Thessaloniki-GREECE 2007

4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1388

EFFECT OF VIBRATING BUILDINGS ON "FREE-FIELD" GROUND MOTION: FROM THE BAGNOLI EXPERIMENT TO MANY-BUILDINGS SIMULATION

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ABSTRACT

A release test on a 2-story R.C. building in Bagnoli (Italy) showed that a vibrating building may affect the "free-field" motion with an influence that may reach 20% of PGA (Gallipoli et al., 2006).
We re-analysed the data of that experiment following the Şafak (1998) approach to building motion, described as propagation of up- and down-going S-waves. The waves are propagating in a multi-layered 1-d model that includes bedrock, soil and a layer for each floor of the structure. Numerical models have been implemented in Simulink, a toolbox of MatLab, thanks to which it has been possible to solve easily the differential equations of the case. The final model is a chain of SDOF oscillators, whose dynamic behaviour depends on mass, stiffness and damping. We modelled both the tested structure and the reaction frame built to displace it. The sum of the two components was propagated to sensors taking into account geometrical spreading and inelastic damping.
The agreement between synthetics and real data encouraged us to simulate a many-building situation. We modelled a virtual village made of three structures of different height to study their effect on an accelerometer located among them. The structures have been designed and analysed with the code SAP 2000 that made possible to develop the models and to calculate all dynamic characteristics of the same models. Then these structures have been reduced to systems with a single degree of freedom, one for each structure. The excitation was provided by three earthquakes with different characteristics of intensity and duration. We run multiple tests varying the azimuth of incident waves and the coupling between building and soil, obtaining a statistical distribution of the influence of vibrating buildings on "free-field" ground motion.

Keywords: Site-city interaction, free field, ground motion

INTRODUCTION

During an earthquake, the vibration of buildings transmitted back to the soil is able to modify the free field ground motion. This idea was theoretically postulated by Wong and Trifunac (1975) and Wirgin and Bard (1996). During an earthquake it is difficult to measure and to separate the source and site effects from ground vibrations introduced by an oscillating building one (Chavez Garcia and Cardenas Soto; 2002). Passive and active experiments have been carried out by Jennings (1970) during forced vibration of buildings, by Kanamori et al. (1991) studying the effects caused by the sonic boom of the Space Shuttle on high-rise buildings in Los Angeles, by Guéguen et al. (2000) and Guéguen and Bard (2005) on a five-story RC-building model (1:3) located in the EuroSeisTest site at Volvi (GR), by

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Mucciarelli et al. (2003) on a base isolated building during a release test, by Gallipoli et al. (2004) and Cornou et al. (2004) using ambient noise. The conclusions of all these experiments confirm the importance that buildings may have as seismic sources.

On the other hand, numerical simulation were made on idealised models, without comparison with real data (see, e.g., Kham et al., 2006 and references therein). The main disagreement among modellers concerns the effects of summations of wave fields from several buildings, which is constructive or destructive interference.

The availability of an existing R/C building to be demolished in the ex-Italsider steel works at Bagnoli-Naples, in the framework of ILVA-IDEM project (Mazzolani et al., 2004), gave us the chance to carry out in situ large-displacement tests on a R/C frame and to model the recorded waves.

MODELLING THE BAGNOLI EXPERIMENT

The building tested in Bagnoli was a two-story, reinforced-concrete former office building. 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 5 meters from the building. Several cyclic and release tests were performed for engineering purposes. We measured the induced ground motion 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 we observed is 5% *g* with a 7 cm displacement of a structure whose frequency was in the range 1-2 Hz. If we consider 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. Both the building and the contrasting frame that was set in motion during the release were modelled using SAP2000 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 at one SDOF per floor. We followed the approach of Şafak (1998), where the building and the foundation soil are idealised as propagators of up- and down-going waves. 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 whole system used for modelling the Bagnoli experiment is reported in Fig. 1.

