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ORIGINAL RESEARCH PAPER

Effect of a single vibrating building on free-field ground motion: numerical and experimental evidences

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Abstract The influence of vibrating buildings on the free-field ground motion could affect the earthquake recordings collected inside or nearby the buildings. Some evidences are known for large structures, but also small buildings could adversely affect the quality of the recordings. An example is given for a station of the Italian Accelerometric Network whose recordings show a clear mark of the frequency of the host building. To tackle this problem in a more general way, we performed numerical simulations whose first aim was to validate existing empirical evidence from a test site. Gallipoli et al. (Bull Seismol Soc Am 96:2457–2464, 2006) monitored a release test on a 2-storey R.C. building in Bagnoli (Italy), showing that a single vibrating building may affect the "free-field" motion with an influence that reaches 20% of peak ground acceleration. We re-analysed the data of that experiment following the Safak (Soil Dyn Earthq Eng 17:509–517, 1998) approach to building-soil motion, described as propagation of up- and down-going S-waves. The numerical model is a chain of single degree of freedom oscillators, whose dynamic behaviour depends on mass, stiffness and damping. The agreement between the synthetic and real data encouraged us to use this model to reproduce generalised structures as systems with a single degree of freedom. We run multiple tests varying the distance, between building and station, and the building-soil coupling, obtaining a statistical distribution of the influence of a single vibrating building on free-field ground motion taking into account the distance.

Keywords Site-city interaction · Free-field · Ground motion · Rotational HVSR · Dynamic identification

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1 Introduction and case histories

The influence of buildings on free-field ground motion recordings has been postulated for the first time more than 30 years ago (Jennings 1970; Wong and Trifunac 1975). In the following years, several papers were devoted to the study of the vibration induced by an impulsive force on real building or on scale models (Kanamori et al. 1991; Erlingsson and Bodare 1996; Guéguen et al. 2002; Mucciarelli et al. 2003; Gallipoli et al. 2006) given the difficulty of separating incoming and back-radiated wave field during an earthquake (Chavez-Garcia and Cardenas-Soto 2002). Some works attempted to use ambient noise to identify the possible fingerprint of building vibration frequencies in the vicinity of the measurement point (Gallipoli et al. 2004; Cornou et al. 2004; Massa et al. 2009). In the meantime, numerical simulation aimed to reproduce the phenomenon (Bard et al. 1996; Wirgin and Bard 1996; Gueguen and Bard 2005; Kham et al. 2006; Ditommaso et al. 2007, 2009; Mucciarelli et al. 2008).

In some cases, when an entire town is concerned, numerical simulations were made on idealised models, without a possible comparison with real data (see, e.g., Kham et al. 2006 and references therein). The main disagreement in the literature (Laurenzano et al. 2009) concerns the effects of summations of wave fields from several buildings, which could be constructive or destructive interference. Past papers focused on the possible influence of built structures on the effects of the earthquake, in terms of greater or lesser damage. In this paper we are interested only in the effect on free-field motion from a stand-alone building. This situation is of potential interest for seismometric or accelerometric stations installed inside or nearby a building. Italian Civil Protection has recently funded a research project aimed to build and maintain an online database of Italian accelerometric data (Working Group ITACA 2008). One of the tasks of the project is to study the influence of the structures on the accelerometric recordings. This effect has been already demonstrated for large engineered structures by Barnaba et al. (2007). They show how the presence of the Ambiesta dam and reservoir strongly affects the recording of the 1976 Friuli earthquake at the Tolmezzo accelerometric station. The problem to tackle now is if smaller structures can also produce a significant effect on free-field recordings. Several accelerometric stations of the Italian national network are located in pre-cast housings (power substations), while others are installed nearby or inside buildings. Figure 1 shows a typical outside view of an accelerometric station, located in the Macchia Romana Campus of Basilicata University at Potenza, Italy. The housing is made of reinforced concrete, but there are no information about its geometric characteristics (infill thickness, beam and pillar width and reinforcements, etc.), and it is located on stiff clay formation. In the considered frequency range there is not a clear peak related to a superficial impedance contrast. The orientation of the building is N 50°. Within the housing there is an accelerometer connected to an Etna data logger, sampling data at 50 Hz up to a maximum of 1 g.

