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Modelling of seismic urban wavefield in highly heterogeneous Site-City configurations

C. Varone
École Supérieure d'Ingénieurs des Travaux de la Construction (ESITC) de Paris, Arcueil, France

L. Lenti
University Paris-Est, Paris, France
IFSTTAR The French Institute of Science and Technology for Transport, development and networks, Marne la Vallée, France

S. Martino & F. Bozzano
Department of Earth Sciences, University of Rome «Sapienza», Rome, Italy
Research Center for the Geological Risks (CERI), Rome, Italy

J.F. Semblat
École Nationale Supérieure de Techniques Avancées (ENSTA) ParisTec, Paris, France
IMSIA UMR 9219, Institute of Mechanical Sciences and Industrial Application, Palaiseau, France

ABSTRACT: The Fosso di Vallerano valley, Rome (Italy), is an alluvial valley characterized by a complex geological setting which implies significant vertical and horizontal heterogeneities. In the last decade, this area experienced an intense urbanization which changes the original seismic response conditions of free field. According to these features, the Fosso di Vallerano valley has been chosen as case study to analyze the influence of buildings on the local seismic response (Site-City Interaction – SCI). A high resolution geological model of the valley has been reconstructed and the dynamic behavior of the buildings has been evaluated. A 2D finite element modelling has been performed by assuming an elastic rheology and accounting for the progressive urban expansions of the Fosso di Vallerano valley. The results point out that the presence of buildings significantly influences the spatial distribution of the urban ground motion within the entire valley and not only close to the buildings.

1 INTRODUCTION

This paper focuses on the assessment of the Site – City Interaction (SCI *sensu* Kham et al., 2006, Semblat et al., 2008) to account for the interference of buildings on seismic ground motion respect to original free field conditions. The chosen case study corresponds to the Fosso di Vallerano valley, SE of Rome city (Italy), where recently an urban district was built. The valley corresponds to an alluvial basin, characterized by a complex and heterogeneous geological setting; it hosts the "Europarco Business Park", which presently includes the tallest buildings in Rome.

Moderate to severe seismicity can affect the study area because of earthquakes that originate in the seismogenic zones that are close to the city. Several studies focused on the local seismic response in Rome's urban area (Bozzano et al. 2008; Martino et al. 2015, Meza-Fajardo et al., 2019) and highlighted the amplification phenomena within the city.

To assess the local seismic response of the Fosso di Vallerano valley considering free field condition as well as the city agglomerate according to a SCI approach, a fully 2D FEM numerical modelling has been carried out considering a linear elastic behavior for both geological (i.e. alluvial soil) and engineering (i.e. bearing structure and foundations of buildings) materials.

2 ENGINEERING GEOLOGICAL MODEL OF THE ALLUVIAL VALLEY

The city of Rome is located in a peculiar geodynamic context on the Tyrrhenian Sea margin, at the transition between northern and central Apennines and its complex geological setting results from the combination of glacio-eustatic, sedimentary, tectonic and volcanic processes from the Pliocene age to present time. The Fosso di Vallerano alluvial valley is part of the river drainage system related to the left tributaries of the Tiber river and it is characterized by a complex geomorphological and geological setting.

A geological model of the valley has been obtained through 250 log stratigraphies from boreholes as well as in-site geotechnical investigations (Bozzano et al., 2015, 2016).

Based on these data 4 main lithotechnical units were distinguished (Bozzano et al., 2017):

1. Pliocene and Pleistocene Marine deposits (Marne Vaticane Formation) composed by high consistent clays with silty-sandy levels (units 13 – 14 in Fig. 1);
2. Pleistocene alluvial deposits of the Paleo Tiber 4 River (650-600 ky) composed by soils including gravels, sands and clays (units from 9 to 12 in Fig. 1);
3. Volcanic deposits of the Alban Hills and of the Monti Sabatini Volcanic Districts (561-360 ky) consisting of highly heterogeneous tuffs (unit 8 in Fig. 1);
4. 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 different soft soils from sands to inorganic or peaty clays (units from 1 to 7 in Fig. 1);

The geological model was integrated by a geophysical dataset available from field surveys in order to provide a high-resolution engineering-geological model of the subsoil (Varone et al. 2015). The geological cross section taken into account in this paper in shown in Fig. 1 and the dynamic properties (Tab. 1) have been attributed to the deposits according to Bozzano et al. (2016).

