SITE-CITY INTERACTION (SCI) IN A RECENT URBANIZED AREA OF ROME (ITALY)

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ABSTRACT

This paper focuses on the influence of buildings on ground motion and local seismic response (Site-City Interaction – SCI). The free-field assumption at the ground surface (i.e. absence of structures) is widely used to assess the local seismic response. This condition leads to a coarse approximation in urban areas. To evaluate the dynamic interaction between urban agglomerates and soil, the Fosso di Vallerano area in Rome (Italy) was selected as a case study. This alluvial valley is characterized by a very complex geological setting; moreover, it was involved in a very recent urban expansion, which locally modified the free field conditions of the original alluvial valley. A high resolution engineering-geological model of the valley was reconstructed and several geophysical investigations have also been carried out by considering both seismic events and noise measurements. Recorded weak motions were used to calibrate the seismo-stratigraphic setting of the valley. At the same time, structural and dynamic features of the different typologies of existing buildings were evaluated. 2D numerical modelling (FEM based) of coupled systems (buildings and soil) was carried out to assess the local response due to the increasing urbanization observed in the last decade. The seismic response of the subsoil was quantified in terms of ground shaking, amplification function and cumulative kinetic energy along the surface. The main findings highlight that the local seismic response of the urban area is significantly modified by the presence of buildings.

Keywords: Site-City Interaction, Ground Motion, Numerical modelling, Rome,

1. INTRODUCTION

Free field condition of the ground surface considers the absence of structures that can generate vibrations and does not consider the multiple soil – structures – soil interaction. This assumption can determine a strong approximation in case of urban areas. Several studies show the transmission of vibrations from the buildings to the soil, i.e. amplification of the ground shaking and generation of a wave field that can propagate far from the city center (Wirgin and Bard, 1996; Guéguen et al., 2000; Kham et al., 2006; Semblat et al., 2008) defining this phenomenon as Site-City Interaction (SCI - Guéguen et al. 2002, Kham et al., 2006; Semblat et al., 2008).

The Fosso di Vallerano valley (Rome, Italy) was selected as a case study to evaluate the SCI, i.e. the influence of buildings on the local seismic response in case of complex geological settings. Several studies modeled the transmission of vibrations from the buildings to the soil, i.e. amplification of the ground shaking, during earthquakes, and generated wave field that can propagate far from the city center. These studies are mainly engineering focused, while the geological component is strongly simplified;

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therefore, complex 1D amplification effects due to soil layering as well as 2D effects due to lateral heterogeneity, topographic and shape of the seismic bedrock are generally neglected. In this regard, the Fosso di Vallerano valley was selected as it is characterized by a highly heterogeneous geological setting and it is one of the most recently urbanized areas of Rome. Moreover, the Fosso di Vallerano valley hosts the “Europarco Business Park” skyscrapers, i.e. presently the highest buildings (120 m) in the city. A preliminary phase of the study has been dedicated to the reconstruction of the engineering-geological model of the valley and to the 1D numerical modeling of the seismo-stratigraphic setting of the alluvial body (Bozzano et al., 2015, 2016; Varone et al., 2014). These results were propaedeutic to the 2D numerical modeling of the seismic response in free field conditions as well as by considering the city agglomerates according to a SCI approach.

2. 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, which results from combined glacio-eustatic, sedimentary, tectonic and volcanic processes from the Pliocene to present. The Fosso di Vallerano valley is an alluvial valley situated in the southern part of Rome; it is composed of two sub-valleys that join before the main Tiber River confluences of the Vallerano and the Cecchignola creeks (Fig. 1). The geomorphology of the Fosso di Vallerano is characterized by a wide flat area, that corresponds to the alluvial plains (10 m a.s.l.) of the creeks, delimited by smoothed hills (35-50 m a.s.l).

![Figure 1. – Satellite view of the Fosso di Vallerano valley. The track of the geological cross-sections considered in this study is also reported.](image)

The study area also exhibits a complex geomorphological setting because of a complex evolution that was linked to the Würmian glacio-eustatic cycle, which led to a series of successive deviations and rearrangements of the riverbed (Ascani et al. 2008). The complex geological setting of the valley is reported in Bozzano et al. (2016) and it was derived through 250 log stratigraphies from boreholes as well as from field investigations.
The deposits which fill the Fosso di Vallerano valley are ascribable to 4 main lithological units (Bozzano et al., 2016) as shown in the geological cross section of Fig.2:

1. Plio-Pleistocene marine deposits consisting in high consistency clays with silty-sandy levels (Marne Vaticane Formation - PP);

2. Pleistocene alluvial deposits of the Paleo Tiber 4 River consisting in gravels, sands and clays (Santa Cecilia Formation - PT);

3. volcanic deposits of the Alban Hills and of the Monti Sabatini Volcanic Districts consisting of highly heterogeneous tuffs (VL);

4. recent alluvial deposits characterized by a basal gravel level and different soft soils from sands to inorganic or peaty clays (AL).