Two 3-directional 24-bit digital tromometers (Tromino–Micromed) were used in order to characterise the main frequencies of the structure. Using ambient noise we assessed the first and the second structural frequency using a 20 min time window sampled at 128 Hz. The acquired signals were pre-processed with baseline correction, trend removal, and 0.1–20 Hz band-pass filter. After these preliminary operations, signals were processed using a 15 s moving window with an overlap equal to 50% of moving window length. We used the spectral ratio between the measurement atop the building and the free-field taken as reference (Fig. 1). Figure 2 shows the transfer functions that returned a first mode along the WE direction at 12 Hz and a second mode along the NS direction at 14 Hz.

Fig. 1 RAN (Accelerometric Italian Network)-Station Code PTZ (Potenza–Italy)

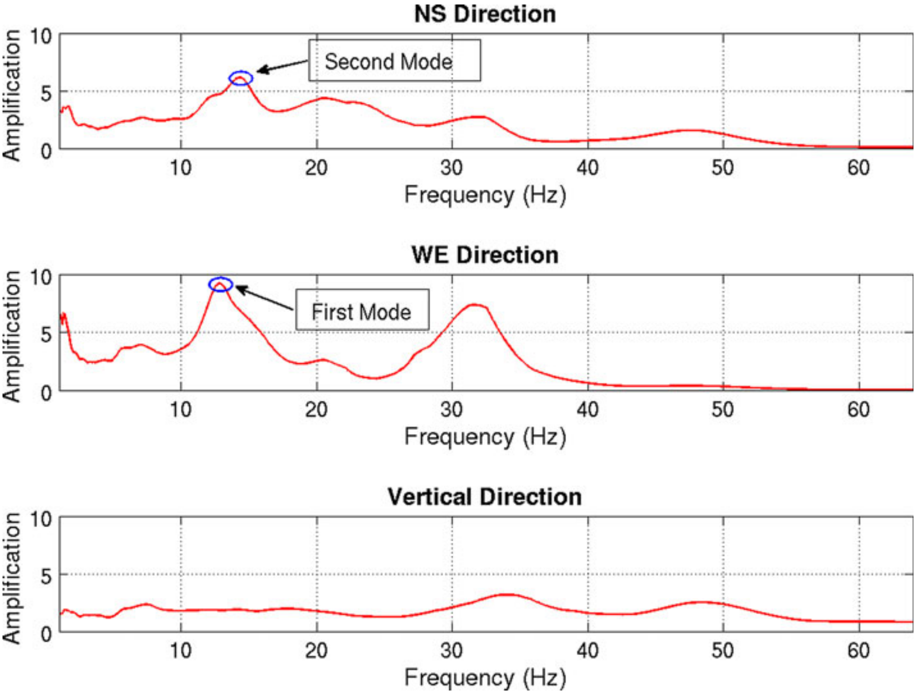

Fig. 2 SSR (Standard Spectral Ratio) evaluated between the roof and free-field

After evaluating the dynamic characteristics of the housing, we analysed the earthquakes recorded by the accelerometer installed inside. Table 1 summarizes the earthquake characteristics.