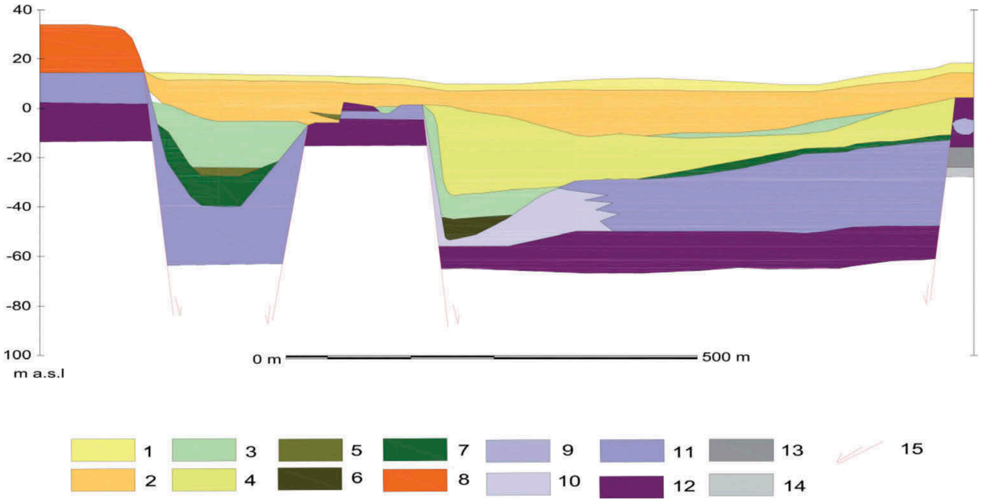

Figure 1. Geological cross sections. 1) Anthropic filling material; 2) Sandy-Clays characterized by a marked volcanic component; 3) Peaty clays; 4) Clays and silts; 5) Peat; 6) Sands and silty sands; 7) Polygenic, loose and heterometric gravels, with volcanic and sedimentary components; 8) Undifferentiated pyroclastic material; 9) Sandy clays and silts; 10) Clays and silts with peaty layers; 11) Sands and silty sands; 12) Loose gravels with heterometric sedimentary component; 13) Marine clays and silty clays; 14) Marine sands and silty sands; 15) Fault (modified from Bozzano et al., 2016).

Table 1. Mechanical properties attributed to the various geological units (Bozzano et., 2016).

Lithological units	ρ (kg/m^3)	Vs (m/s)	Vp (m/s)	ν	G (MPa)	E (MPa)
1	1733	118	221	0.30	24.3	61
2	1682	225	421	0.30	85.1	213
3	1753	150	281	0.30	39.4	99
4	1865	235	440	0.30	103.0	257
5	1295	140	262	0.30	25.4	63
6, 12	1957	417	780	0.30	340.3	851
7	2141	713	1334	0.30	1088.3	2721
8	1835	1100	1905	0.25	2220.2	5550
9	2141	550	1029	0.30	647.6	1619
10	1865	250	468	0.30	116.6	291
11	1865	357	668	0.30	237.7	594
13	2141	1100	2058	0.30	2590.2	6475
14	2141	1100	1905	0.25	2590.2	6475

3 NUMERICAL MODELLING

The geometry of the geological cross sections (Fig. 1) was implemented in FEM (CESAR-LCPC software Humbert et al. 2005) and a linear elastic behavior was assumed for all the materials in order to assess the SCI effects in the worst condition in terms of amplification of the ground motion.

A seismic input represented by a 0th order Ricker wavelet (Ricker 1953) with a PGD (Peak Ground Displacement) of 1 m and with a non-negligible frequency content in the band 0.1 - 15 Hz has been applied.