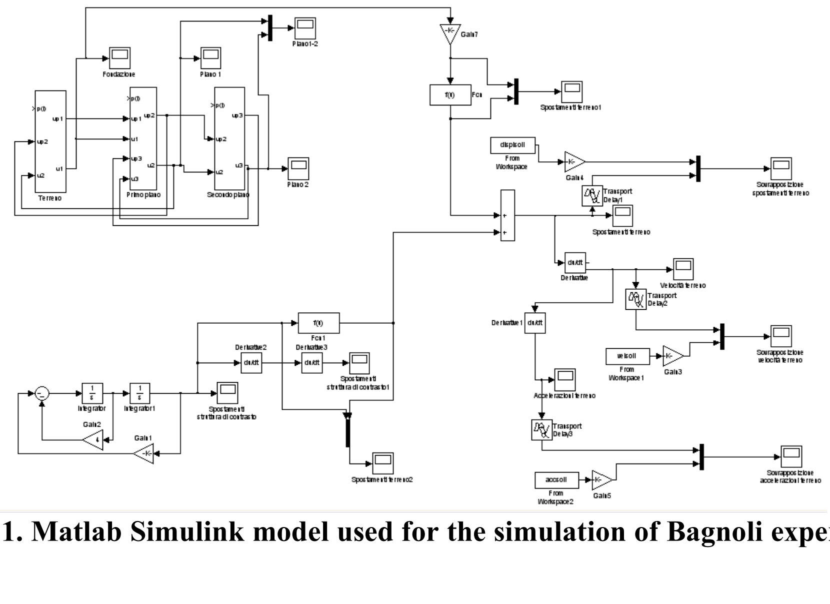

Figure 1. Matlab Simulink model used for the simulation of Bagnoli experiment

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:

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

where A is the signal amplitude as a function of the travel distance r, A0 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 strain 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 Tab. 1

Table 1. Parameters used in the simulation

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

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

The equation where solved for a discrete model, a duration of 15 seconds, a variable step with Ode 45 resolution algorithm. The result for the displacements is shown in Fig.2.

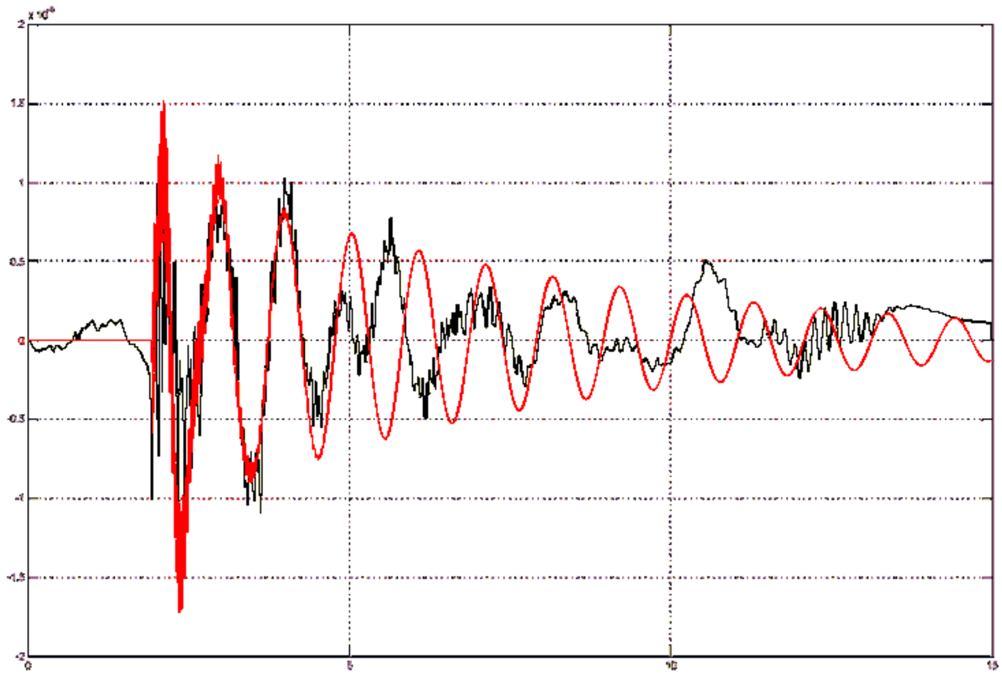

Figure 2. Comparison between real (black) and simulated accelerogram (red)

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. 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 building. This translated into a greater coupling between 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 seconds. After that, the real data shows the effect of a possible reflection at the bedrock, which is not possible to simulate with the half-space soil model. We preferred not to include detailed stratigraphy, since no reliable information was available about the depth of the bedrock. The model was able to reproduce the observed data, and this encouraged us to go further, trying to solve another problem.