Recordings were pre-processed (de-trended, filtered and tapered) and then analysed using the rotational HVSR (Horizontal to Vertical Spectral Ratio) using a 15 s moving window

Table 1 Earthquakes recorded at PTZ station

Date time	Event name	Epicentral location	Epicentral distance (±0.2 km)	Lat	Long	Province	PGA (g)	M_L
03/02/2003 11.24	POTENTINO	BELLA	16.18	40.73	15.65	PZ	0.00224	3.6
03/02/2003 12.18	POTENTINO	BELLA	15.51	40.74	15.67	PZ	0.00132	3.5
24/02/2004 5.21	VALLO DI DIANO	SAN GREGORIO MAGNO	35.67	40.69	15.39	SA	0.00136	3.9
03/09/2004 0.04	POTENTINO	PICERNO	13.86	40.68	15.65	PZ	0.00877	4.1
27/09/2004 23.20	POTENTINO	RUOTI	9.44	40.70	15.72	PZ	0.0180	2.6

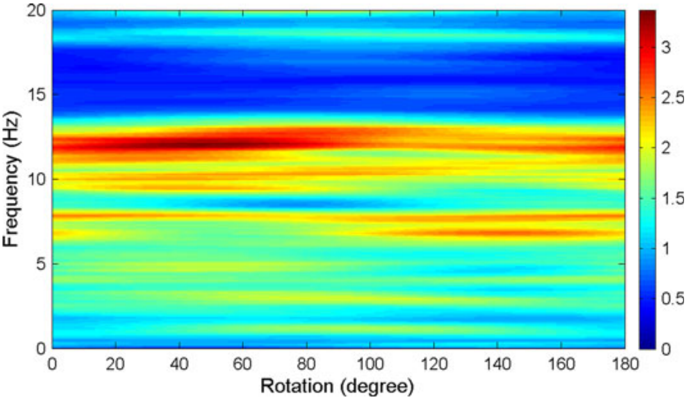

Fig. 3 Average of rotational HVRS evaluated on all events recorded at PTZ

with an overlap equal to 50% of moving window length. For each event we calculated rotational HVSR and then performed the average for all the events. The results are reported in Fig. 3, which shows a very clear peak at 12 Hz that coincides with the fundamental mode of the housing. The peak is the highest of the entire HVSR, thus the recordings are strongly contaminated by the building frequency.

Since it is not possible to perform measurement in all the buildings near a station, we would like to have a more general model based on numerical simulation validated on experimental data. An additional aim of the model is to provide a statistical study of the probability that a generic building may influence free-field recordings, focusing on possible effects on different parameters (peak motion values, integral/energy parameters or spectral ordinates).

2 A model validating real data

The availability of an existing R/C (Reinforced Concrete) building to be demolished in the ex-Italsider steel works at Bagnoli-Naples in the framework of ILVA-IDEM project

Table 2 Parameters used in the simulations of the Bagnoli experiment

Structure	f (Hz)	r (m)	Q	v (m/s)
Building	1.2	8	10	100
Contrast frame	27	13	10	100

(Mazzolani et al. 2004), gave us the chance to carry out in situ large-displacement tests on a real R/C frame and to model the recorded waves and then to prepare a more general model. The building tested in Bagnoli was a two-story, reinforced-concrete former office building, linked to a moment resisting steel frame (used as contrast frame). The structure and the soil were monitored with several accelerometers and seismometers. Full details can be found in Gallipoli et al. (2006). Here we want to reproduce the strong-motion time history recorded at 8 meters from the building. Several cyclic and release tests were performed for engineering purposes. The induced ground motion was measured during a 7 cm displacement test. This displacement is representative of the maximum excitation that this kind of building might withstand during an earthquake. The highest PGA observed in ground motion recordings was 5% g with a 7 cm displacement of the structure, whose frequency was in the range 1–2 Hz. Considering the standard 5% damping response spectra provided by the Italian Seismic Code, a 6 cm displacement at 1 Hz is obtained for the Zone 2—Soil A spectrum, whose PGA is 0.25 g. Thus the observed PGA is about 20% of the hypothetical unmodified free-field PGA.

