2D NUMERICAL MODELLING OF SEISMICALLY INDUCED STRAIN EFFECTS IN A COMPLEX GEOLOGICAL SYSTEM HOSTING A RECENTLY URBANIZED NEIGHBOUR OF ROME

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Introduction. The Fosso di Vallerano valley (Rome, Italy) was selected as case study to evaluate the Site-City Interaction (SCI - Kham *et al*., 2006; Semblat *et al*., 2008), i.e. the influence of buildings on the local seismic response and on the seismically-induced effects of alluvial fills. The valley was chosen as 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. The first phase of the study was focused on the reconstruction of the engineering-geological model of the valley as well as on 1D numerical modeling of the seismo-stratigraphic setting of the alluvial body (Bozzano *et al*., 2015; Varone *et al*., 2014) that was used to calibrate the dynamic properties of the local seismostratigraphy. In a second phase, 2D numerical models were performed to analyze the local seismic response and the inducted strain effects assuming visco-elastic and visco-plastic modelling conditions for the free-field. Preliminary considerations were obtained on possible interactions between site and buildings even if more specific models will be implemented to better highlight the Site-City Interaction of the area.

Engineering-geological model. The subsoil geology of the Fosso di Vallerano valley was reconstructed thanks to 250 borehole logs as well as in-site geomechanical investigations, available from technical reports and official documents (Varone *et al*., 2014). The geological model was integrated by a geophysical data set available from field surveys in order to provide a high-resolution engineering-geological model of the valley.

Based on such data four main lithotechnical units were distinguished: i) Plio-Pleistocene marine deposits (Marne Vaticane Formation) composed by high consistency clays with silty-sandy levels; ii) Pleistocene alluvial deposits of the Paleo Tiber 4 River (650-600 kyr) composed by soils including graves, sands and clays; iii) volcanic deposits of the Alban Hills and of the Monti Sabatini Volcanic Districts (561-360 kyr) consisting of highly heterogeneous tuffs; iv) recent alluvial deposits that filled the valley incisions since the end of the Würmian regression (18 kyr-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 (Tab. 1) were attributed to each lithotechnical unit according to literature data (Bozzano *et al*., 2015 and references therein).

Numerical modeling. The numerical modeling actually represents the main tool to estimate local seismic response and seismically inducted effects, particularly in the urban area where the geophysical measurements are often not suitable for highlighting the local seismic response. A proper 2D numerical modeling was performed through CESAR-LCPC code implemented by the Institute of Paris IFSTTAR based on the Finite Element Method (FEM) considering the geological cross section shown in Fig. 1 (bottom).

Calibration of the absorbing boundary conditions for 2D numerical modeling. The numerical analysis of elastic wave propagation in unbounded media can be difficult due to spurious waves reflected at the mode artificial boundaries; this point is particularly 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,

