measurements are often not suitable for highlighting the local seismic response.

Calibration of the seimo-stratigraphic subsoil model. A calibration process by using the seismometric records collected in the Fosso di Valerano study area and the outputs from a 1D numerical modeling performed by EERA code [Equivalent – linear Earthquake Response Analysis: Bardet *et al.* (2000)] was performed to refine the seismo-statigraphy of the Fosso di Vallerano valley as well as to highlight the role played by the different layers (i.e., corresponding to the distinguished lithotecnical units) on the amplification function (A(f)). Based on the available high-resolution geological model, the calibration process was performed only by varying the shear wave velocity (Vs) of each lithotechnical units. To best fit the numerical model outputs with the A(f) derived from the recorded weak motions the records obtained at the reference site were de-convoluted to the local seismic bedrock. At this aim the soil column corresponding to the site of seismometric station that was operative during the Summer 2009 was selected (Fig. 1a).

The average site to reference spectral ratio (SSR) obtained from the recorded weak motions (Borcherdt, 1994; Lanzo and Silvestri 1999) were compared with the ones obtained from the 1D numerical modelling performed by assuming different Vs values for the log-stratigraphy of the analysed soil column. The Vs profile shown in Fig. 1a corresponds to the best fit between the records and the model outputs (Fig. 1b).

The resulting differences between the modeled and the recorded A(f) functions are attributed to 2D effects due to both the valley shape and the heterogeneous soil fill that cannot be modeled by the 1D EERA code.

Results of the 1D numerical modeling. The seismo-stratigraphic model of the subsoil was extrapolated to be applied at the entire Fosso di Vallerano valley; at this aim, 13 soil columns were selected from the reconstructed engineering-geological model that are representative for different layering conditions. The resulting A(f) functions were compared each other to highlight



Fig. 1 - Results of the calibration process: a) Vs profile corresponding to the best fit; b) comparison between numerical and experimental A(f).



Fig. 2 – Results of the 1D numerical modeling of the 56 soil columns composing the geological cross-section FF': a) contour map of the A(f) vs distance along the section b) geological cross-section FF' Legend: *Recent alluvial deposits* (18 ky-present): lithological units from 1 to 7. Deposits of the volcanic district of Alban Hills and of the M. Sabatini (561-360 ky): lithological unit 8. PaleoTiber 4 deposits (Santa Cecilia Formation) 650-600 ky: lithological units from 9 to 12. Plio-Pleistocenic bedrock "Marne Vaticane - Monte Mario - Monte delle Piche Formation": lithological units 13-14.

differences in the local seismic response; as it resulted from this comparison the first resonance mode range between 0.5-4.5 Hz, with a maximum FFT-spectral of 5. The higher resonance modes are represented by a minimum of 3 up to 6 in a frequency range 3-15 Hz. Moreover, a geological-cross section passing from the "Europarco Business Park" was discretized by 56 soil columns, whose lateral representativeness is of about 10 m, in order to obtain the 1D spatial distribution of the A(f) under free field conditions and by assuming a linear model performed by the EERA code.

The obtained A(f) distribution (Fig. 2a) is influenced by the stratigraphic effect only, i.e. related to the thickness of the alluvial deposits (including the recent alluvia and part the Paleo Tiber 4 deposits) with respect to the seismic bedrock depth. In particular, it is worth noticing that the first resonance mode range very closely between 0.5-0.6 Hz and remains constant for a large part of the cross section where the thickness vary in a range 35-65 m; on the contrary, in the portion of the valley where the thickness of the alluvia significantly decrease (15-20 m), due to the local structural setting, the first resonance mode corresponds to higher frequency values

(2.0-4.5 Hz). The higher resonance modes, in terms of both frequency value and FFT-spectral intensity, are related to the different seismo-stratigraphic conditions of each soil columns and, in particular, to the presence and stratigraphic setting of the layers that are responsible for the highest impedance contrast. The obtained A(f) distribution have to be regarded as influenced by the 1D stratigraphic layering only while it cannot take into account nor the lateral heterogeneity of the alluvial fill neither the shape of the valley.

Since it is reasonable to think that the local seismic response and the seismically-induced effects in a heterogeneous geological settings significantly conditioned by 2D effects, in terms of both amplification and shear strain distribution, as demonstrated by GIACOMI, 2013 for the Tiber Rivel valley in the historical centre of Rome, the here obtained results can be considered as a starting point for quantifying properly 2D seismic effects along he analyzed section.

Calibration of the absorbing boundary conditions for 2D fully numerical modeling. A proper 2D numerical modeling is planned to be performed through numerical codes implemented by institute of Paris, IFSTTAR, and these codes are based on different numerical solutions, the Finite Element Method (FEM) and the Boundary Element Method (BEM). As reported in Semblat et al., 2011, the numerical analysis of elastic wave propagation in unbounded media can be difficult due to spurious waves reflected at the model artificial boundaries; this point is particular critical for the analysis of wave propagation in heterogeneous or layered systems as in the present study. In this regard, Semblat et al. (2011) proposed an absorbing layer solution, based on Rayleigh/Caughey damping formulation that considers both homogeneous and heterogeneous damping in the absorbing layers. The efficiency of the method was tested through 1D and 2D FEM simulations, and the best results were obtained considering a damping variation up to $Q_{min}^{-1} \approx 2$ ($\xi = 1.0$) defined by a linear function in the heterogeneous case (five layers with piecewise constant damping) and linear as well as square root function in the continuous case. This theoretical study was performed considering a simple model composed by a homogeneous elastic medium and an absorbing lateral layered boundary. Such an approach was not yet tested for heterogeneous deposits, i.e characterized by vertical and lateral contacts among layers with different mechanical and dynamical properties. For this reason, the efficiency of the absorbing layers in case of highly heterogeneous deposits needs to be checked by additional numerical tests.