We modelled both the building and the contrast frame using SAP2000 finite element program. The frequency obtained for the first modes of the structures matched the ones observed from the experimental data, which are around 1 Hz for the building and 30 Hz for the frame. The frame was then reduced to a SDOF with equivalent mass, stiffness and damping, while the building was reduced to one SDOF per floor. We followed the approach proposed by Şafak (1998), where the building and the foundation soil are idealised as propagators of up- and down-going waves. This leads to the need of solving a system of recursive differential equations. The whole system was modelled using Matlab® Simulink. The advantage of this approach is that one can work with subsystems (i.e., soil strata or building floors), adding as many as it is necessary. The only unchanged sub-systems are the bedrock (half-space with inelastic attenuation) and the building's roof.

The two signals coming from the building and the contrasting frame were propagated in an inelastic medium reproducing the characteristics of the soil underlying the test site (volcanic ashes and alluvium). The distances were calculated from the centre of mass of the two structures projected on the ground to the accelerometer, with the attenuation given by Eq. 1:

$$A(r) = \frac{A_0}{r} \cdot \mathrm{e}^{-\frac{f \cdot r}{Q \cdot V}} \tag{1}$$

where A is the signal amplitude as a function of the travel distance r, A_0 is the initial amplitude of the signal, f is its frequency, Q is the quality factor and V is the shear wave velocity. The small strains involved allow for the assumption of soil linear behaviour. However, the model can be modified to take into account non-linearity if needed. The parameters used are reported in Table 2.

The initial condition reproduces the experiment: a 7 cm displacement in the middle of the building that is instantaneously released. The frame was dislocated according with the amount given by the SAP2000 static simulation.

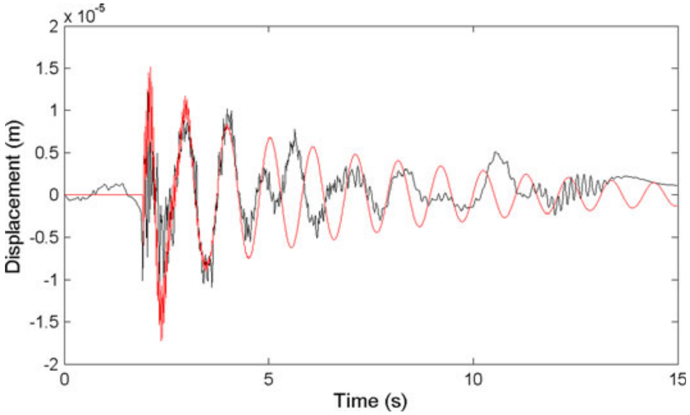

Fig. 4 Comparison between real (*black*) and simulated displacement (*red*)

The equations where solved for a discrete model, a duration of 15 s, a variable step with Ode 45 resolution algorithm. Figure 4 shows the result for the modelled displacements compared with the recorded ones.

It has to be noted that this fit was achieved adjusting a free parameter, for which we do not have information: the dynamic coupling factor between structures and soils (range of variation 0–1, see Şafak 2006). The foundation system is unknown for the building (perhaps plinths), while the frame was bolted to a pre-existing concrete slab running all along the dismissed buildings. This translated into a greater coupling between resisting frame and soil, with more than 90% of the energy transferred to the ground, while the coupling between building and soil is rather poor with just a small fraction of the energy radiated into the ground. The final fit is satisfactory, at least for the first 4 s. After that, the real data shows the effect of a possible reflection at the bedrock, whose depth is not known and thus not considered in the model. The model was able to reproduce the observed data, and this encouraged us to go further, trying to use it to answer practical questions. As observed for Potenza station, can ground motion recordings be contaminated by building frequency? How often may this happen, and which parameters (peak values, integral parameters or spectral ordinates) could be the most affected? How can we tackle the problem of unknown foundation systems?

3 Monte-carlo simulation of a building influence on ground motion

Using the Matlab® Simulink model prepared to reproduce the ground motion induced by the release test as described in the previous chapter, we performed several analyses to study the effect of a building on free-field ground motion recordings. We investigate the variation of the effects as a function of the distance between a single building and the accelerometric station. The 0.1–25 Hz frequency range was been investigated.