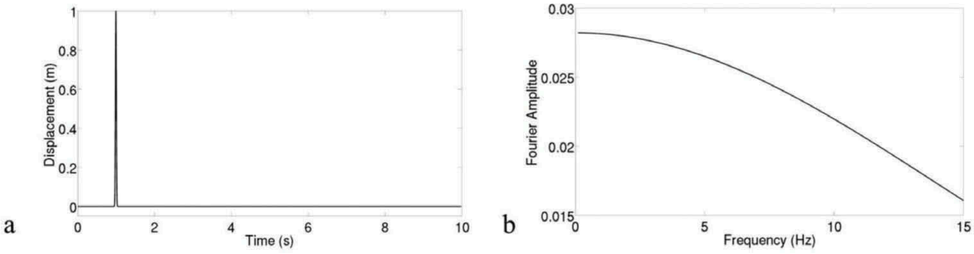

Figure 2. Time variation (a) and frequency content (b) of the Ricker wavelet applied as input in the numerical modeling.

The numerical models have been discretized by a three-noded linear mesh with a size chosen to solve the problem up to a frequency of 10 Hz. A set of heterogeneous absorbing layers (C.A.L.M. Semblat et al., 2011) has been modeled to avoid spurious waves reflected at the boundaries of the numerical model.

The C.A.L.M. absorbing layer solution (Semblat et al., 2001) is based on Rayleigh/Caughey damping formulation, and it is characterized by homogeneous or heterogeneous damping. The efficiency of the method in case of highly heterogeneous soil deposits has been assessed through 1D and 2D FEM simulations. The best results were obtained considering a solutions characterized by a damping variation up to Qmin-1 ≈ 2 (ξ =1.0) defined by a linear function in a heterogeneous C.A.L.M. (five layers with piecewise constant damping) (Lenti et al., 2015). The seismic response of the cross section has been assessed assuming free field condition as well as SCI condition.

3.1 *Numerical modeling of the SCI models*

The progressive urban development has been modeled assuming two urbanization steps corresponding to:

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

ID of the building	Height (m)	Fundamental period (s)
1	24	0.24
2	120	2
3	32	0.26
4	120	2
5	6	0.05
6	7	0.03

1. Model TS1 (2006): One building was built in the eastern portion of the section (Fig. 3 top):
2. Model TS2 (2011): Three buildings in the "Europarco Business Park" (including Europarco and Eurosky Towers) and two minor buildings (Fig. 3 bottom)

In summary, two time steps were defined for a total of 6 buildings.

Each building was previously characterized from a structural perspective: they are mainly reinforced concrete structure with shallow foundation except for buildings 2 and 4 (Fig. 3) that are characterized by mixed bearing structure of steel and reinforced concrete with deep foundations. Their dynamic behavior was modelled through FEM based modal analysis considering buildings as stand-alone structures. The super – structure of each building has been modelled assuming perfectly stiff beam-to-column junctions and fixed base to evaluate the fundamental period and modes of vibration. The computed fundamental periods are displayed in Tab. 2.

4 RESULTS

The main physical parameters representative of the ground shaking were calculated and a spatial distribution of the correlation, respect to the ground motion in correspondence of the outcropping bedrock, of the ground motion along the surface of the models are here presented to assess the spatial variability of the urban ground motion.

A cross-correlation analysis has been performed considering the covariance between a given signal (reference signal, i.e. seismic bedrock) and the signals along the surface.

The covariance C of the ground motions is defined as follows (1):

$$\mathrm{C(r)} = \frac{\langle \mathrm{u(x)}^{*}\mathrm{u(x')}\rangle_{\mathrm{r}=\|\mathrm{x}-\mathrm{x'}\|}}{\sqrt{\langle \|\mathrm{u(x)}\|^{2}\rangle\langle \|\mathrm{u(x')}\|^{2}\rangle}} \tag{1}$$

where u is the displacement, x and x' are respectively the location of a reference point of the model (taken on the left portion of the domain where the seismic bedrock outcrops) and the location of a generic point all along the surface of the model, r is the distance between x and x', * indicates the convolution product. The spatial distribution of the covariance normalised with respect to the reference covariance is displayed in Figure 3 for both SCI models.

The spatial distribution of the cross-correlation considering SCI-based models confirms that the presence of the buildings can strongly modify the local seismic response of the entire valley. In particular, the presence of the buildings leads to spatial correlation redistribution with respect to the free field condition that seems to not be directly due to a particular typology of building or soil condition.