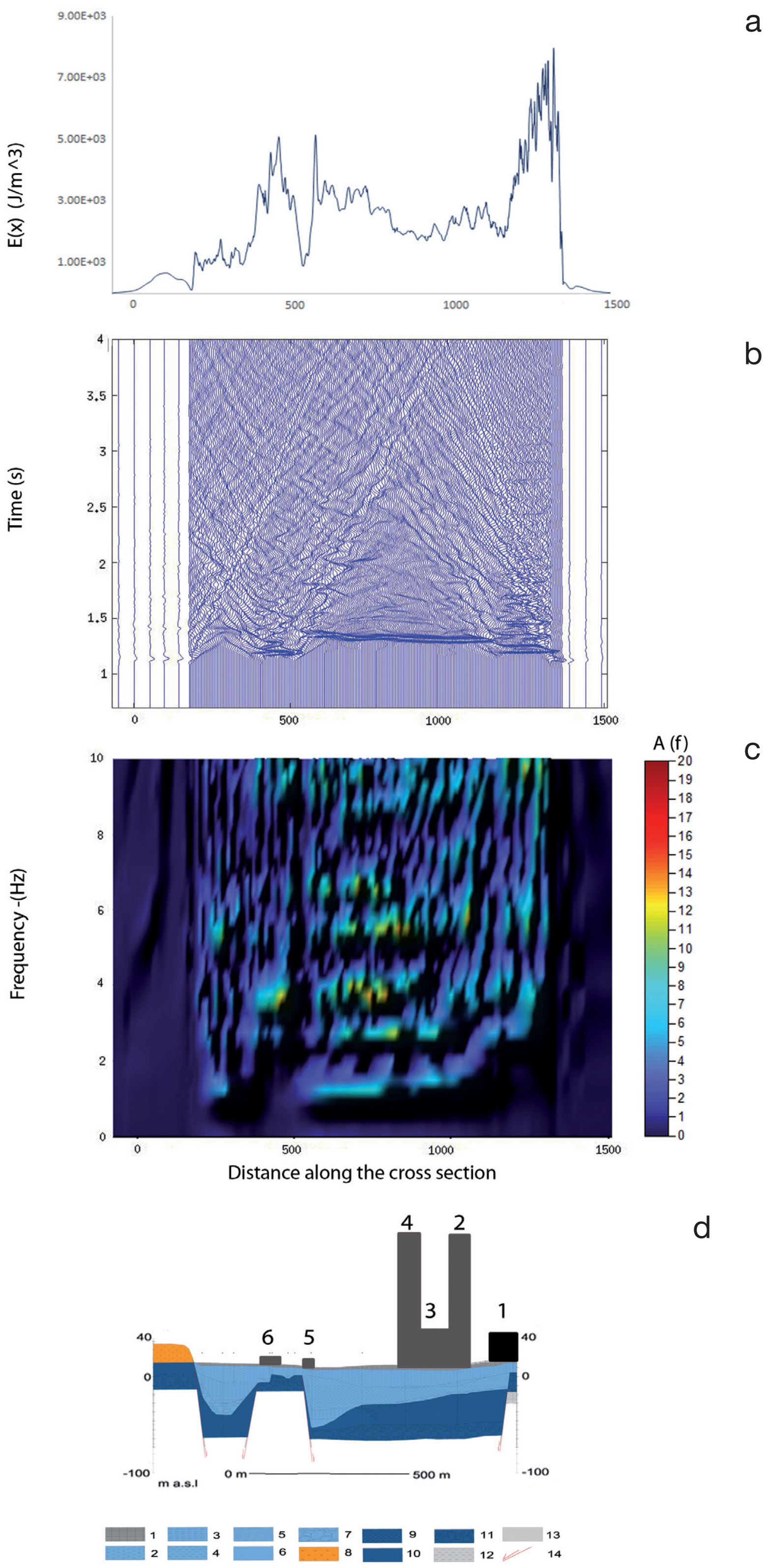

Fig. 1 – Variation of the E(x) index (a), propagations of the waves in the time (b) and amplification function (c) along the 2D section considered. Geological cross-section (d). Legend: recent alluvial deposits: (1-2-3-4-5-6-7); volcanic deposits (8); Paleo-Tiber 4 deposits (9-10-11); Plio-Pleistocenic bedrock (12-13); fault (14). Along the geological cross-section are represented the buildings built in 2006 (black) and in 2007 (grey) that will be modelled in the following 2D numerical modelling considering Site-City Interaction condition.

Tab. 1 - Mechanical and dynamic properties of the materials present along the geological cross section shown in Fig. 1.

Lithotechnical units	Lithology	Wave S velocity (m/s)	Density (kg/m^3)
1	Human fill	118	1733
2	Sandy clay	225	1682
3	Peaty clay	150	1753
4	Clay	235	1865
5	Peat	140	1295
6	Sand	417	1957
7	Gravel	713	2141
8	Volcanic deposits	1100	1835
9	Clay	357	1865
10	Sand	417	1957
11	Gravel	1100	2141
12	Clay	1100	2141
13	Sand	1100	2141

and the best results were obtained considering a damping variation up to $Q_{min}^{-1} \approx 2$ (ξ =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 approach was already experienced by considering a homogeneous elastic medium and an absorbing lateral layered boundary, but it was not yet tested for heterogeneous deposits, as in the here considered case study. As reported by Varone *et al*. (2014) a new numerical solution was designed according to the parameters used by Semblat *et al*. (2011) but introducing two horizontal and homogeneous sub-layers and considering impedance contrasts from 1.4 up to 12.5 to monitoring the efficiency of the lateral absorbing layers assuming different hypothesis.

The obtained results demonstrated that also for the heterogeneous domains, the best solution for an efficient attenuation of the spurious waves reflected at the model artificial boundaries consists in 5 absorbing layers with damping linearly varying; this optimal solution is considered for the 2D numerical modelling here presented.