We considered two different buildings with 2 and 10 storeys respectively, designed according to the most recent Italian seismic code. Each structure has been modelled with a single degree of freedom oscillator equivalent to the main vibration mode of the structure. The 2 floors building is representative of electrical power distribution stations, while the 10 floors building simulates a structure that may host a station in the basement or in the vicinity.

Table 3 shows the dynamic characteristics of equivalent oscillators in terms of mass, stiffness and damping. Table 4 shows the ground parameters. It is important to note that we used a semi-space approximation for the soil. A layered soil with impedance contrast at the

Table 3 Linear equivalent parameters of oscillators

2-Storey building			10-Storey building		
Mass (kg)	Stiffness (N/m)	Damping (%)	Mass (kg)	Stiffness (N/m)	Damping (%)
149,696	75,920,931	5	6,260,610	204,056,563	5

Table 4 Soil parameters

Density (kg/m^3)	Shear wave velocity (m/s)	Quality factor
1,900	1,000	10

Table 5 Earthquakes extracted from the European Strong-Motion Database

Event code	Event name	PGA (g)
359	000359a	0.066
365	000365a	0.099
361	000361a	0.157
123	000123a	0.232
159	000159a	0.237
1313	001313a	0.265
27	000027a	0.294
196	000196a	0.306
501	000501a	0.346
1226	001226a	0.361
199	000199a	0.363

interfaces would produce possible resonances between buildings and soil frequency, thus enhancing the contribution of the back radiated energy. This makes the problem more complicated because each building could be resonating or not, and in case of building damage or soil non-linearity both frequencies could vary. In our model, the back-radiated energy is attenuated away from the building and there is no trapping of energy in the upper soil layers. The absolute value of ground motion perturbation that we will obtain is thus the lower bound of the problem.

For the analysis we used 11 different earthquakes (Table 5), randomly extracted from the European strong motion database to uniformly sample the PGA range 0.05–0.35 g. Using a random coefficient of structure-soil coupling (0.01–0.99) and a building-accelerometer random distance (5–150 m), we performed 1,000 simulations for each building and for each earthquake, for a total of 22,000 simulations.

For each simulation, hence for each distance, we calculated Peak Ground Acceleration (PGA), Housner Intensity (HI) and the spectral acceleration at 5% damping (Sa), then we estimated the ratio between each value and the related free-field recording. For each distance between building and accelerometer, having more than one value, we calculated four statistics: the maximum value, the minimum value, the 75th and 50th percentile (median) values.

Figures 5, 6, 7 show the results related to the two-storey building, while Figs. 8–10 are relevant to the 10-storey building.

From the graphs related to the acceleration ratio (Figs. 5, 8) it is clear how the possibility of having constructive and destructive interference leads both to amplification and de-ampli-