It is worth to mention that correlation decrease down to 0.92 in the portion of the cross section not occupied by buildings but in their vicinity. Moreover, an increasing of the correlation is detected when the buildings are located in the portion of the cross section in which strong 2D site effects are expected (i.e. edge of the basins).

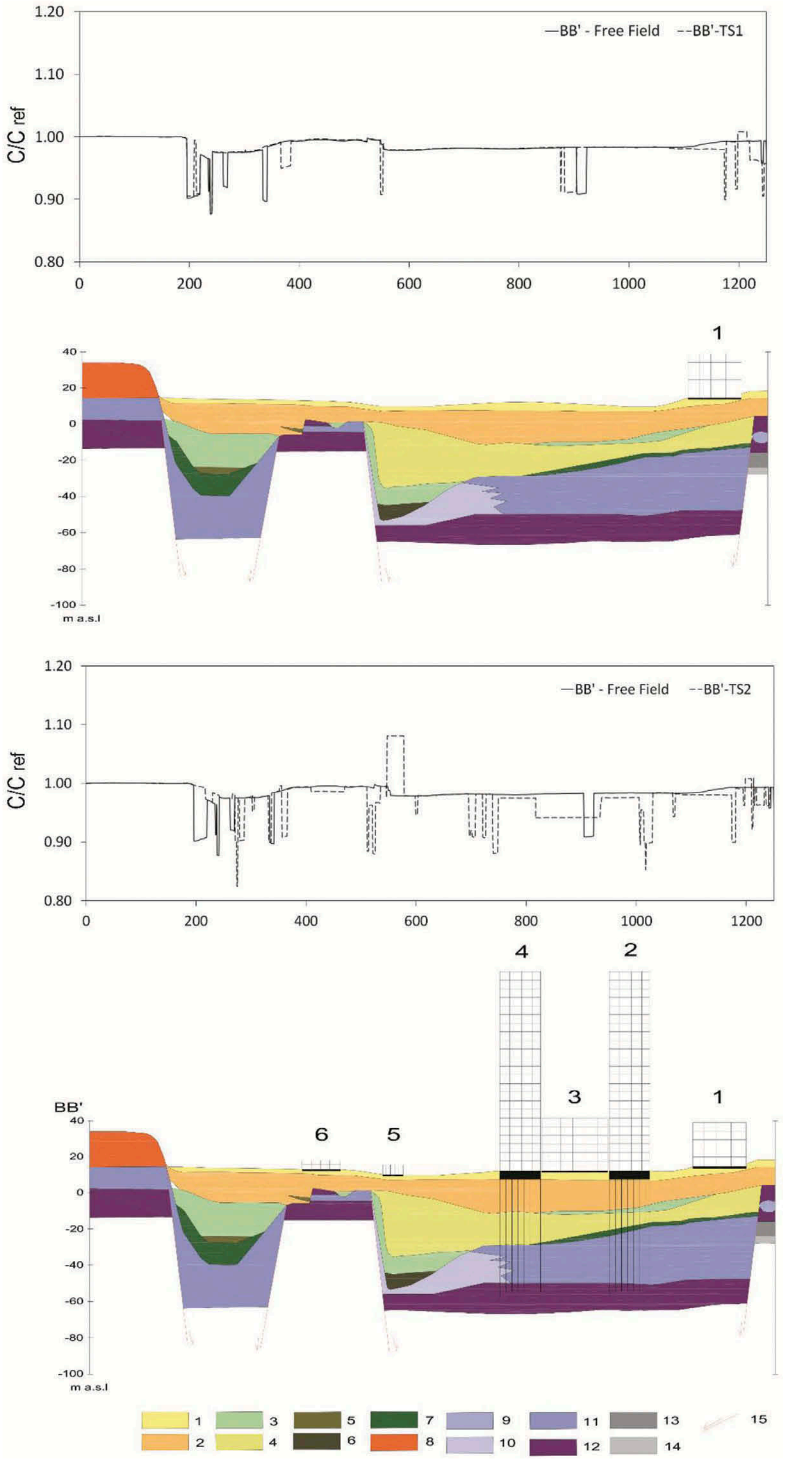

Figure 3. Comparison between the spatial correlation of the ground motion assuming free-field (solid) and SCI condition (dashed).