MODELLING A VIRTUAL VILLAGE

Gallipoli et al. (2006) pointed out three reasons why what we observed could be a lower boundary value. The first reason is that the total mass of the building plus the reaction structure reaches only 38,100 kg, which is two times the one of the Volvi model described by Guéguen et al. (2000) and Guéguen and Bard (2005), but still below the mass of a full-functional building, due to the lack of roof tiles, infills, services and internal loads.

The second reason concerns the coupling with the ground. This plays an important role in the efficiency of the structures as wave generators; taller buildings, besides having much larger masses, have deeper foundation, so in an actual city-soil interaction a higher coupling factor is expected.
The thirds reason is the lack of soil-building resonance in the Bagnoli test. Bard et al. (1996) and Cornou et al. (2004) pointed out the importance of trapped waves in a resonant layer as a cause for far away propagation of structure frequencies. In our case, no resonance is present between soil and building, and thus the observed values are a lower bound.

We then wanted to answer these doubts, building a model for standard buildings, with varying dynamical coupling and with a resonant stratum above the bedrock.

Using SAP2000, 3 buildings of different mass and height were designed, following the rules for anti-seismic design provided by the Italian code (largely similar to EuroCode8).

Table 2. Parameters used for the "virtual village" simulation

2 storey			4 storey			6 storey		
(kg)	K (N/m)	c (%)	M (kg)	K (N/m)	c (%)	M (kg)	K (N/m)	c (%)
149,696	75,920,931	5	1,847,000	409,450,806	5	3,053,940	225,008,060	5

Again, the full model was reduced to a system of SDOFs to be used with the Simulink model. This time the input was provided by three real accelerograms with PGA equal respectively to 0.15 *g*, 0.25 *g* and 0.35 *g*.

To take into account the variability of the position of the buildings among them and with respect to the accelerometer, a random delay time was included in the model. The output of each building was summed to the input ground motion with a variable delay, uniformly distributed from -0.1 to 0.1 sec. The velocity in the soil layer was set to 100 m/s, thus leading to simulated change in position in the range -10 to 10 m.

To account for the variability in the dynamic coupling between building foundation and the soil, and thus to represent the different quantity of energy transferred back to the soil by the vibrating structure, a random coefficient was included in the simulation, with uniformly distributed values in the range from 1% to 90%. A Monte Carlo simulation was then performed, with 1000 runs of the Simulink model for each of the three inputs. From each run we extracted the Peak Ground Acceleration and the Peak Ground displacement, plotting the relevant histograms in Fig. 3.