These latter unit filled the valley incisions since the end of the Würmian regression to the present, the Marne Vaticane Formation represents the local geological bedrock while the local seismic bedrock is located at the top of the Pleistocene gravels (Paleo Tiber 4 deposits).

Figure 2. Geological cross sections traces of Fig. 1. Legend: AL deposits: from 1 to 7. VL deposits: 8. PT deposits: from 9 to 13. PP deposits: from 14 to 15. 16) Fault. 17) Borehole (modified from Bozzano et al. 2016).

The dynamic properties attributed to the subsoils of the Fosso di Vallerano valley are summarized in Tab.1 and were derived by field investigations and laboratory tests as reported in Bozzano et al., (2016).

Table 1. Dynamic properties attributed to the lithological units characterizing the cross section shown in Fig. 2. (Modified from Bozzano et al., 2016).
### Lithology Properties

<table>
<thead>
<tr>
<th>Lithology</th>
<th>$\gamma$ (kN/m$^3$)</th>
<th>$G_0$ (MPa)</th>
<th>$V_s$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Anthropic fill material</td>
<td>17</td>
<td>82</td>
<td>118</td>
</tr>
<tr>
<td>2 Volcano-elastic sandy clays</td>
<td>16.5</td>
<td>53</td>
<td>225</td>
</tr>
<tr>
<td>3 Peaty clays</td>
<td>17.2</td>
<td>64</td>
<td>150</td>
</tr>
<tr>
<td>4 Silty clays</td>
<td>18.3</td>
<td>66</td>
<td>235</td>
</tr>
<tr>
<td>5 Peat</td>
<td>12.7</td>
<td>25</td>
<td>140</td>
</tr>
<tr>
<td>6 Sands</td>
<td>19.2</td>
<td>334</td>
<td>417</td>
</tr>
<tr>
<td>7 Gravel</td>
<td>21.0</td>
<td>1068</td>
<td>713</td>
</tr>
<tr>
<td>8 Tuffs</td>
<td>21.0</td>
<td>1068</td>
<td>800</td>
</tr>
<tr>
<td>9 Silty clays</td>
<td>18.3</td>
<td>101</td>
<td>357</td>
</tr>
<tr>
<td>10 Sands</td>
<td>19.2</td>
<td>334</td>
<td>417</td>
</tr>
<tr>
<td>11 Gravel</td>
<td>21.0</td>
<td>1068</td>
<td>1100</td>
</tr>
</tbody>
</table>

### 3. NUMERICAL MODELLING

A fully 2D numerical modeling has been performed through the Finite Element Method (CESAR – LCPC code) by considering the geological cross section shown in Fig. 2 and assuming the urban development of the last ten years. An absorbing layer system (CALM - Semblat et al. 2011) has been calibrated and integrated to the models to avoid the reflection of the waves at the numerical boundaries.

#### 3.1 Calibration of the absorbing boundary solution for full 2D numerical modeling

The numerical analysis of elastic wave propagation in unbounded media can be affected by the presence of spurious waves reflected at the model artificial boundaries (Semblat et al., 2011). This effect is particularly relevant for the analysis of wave propagation in heterogeneous or layered systems as in the present study. To avoid the presence of spurious waves, Semblat et al. (2011) proposed an absorbing layer solution (CALM), based on Rayleigh/Caughey damping formulation, and characterized by homogeneous or heterogeneous damping in the absorbing layers.

The authors assessed the efficiency of CALM solution for both 1D and 2D condition and the best solutions proposed are characterized by a damping variation up to $Q^{-1}_{\text{min}} \approx 2$ ($\xi = 1.0$) 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. These evaluations have been performed considering a homogenous artificial model so the efficiency of CALM solution in case of highly heterogeneous deposits needed to be assessed.

As reported by Varone et al., (2014), the CALM solution introduced by Semblat et al. 2011 to absorb spurious waves, available for homogeneous materials, was improved to be used in heterogeneous configurations. In particular these improvements are used here in the following numerical modeling.

#### 3.2 Structural and dynamic characterization of the buildings

An intense urban expansion characterized the Fosso di Vallerano valley in the last decades. Residential buildings, with a rectangular or square geometry and a height varying from 6 m up to 25 m mainly characterized the urban agglomerates. The “Europarco Business Park” which includes the two skyscrapers (named “Europarco Tower” and “EuroSky Tower”) that are 120 m and 155 m high, is also hosted in the study area (Fig. 3). These buildings are characterized by a rectangular geometry and they
are constituted by a steel coupled with a reinforced concrete structure.

Figure 3. View of the “Europarco Business Park” during its construction in 2012 (left) and nowadays (right)

The dynamic characteristics of the buildings have been evaluated through a modal analysis by FEM (CESAR – LCPC code). All the buildings have been modeled considering their super-structure, i.e. columns, beams and foundations, and assuming the concentrated masses and stiffnesses in 2D. The computed fundamental periods are displayed in Tab. 2.