Structural and dynamic characterization of the buildings. The Fosso di Vallerano valley is a portion of Rome characterized from the last decades by a strong urbanization. The urban agglomerate is mainly composed by residential buildings, characterized by rectangular or square geometry and height varying from 6 m up to 35 m; under the structural point of view, these edifices consist of concrete reinforcing structures. The valley also hosts particular kinds of buildings that are part of the "Europarco Business Park" and include the two skyscrapers (named "Europarco Tower" and "EuroSky Tower") that are 120 m and 155 m high, respectively. These towers are characterized by a rectangular plan geometry and they are composed by a steel coupled with a concrete reinforcing structure.

The characteristic oscillation period of each building was calculated applying some empirical relations present in literature (NTC08, NEHRP-97, Mucciarelli *et al.,* 2012; Kobayashi *et al.,* 1996; Enomoto *et al.,* 1998; Navarro *et al.,* 1998, 2007; Guler *et al.,* 2008, Italian Law. n.22631, USCGS 1949) with the aim of evaluating the variability of the value and choosing the values more representative (Fig. 3).

2D numerical modeling. A fully 2D numerical modeling of the geological cross section was performed through CESAR-LCPC (FEM code); an Ricker wavelet of 0 order with PGD (Peak Ground Displacement) of 1 m and an aftershock of the L'Aquila seismic crisis were applied

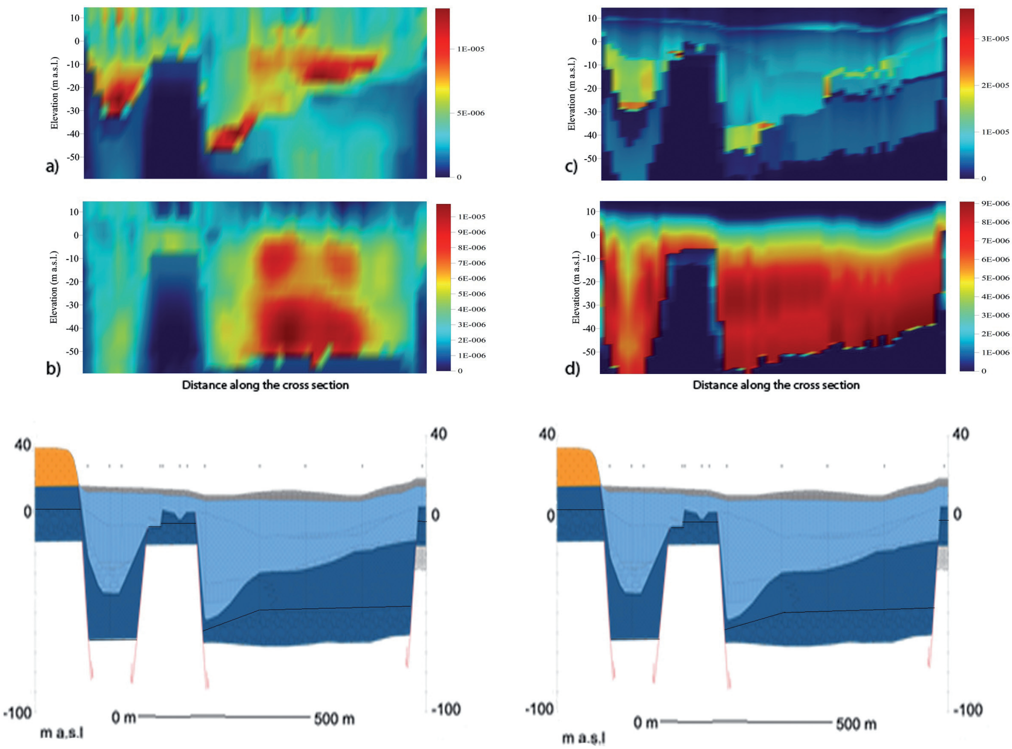

Fig. 2 – Results of the 1D and 2D numerical modeling (top and middle) and the geological cross-section considered (vertical exaggeration). With the black line is indicated the position of the seismic bedrock. Contour maps of the maximum shear strain: a) 2D heterogeneous model; b) 2D homogeneous model; c) 1D heterogeneous model; d) 1D homogeneous model.

as a vertically incident SV-wave at the model bottom. The amplification function distribution, $A(f)_x$, was computed along the numerical domain, as ratio in the frequency domain between the motions calculated on the sediments and the reference outcropping bedrock motion at the location of the volcanic deposits (Fig. 1). The numerical domain is characterized by specific lateral heterogeneous absorbing layer systems. For the modeling a perfectly elastic rheology were assumed so estimating the maximum expected displacements at the valley surface. Other simulations are actually ongoing by considering a visco-elastic rheology.