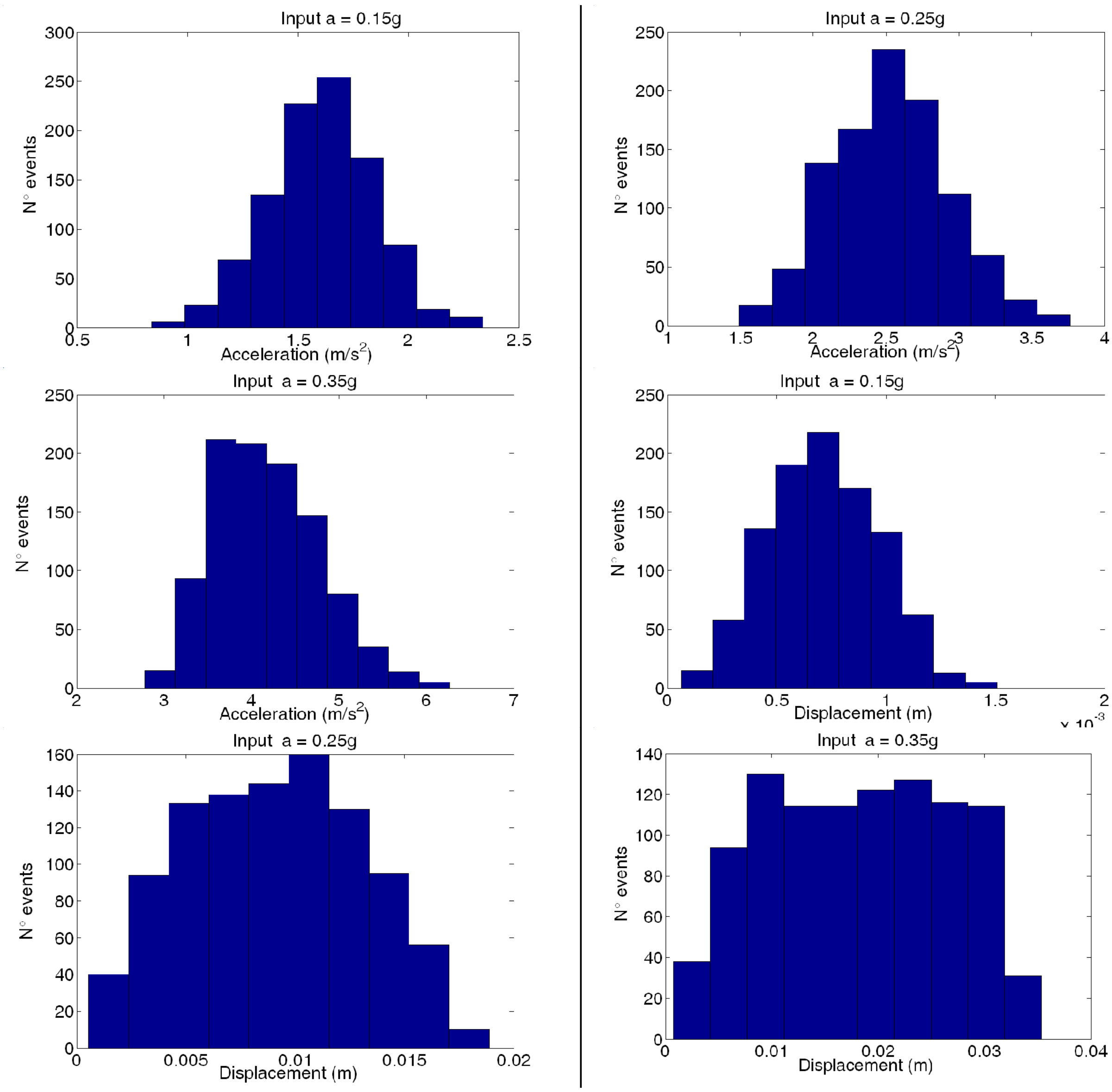

Figure 3. Distribution of simulated PGA and PGD

It is possible to note that the distribution is centred on the input value, with minimum and maximum variation of the order of 50% and with most of the values in the range ±25%. This implies that real accelerogram recorded in free-field may be affected by the presence of building when the recording is made in an urbanised area.

The last step was the analysis of spectral response. For each input we selected randomly 70 time histories and calculated the relevant response spectra. Then we estimated the ratio between each spectrum (both in acceleration and displacement) and the one of the input signal, and finally computed the average of the ratios. The result is plotted in Fig. 4. The values above unity are concentrated around the periods of buildings fundamental mode, while the ratio tends to be lower for longer period. At longer periods, the ratio slightly differs from unity because the simulated accelerograms are not high-pass filtered.