A new numerical model was designed according to the geometry used by Semblat *et al.*, 2011 but introducing two horizontal and homogeneous sub-layers (Fig 3a-3c). The results of the model were analyzed in order to choice the most efficient features (i.e. thickness and damping) of the absorbing layer system, and considering impedance contrasts from 1.4 up to 12.5 between the 2 horizontal sub-layers representing the physical domain of interest.

This parametric analysis was performed to evaluate the reduction of efficiency of the adsorbing layer in relation with the longest wave lengths propagated in the model, these latter functions of the maximum wave velocity of the 2 considered sub-layers.

Some preliminary results of the performed modeling are here presented for the case in which the two modelled sub-layers, are characterized: i) by the same velocity values for the P and S seismic waves respectively (i.e. 231 m/s and 400 m/s) and ii) by a different density (1800 $- 2500 \text{ kg/m}^3$ respectively); the so resulting impedance contrast is of about 1.4.

The modeling was performed by the FEM CESAR-LCPC code, by applying a synthetic input characterized by a predominant frequency of 10 Hz according to Semblat *et al.* (2011).

Two different typologies of absorbing layer system were considered, the first one corresponding to a homogenous absorbing layer (HOL) characterized by homogenous damping value equal to $Q_{min}^{-1} \approx 0.5$, or $\xi = 0.25$ (Rayleigh/Caughey damping), and the second one to a heterogeneous layer (HEL) constituted of 5 sub-layers that are characterized by a damping linearly varying from $Q_{min}^{-1} \approx 0.2$, or $\xi = 0.1$ (in the inner part of the absorbing layer system), to $Q_{min}^{-1} \approx 2$, or $\xi = 1.0$ at the boundary of the numerical model.

In agreement with the results obtained by Semblat et al. (2011), the here obtained preliminary



Fig. 3 – Efficiency analysis of the absorbing layer system in heterogeneous model: a) numerical model constructed for the numerical modeling considering HOL; b) results, in terms of displacement, from the numerical modeling made using homogenous HOL; c) numerical model constructed for the numerical modeling considering HEL; d) results, in terms of displacement, from the numerical modeling made using HEL.

results demonstrate that for the heterogeneous model the HEL solution provide results better than the HOL one. In particular, considering the HOL solution, the results show that in its lateral part the peak of the vertical component of the displacement (PGDv) induced by the seismic input in the most external part of the absorbing layer system (Point B in Fig. 3a) is equal to the 18.0% (Fig. 3b) of PGDv recorded in the inner part of the model (Point A in Fig. 3a). The PGDv in the most external part of the bottom portion of the absorbing system (Point D in Fig. 3a) is equal to 35.2% (Fig. 3b) of the peak recorded in the inner part of the model (Point E in Fig. 3a). These results lead to a preliminary finding: the absorbing layer system is more efficient in the later part of the model than in the bottom part. Analyzing the results obtained considering the HEL solution, it can be seen that the PGDv in F in the Fig. 3c (most external part of the heterogonous absorbing layer system) is equal to the 2.3% (Fig. 3d) of the PGDv recorded in the inner part of the model (Point E in Fig. 3c). The PGDv in the most external part of the bottom portion of the absorbing system (Point H in Fig. 3c) is equal to 9.9% (Fig. 3d) of the peak recorded in the inner part of the model (Point G in Fig. 3c). Similar results were obtained analyzing the reduction of the Arias Intensity associated to the vertical component of the acceleration within the absorbing layer. In fact, in the case of HOL (Fig. 3a) the Arias Intensity in the point B is the 0.6% than in the point A and in the point E is the 9.0% than in the point D. For the HEL solution (Fig. 3c), the Arias Intensity in the point F is equal to the 0.005% of the value in the point E and in the point H equal to the 0.6% respect to the value in the point G. These preliminary results encourage further studies in order to better design the absorbing layers at the boundaries of the model to improve their efficiency, above all in study models where an important heterogeneity of the soils involved in the propagation is present both vertically and laterally

Conclusions. Based on a high-resolution geological model reconstructed for the Fosso di Vallerano valley, a calibration of the subsoil seismo-stratigraphic was performed by considering the seismometric records of the aftershocks of the L'Aquila seismic sequence collected during the Summer 2009.

The calibration analysis pointed out the relevant role on the local seismic response of the 1D sub-layering of the subsoil deposits. This evidence was confirmed by a 1D modelling performed on 56 soil columns that discretized a geological cross section obtained along the Fosso di Vallerano valley in correspondence to the "Europarco Business Park".

To carry on a proper 2D numerical modelling of the valley, including the lateral heterogeneity of the alluvial deposits as well as the Site-City Interaction, a preliminary numerical experiment was performed aiming at calibrating the typology and the thickness of the absorbing layers system to reduce the presence of spurious waves reflected at the model artificial boundaries. The results obtained so far, demonstrate that the best solution consist on a heterogeneous absorbing layer (HEL) system, i.e. constituted of 5 sub-layers characterized by a damping linearly varying from $Q_{min}^{-1} \approx 0.2$ to $Q_{min}^{-1} \approx 2$.

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