The model was discretized considering a triangular mesh with linear interpolation, the size of the elements was chosen according to the minimum inter-nodal distance respect Eq. 1:

$$\Delta h = \frac{\lambda}{12} \qquad (1)$$

with λ = wavelength and Δh = minimum inter-nodal distance.

Considering the value of 118 m/s as the lowest S-wave velocity (Vs) characterizing the alluvial deposits and the corresponding value of 1100 m/s for the seismic bedrock , the minimum inter-nodal distances retained are of 1 m and of 10 m for the deposits and for the seismic bedrock respectively. These inter-nodal distances ensure a frequency resolution up to 10 Hz. The model is composed by 269,917 nodes each with 2 degrees of freedom. The obtained results were analyzed in terms of wave propagation, amplification functions and ground-shaking energy along the considered profile (Fig. 2).

The resulting $A(f)_x$ were interpolated through a Kriging method to obtain a representation along the section as function of the frequency.

The energy $E(x)$ reached at the surface along the section was calculated according to the Eq. 2 as proposed by Kham *et al*. (2006):

$$E(\mathbf{x}) = \frac{\rho(x)}{T}\int_0^T \left[\frac{du}{dt}(x,t)\right]^2 dt \qquad (2)$$

where T is the signal duration, u the horizontal displacement, ϱ the density, and t the time. These parameters represent a cumulated kinetic energy, for unit of volume, normalized to the signal duration.

The seismically induced strain, in terms of maximum shear strain (MSS) along the geological section was calculated starting from the displacement values:

$$\gamma_{2D\_HE} = \frac{\Delta U}{\Delta H} \qquad (3)$$

where ΔU is the difference between the displacement values corresponding to two points located at two difference depths and at the same distance along the section, ΔH is the difference between the two depths at which the displacement values are related to.

Since it is was already proved that seismically-induced strain effects in a heterogeneous alluvial fills are significantly conditioned by 2D effects (Martino *et al*., 2015), a numerical modelling of the valley with a clayey homogeneous filling (lithological unit 4 in Tab. 1) was also carried out.

The maximum shear strains (MSS) obtained by the 2D numerical modelling, considering heterogeneous and homogeneous fill respectively were compared with the MSS obtained by 1D modeling carried out through the EERA code (Bardet *et al*., 2000) by discretizing the numerical domain in soil columns distant 10 m each other.

Results. The distribution of the $E(x)$ values along the geological cross-section of the Fosso di Vallerano valley (Fig. 1 top) shows that the thickness of resonant body, i.e. recent alluvial deposits and part of the Paleo-Tiber 4 deposits, plays an important role on the energy reached at the surface. In fact, the highest values (up to 8000 J/m^3) are reached in the portion of the alluvial body where the thickness is lower.

The wave propagation maps shown in Fig. 1 (middle) point out the efficiency of the absorbing layer system, in particular is possible to notice that, at the lateral boundaries, the portion of the model that correspond to the inner side of the absorbing layer system is characterized by the absence of spurious waves due to lateral reflections. Moreover, it is worth noticing that the wave propagation along the geological section is strongly influenced by the shape of the valley.

The analysis of the $A(f)_x$ (Fig. 1 bottom) highlight a non-homogenous distribution of the resonance peaks along the valley; more in particular, a wide part of the section is characterized by a first resonance peak around 1 Hz while the upper resonance modes are due to the peculiar heterogeneity in each portion of the valley. Indeed the central and the eastern portion of the valley show a first resonance peak at a higher frequency value (around 3 Hz) while upper modes due to the peculiar heterogeneity in each portion of the valley are also present.