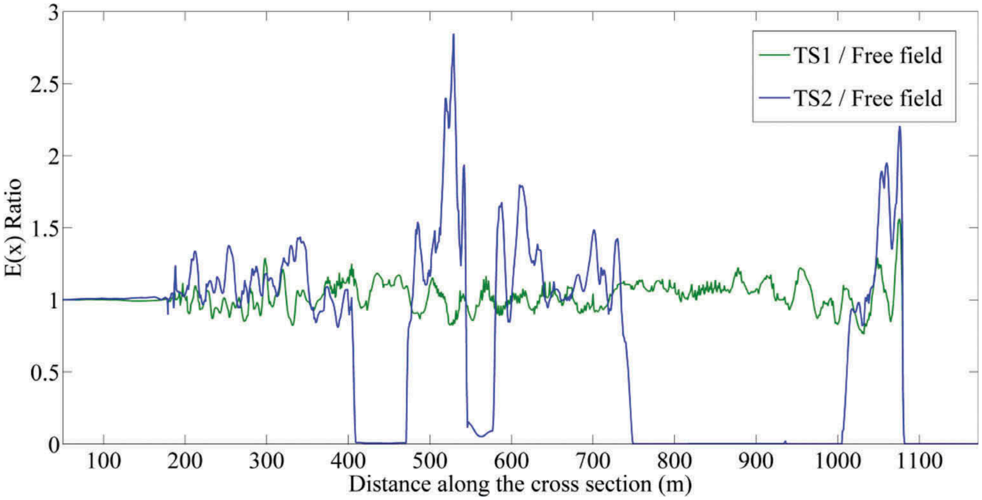

Figure 4. Ratio between the kinetic energy E(x) index considering SCI and free field conditions

The cumulative kinetic energy E(x) reached at the surface along the section was calculated according to the relation (2) proposed by Kham et al. (2006):

$$E(x)=\frac{1}{T}\int_0^T \left[\frac{du}{dt}(x,t)\right]^2 dt \tag{2}$$

where *T* is the signal duration, *u* the horizontal displacement and *t* the time.

The ration between E(x) distributions for the SCI models (TSI and TS2 in Fig. 2) and the corresponding free field models were computed and its spatial distribution is shown in Fig. 4.

The E(x) index distribution (Fig. 4) shows a strong reduction close to the buildings and an increase in the surrounding areas. This reduction can be complete close to buildings characterized by a larger volume and mass (ex. buildings 1 in TS1) and strong but not complete close to the buildings with smaller volumes and masses (buildings 5 – 6 in TS2). It results that the variability of cumulated kinetic energy along the surface is controlled, rather than by frequencies match between the soil and building (as highlighted by Kham et al. 2006), by the buildings density and by the typologies of dynamic SSI (Soil – Structure Interaction). The more the SSI is characterized by an inertial component, the more the reduction on the cumulated kinetic interaction results.

The areas that surround the buildings are characterized by an increase in the kinetic energy up to 3.3 respects to the free field condition. This increasing appears to be more pronounced when a building is located in correspondence of an edge of the basin.

5 CONCLUSIONS

This paper focus on the influence of SCI on spatial variability of the ground motion in terms of signals spatial correlation and cumulative kinetic energy.

The obtained results demonstrate that the presence of the buildings causes a reduction of spatial correlation in ground motion respect to free field conditions. This reduction is detected close to the building while in the surrounding an increasing of the correlation is detected when this area corresponds to an edge of the basin.

The spatial distribution of the kinetic energy along the surface shows that the buildings strongly reduced the E(x) value in comparison with the free field condition. The reduction is mostly controlled by the typology of buildings, while the areas surrounding the buildings are characterized by an increase in the kinetic energy.

The main findings show that the presence of buildings induces significant changes of the physical parameters in the areas close to the buildings and may change at least locally the expected local seismic response.

Future perspectives of this research are represented by analysis of the influence of buildings on the local seismic response considering a visco-elastic and/or a non-linear behavior of the materials. Furthermore, additional analysis on the influence of SCI on the spatial variability of the ground motion in case of real earthquakes could represent an important contribution to the understanding of the phenomenon.

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