Table 2. Dynamic characteristics of the buildings built during the last decade in Fosso di Vallerano valley.

<table>
<thead>
<tr>
<th>ID of the building</th>
<th>Height (m)</th>
<th>Fundamental period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24</td>
<td>0.24</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
<td>0.26</td>
</tr>
<tr>
<td>4</td>
<td>120</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>0.05</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>0.03</td>
</tr>
</tbody>
</table>

3.3 Numerical modeling of the SCI models

Three different conditions have been modelled starting from the geological cross section shown in Fig. 2. The first is a free field condition model characterized by the absence of structures able to vibrate, and in a second step the buildings were added in order to create coupled Site-City Interaction (SCI) models. To create these last models, the urban development of the area in the last 10 years has been taken into account. A fully numerical modelling was performed for each above mentioned condition resulting in the following three modelling:

1. Model 1: Free field conditions (Fig 5a).

2. Model 2: SCI condition, i.e. presence of one building founded on the soil through raft foundation (shallow foundations) that represents the urban evolution along the section during 2006 (Fig 5b).
3. Model 3: SCI condition corresponding to 2007. This model is characterised by the presence of six buildings, four founded on a raft foundation and two founded on piles (deep foundations) (Fig 5 c).

An original Ricker wavelet (Ricker 1943, 1953) of order 0 with PGD = 1m (synthetic wavelet) (Fig. 4) and 3 natural earthquakes recorded in the valley (Bozzano et al., 2015) have been applied as seismic input within the seismic bedrock at the bottom of the heterogeneous alluvial body. Only the results obtained from the application of the Ricker wavelet (Ricker 1943, 1953) will be presented since these are in good agreement with the ones obtained from the application of naturals inputs.

Figure 4. Time variation of the Ricket wavelet applied as input in the numerical modeling.

A triangular mesh with linear interpolation has been considered to discretize the model, the size of the elements was chosen according to the equation (1):

\[
\Delta h = \frac{\lambda}{12}
\]

with \( \lambda = \) wavelength and \( \Delta h = \) Element size.

The lowest S wave velocity that characterize the alluvial deposits is 118 m/s and the largest one is 1100 m/s, an element size of 1m in the first case and 10 m in the latter were chosen to solve the problem up to a frequency of 10 Hz. The models are composed of 269,917, 274,810 and 323,702 nodes respectively and are characterized by 2 degrees of freedom. The numerical modelling was performed assuming an elastic behavior of the materials.

The main physical parameters representative of the ground shaking were computed. In particular, the propagated wave field along the section and the amplification functions distribution (Fig. 5) were derived. The amplification functions \( A(f) \) (Borcherdt, 1994) were obtained considering the spectral ratio between the signals in the valley and the input recorded on the outcropping seismic bedrock. The resulting \( A(f) \) have been interpolated through a Kriging method with the aim to obtain a map of the amplification functions distribution, \( A(f)_x \), along the analyzed 2D section.

4. RESULTS

The effectiveness of the absorbing layer system introduced on both sides and at the bottom of the model to dampen spurious waves is shown in Figure 5 (top). No spurious waves come back in the valley from the boundaries and the bottom of the model.
From left to right: Model 1, 2 and 3.  

From Fig. 5 (top) it is also possible to notice the influence of buildings: the presence of the buildings induces major changes in the propagated wave field, leading to a low ground motion at the building’s foundation level (Fig. 5 top). Previous studies already showed this strong kinematic effect (Boutin and Roussillon 2004, Kham et al. 2006). This effect is evident at the base of all the buildings regardless of the type of foundations. Some additional numerical modelling with and without deep foundation were performed and confirmed the independence of the effect from the foundations typology. The influence of the presence of buildings is relevant also in terms of amplification functions (Fig 5 middle): all modes present in the case of model 1 (free surface conditions) are nullified in the portions occupied by the buildings and larger amplifications are calculated laterally and near the buildings foundations.

5. CONCLUSIONS

This study aims at evaluating the Site–City Interaction (SCI), to assess the role of different typologies of buildings on seismic wave field and on the amplifications distribution within an alluvial valley. The obtained results demonstrate that the presence of buildings induces a strong reduction of the ground motion under their foundations so that the amplification peaks characterizing the free field condition are nullified. At the same time, an increasing of the amplification is detected in the surrounding of the buildings causing energy redistribution at ground surface. These observations show that the presence of buildings may modify the local seismic response expected assuming free field conditions. Additional numerical modelling is required to better explore the SCI effect in highly heterogeneous alluvial filling, in particular 3D numerical modelling of both buildings and soil to better understand the phenomenon. Future perspectives consist in accounting for different spatial arrangements of buildings and subsoil geometries to evaluate effects induced on SCI.

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