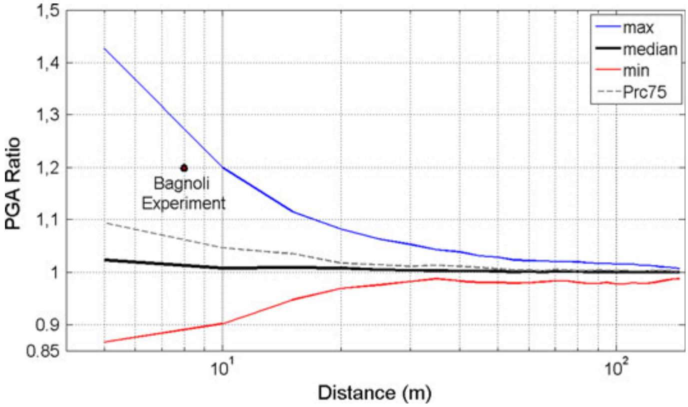

Fig. 5 Ratio between PGA with and without the presence of the 2-storey building

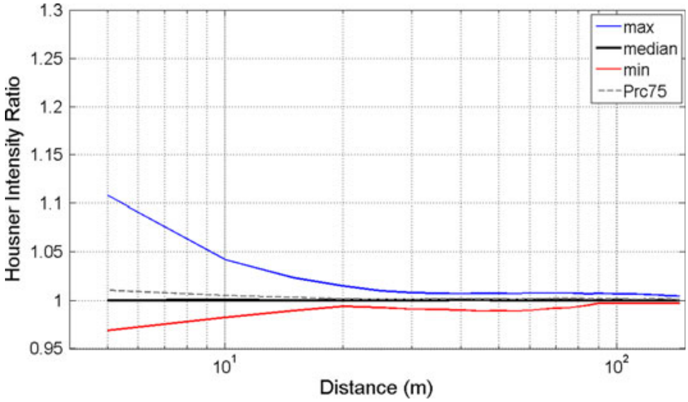

Fig. 6 Ratio between HI with and without the presence of the 2-storey building

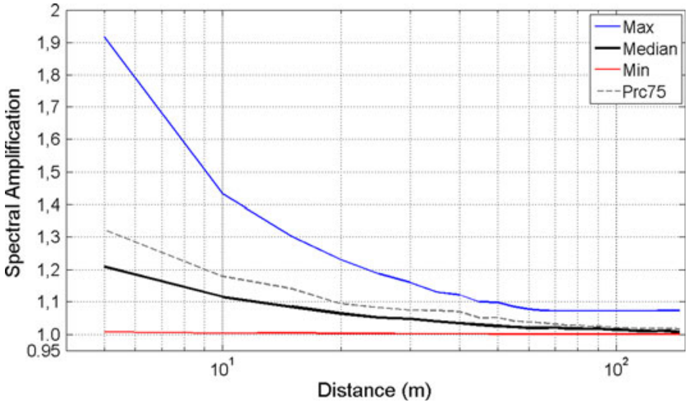

Fig. 7 Ratio between maximum Sa with and without the presence of the 2-storey building