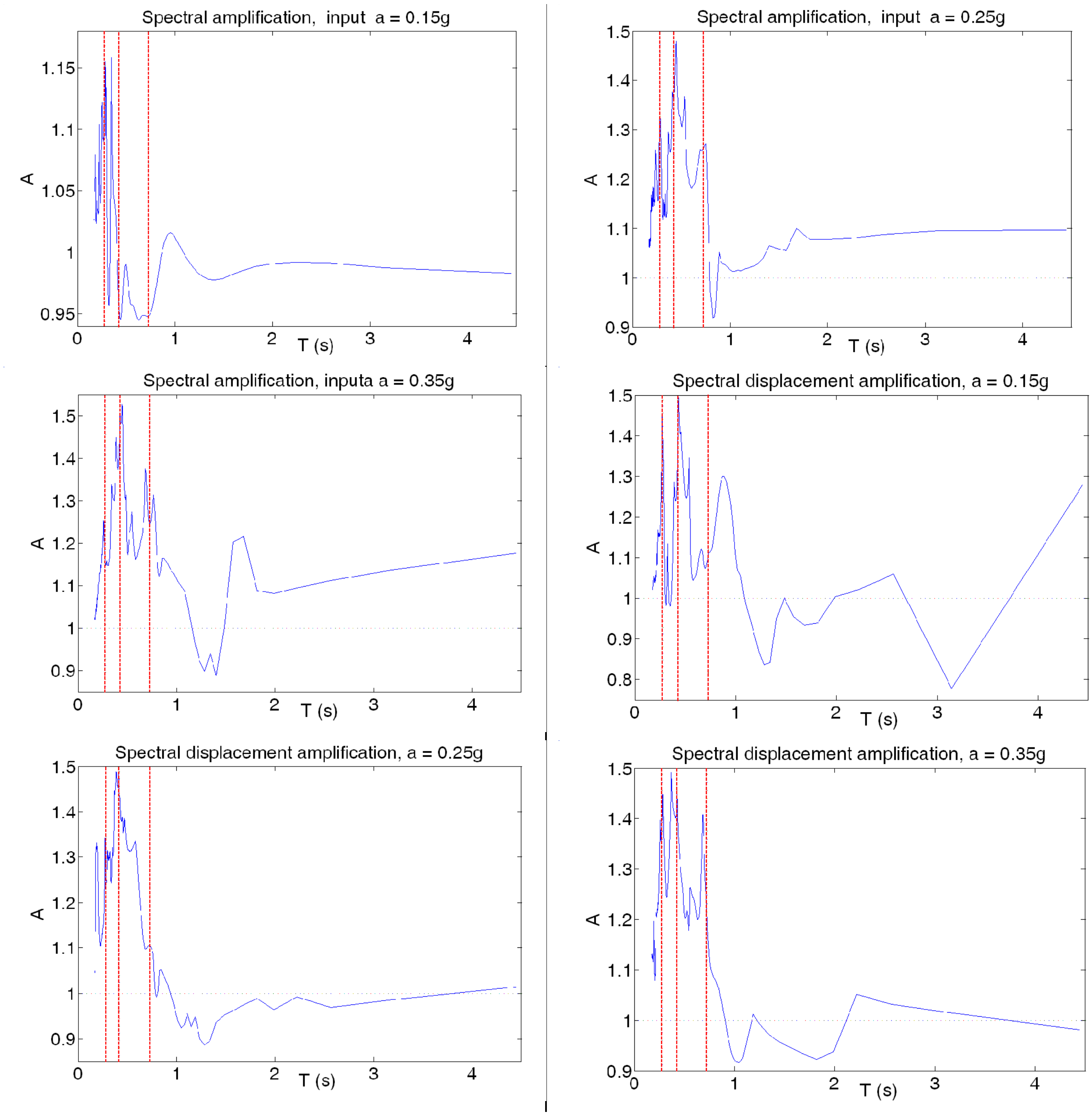

Figure 4. Difference in acceleration and displacement response spectra due to the presence of buildings. Red line are the buildings fundamental modes

This result was expected, with most of the back-radiated energy around building periods, and together with the distributions of PGA and PGD leads to the main conclusion of this work: the presence of buildings strongly affects the "free field" ground motion. Inside an urban area it is difficult to record a real free field motion. On average, the PGA remains similar, but can be increased or lowered by the presence of buildings. It is not possible to drawn general conclusion about the possibility of having larger or smaller PGA since it depend on the typology and space pattern of the buildings. The energy balance is slightly increased, with energy added at buildings fundamental modes and subtracted at longer periods.

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