The distribution of the MSS values were obtained along the geological cross sections by interpolating through a Kriging regression the MSS values computed with the 1D and 2D numerical modelling of the heterogeneous and of the homogenous geological sections. For each assumed condition, the results are reported in contour maps (Fig. 2). The MSS distribution in the heterogeneous model (Figs. 2a-2c), both in 1D and 2D condition, shows that the highest shear strain values are concentrated in the recent alluvial body, more in particular in the lithological unit 3 (peaty clay). In the homogenous model (Figs. 2b-2d), the MSS values show highest values in the western part of the valley that is characterized by a wide shape of the valley respect to the eastern portion; anyway, these values are lower respect to the ones resulted in the same location by considering a heterogeneous filling.

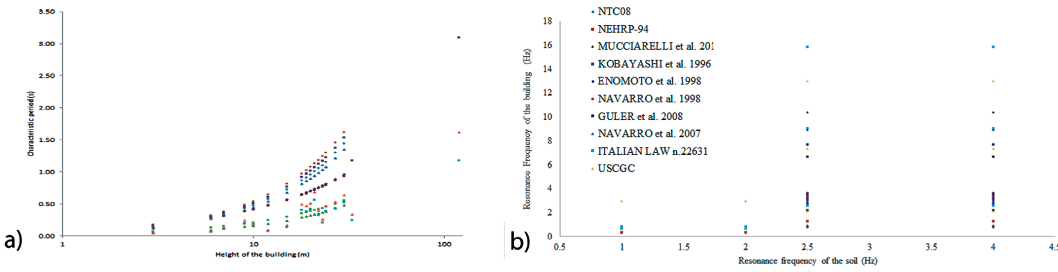

Fig. 3 – Variation of the characteristic period (left) and of the resonance frequency (right) of the building in function of their height. On the right side is also indicated the resonance frequency characteristic of the soil calculated through the 1D and the 2D numerical modelling.

The distribution of the period of vibration (T_b) of the buildings that are present in the valley in relations with their height shows a wide range of values (Fig. 3a). For this reason, it is not easy to select a unique value as representative for the dynamic behavior of a specific building. As indicated by Kham *et al*. (2006), the influence of the building on the local seismic response is higher in resonance condition between the building and the soil. An analysis of the distribution of the vibration period compared with the first resonance peak of the soil on which the buildings are founded, considering both the 1D (Varone *et al*., 2014) and the 2D (Fig. 1 bottom) model, was carried out to evaluate the empirical relations that predict values of buildings fundamental frequencies close to the resonance frequency of the soil (Fig. 3b). As also this analysis did not allow the selecting of an empirical formulation adapt for this case study, in the following specific modeling of the dynamic behavior of each building of the Europarco neighbor should be performed.

Conclusions. Starting from literature data on the geological setting of the Fosso di Vallerano valley in Rome and from the seismic background noise data collected during two measurement surveys, it was possible to obtain the geological and geotechnical model of the site. This profile was modelled to evaluate the propagation of seismic waves, the amplifications, the energy expected at the surface of the valley and the seismically induced strain in term of MSS.

The distribution of the $E(x)$ values along the geological cross-section (Fig. 1 top) and of the wave propagation maps (Fig. 1 middle) show that the shape of the valley and the thickness of the resonant body strongly influence these parameters. Moreover, the efficiency of the absorbing layer system as calibrated by Varone *et al*. (2014), was confirmed by the results obtained by the 2D numerical modeling. The analysis of the $A(f)_x$ (Fig. 1 bottom) highlight a non-homogenous distribution of the resonance peaks along the valley; more in particular, a wide part of the section is characterized by a first resonance peak around 1Hz indeed the central and the eastern portion of the valley show a first resonance peak at a higher frequency value (around 3Hz).

The distribution of the MSS shows that, in the heterogeneous model (Figs. 2a-2c), the highest shear strain values are concentrated in the recent alluvial body, in particular in the lithological unit 3; in the homogenous one (Figs. 2b-2d) the MMS values are lower respect to the ones resulted in the same location by considering a heterogeneous filling.

The analysis of the period of vibration (T_b) of the building did not allow to select an empirical formulation adapt for this case study, in fact the distribution of the obtained values with their height shows a wide range of variation. For this reason, it was not possible to chosen a unique value as representative of the dynamic behavior of the buildings and specific modelling are required to understand the dynamic behavior of each building of the Europarco neighbor.

Other simulations are necessary to understand the role of the Site-City Interaction (SCI), i.e. the effect of the presence of the buildings built during the last decade on the propagation of the seismic waves, on the amplifications and on the energy expected at the surface level of the valley.

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