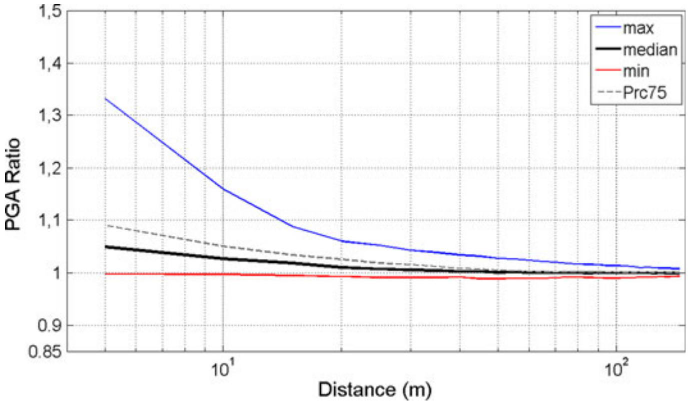

Fig. 8 Ratio between PGA with and without the presence of the 10-storey building

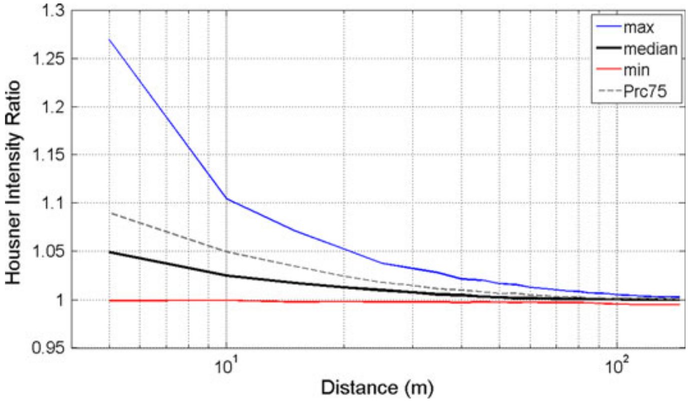

Fig. 9 Ratio between HI with and without the presence of the 10-storey building

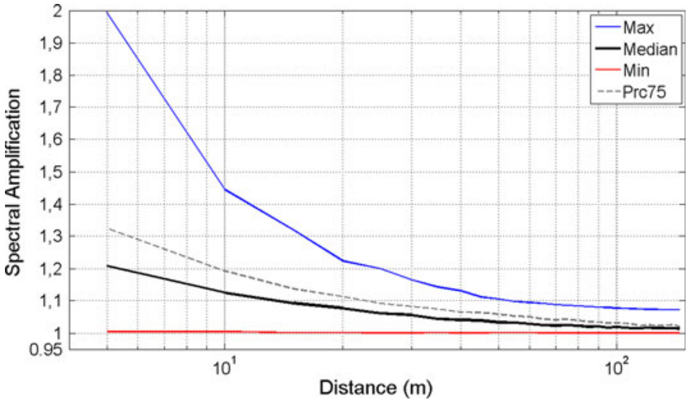

Fig. 10 Ratio between Sa with and without the presence of the 10-storey building

fication. For small distances, the median shows an increment around 10% that decrease with distance. For exceptional cases we could have an increase of 40% (maximum) or a decrease around 5% (minimum). We can make similar comments about the graph that represents the HI ratio, but in this case the increase is lower and median values start from 2% and decrease with distance.

Different considerations apply to Sa graphs (Figs. 7, 10). In this case the curve of minimum values does never descend below unity, while the curve of maximum values highlights the possibility, for extreme cases, of an increase around 90%. Median curve starts from an increase of 20% and decreases with distance.

The 10-storey building has a very different influence on free-field ground motion. For example, both in terms of PGA and HI we never observed a decrease, not even for extreme cases. On the contrary, we always have an increase of the observed parameters. We also note a modest increase in terms of PGA amplification compared with those observed in case of 2-storey building. This was to be expected because the frequency of the 10-storey building is lower and thus not affecting the high frequency end of the spectrum. In this case the median curve starts with an increment of 5% and decreases with distance. Housner Intensity has significant increments compared with those observed for the 2-storey building, both for median curve and for extreme cases. Median HI ratio curve starts from an increment of 5% for small distance. Regarding the spectral amplification values, we observe a good agreement with those evaluated for the 2-storey building. There is only a little increment for the most extreme values.

4 Conclusions

We investigated both the numerical and experimental aspect of the dynamic building-soil interaction. We first discussed an experimental evidence regarding the ability of buildings to back-radiate energy into the soil, thus modifying the free-field ground motion, as shown for the case of Potenza accelerometric station.

Then we prepared a numerical model, which has been validated comparing the synthetic signal with the time-history recorded during the release test of a real RC frame.

Finally, we performed a Monte-Carlo simulation starting from the same model applied to realistic buildings with different masses and fundamental period. The random parameters varied during the simulation were the impedance function of the foundation system and the building-station distance. The variation of extreme values, median and 75% was plotted against distance for PGA, HI, and Sa.

As shown in Ditommaso et al. (2009) for the effect of a building set in motion by a nearby explosion, the spectral parameters are the most affected, while the integral ones are not so disturbed. This is due to the fact that the presence of the structure has both the effect of a damper (thus reducing the total energy) and of a filter, focusing energy in the band of building eigenfrequencies.

In conclusion we can say that buildings are able to modify the free-field ground motion, contaminating the signals recorded near or within them. The less affected parameter by the presence of buildings is the Housner intensity, however, PGA and Sa are more contaminated. In order to give recommendations on the use of signals contaminated by the back-radiated energy from buildings, further numerical studies and in situ experiments are needed.

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