

## **EFFECT OF VIBRATING BUILDINGS ON “FREE-FIELD” GROUND MOTION: THE BONEFRO (ITALY) CASE HISTORY**

**Giovanna LAURENZANO<sup>1</sup>, Enrico PRIOLO<sup>2</sup>, Maria Rosaria GALLIPOLI<sup>3</sup>,  
Marco MUCCIARELLI<sup>4</sup>, Felice C. PONZO<sup>5</sup>**

### **ABSTRACT**

During the 2002 Molise sequence, a damaging shock was recorded inside a building (Mucciarelli et al., 2004). The availability of such data, plus others that were acquired in the following, lead to an international workshop of structural engineers that tried to reproduce the observed evolution of damage (Goretti & Mucciarelli, 2006).

The aim of the present work is to model the damaged building, the adjacent and undamaged one, and a large section of the subsoil to gain insight on two possible phenomena: 1) the city-soil effect, i.e. the modification induced by vibrating buildings to the free-field ground motion and 2) the possible interaction between the two buildings.

The model was performed using the SPEM technique for a 2-d section. The model, that includes topography, comprises the bedrock (limestone) with the overlaying layer of about 30m of clay. The velocity of shear waves in the buildings has been derived from their well known mechanical properties.

We first verified that the model was able to reproduce the motions recorded inside and outside the building. Then we selectively removed one or both the buildings to study their effect.

The influence of the presence of buildings on the free-field motion is about 30-40% on spectral values up to a distance approximately twice the height of the structure. The presence of resonance between buildings was also reproduced by the model.

**Keywords:** Resonance, site effect, city-site interaction, Molise earthquake.

### **INTRODUCTION**

During the seismic sequence occurred in Molise (Italy) in 2002 two adjacent buildings located in the municipality of Bonefro suffered a different damage pattern. The two buildings have similar shape but different height: one is three storeys while the other is four storeys high. The tallest one suffered serious structural damage (EMS=4), while the smaller suffered just non structural damage (EMS=2).

A previous study (Mucciarelli et al., 2004) hypothesised that the main reason for the different damage was the resonance between the tallest building fundamental mode and soil dominant frequency. More in detail, the first mode of the 4-storey building starts at 2.5 Hz and reaches 1.3 Hz during the damaging earthquake. The smaller building has a fundamental mode at about 4 Hz. The soil fundamental frequency estimated by free field recordings of aftershocks and confirmed by 1-D numerical modelling is it about 2.5 Hz.

---

<sup>1</sup> PostDoc Fellow, I.N.O.G.S, Trieste, Italy.

<sup>2</sup> Senior Researcher, I.N.O.G.S, Trieste, Italy.

<sup>3</sup> PostDoc Fellow, I.M.A.A.-C.N.R, Tito Scalo, Italy.

<sup>4</sup> Professor, DiSGG, University of Basilicata, Potenza, Italy. E-mail: marco.mucciarelli@unibas.it

<sup>5</sup> Professor, DiSGG, University of Basilicata, Potenza, Italy.

The study of Mucciarelli et al. (2004) was limited to data analysis, without modelling the observation. Thus, it was not possible to explain a phenomenon appearing in wavelet analysis as well as in Gabor transform: after the main arrival of direct S-waves, the instrument atop the 4-story building recorded a burst of energy at about 4 Hz, a frequency that it is a characteristic of the smaller building. This paper aims to study the modification that the energy back radiated by the two buildings induces in the free-field motion and possibly in the adjacent structures.

The possibility that the vibration of buildings transmitted back to the soil is able to modify the free field ground motion was theoretically postulated by Wong and Trifunac (1975) and Wirgin and Bard (1996). Passive and active experiments have been carried out by Jennings (1970), Kanamori et al. (1991) and more recently 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 Gallipoli et al. (2004) and Cornou et al. (2004) using ambient noise, by Mucciarelli et al. (2003) and Gallipoli et al. (2006) on real buildings during a release test. The conclusions of all these experiments confirm the importance that buildings may have as seismic sources.

To investigate more in detail the soil building resonance and the possible presence of city-site interaction, the present study performed a numerical modelling of the seismic wave field.

The modelling uses the 2-D Chebyshev spectral elements method (SPEM 2-D; Priolo, 2001 and 2002). The method is well suited to solve the propagation effect through a realistic geological structure with irregular topography, described as a field of wave velocity and damping.

## MODEL AND SOURCE PARAMETRISATION

In order to understand the effect due to the presence of the buildings and their mutual interaction we built three different models. The first one (model 0) represents the geological structure without the buildings (Fig. 1 upper right corner); the second one (model 1) has just one building at the surface, that is the tallest and more damaged one (Fig.1 lower right); the third one (mod. 2) reproduces the real situation with both buildings (Fig. 1 left). The overall dimensions of the model are 2000 x 700 m.

The structural model built along the section given in Fig. 1 (above) was subdivided in sub-domains characterised by different values of the following parameters: density, velocity of shear waves, velocity of P waves and quality factor Q. Fig. 2 and Fig. 3 show the distribution of shear waves velocity in different sub-domains. The main parameters are reported in Tab. 1.

**Table 1. Main parameters of model 2.**

	Density (Kg/m <sup>3</sup> )	Vs (m/s)	Q
Buildings	300	170	20
Soil	1500-1800	100-400	15-25
Bedrock	2500	1500	100

The clayey soil is characterised by a constant velocity gradient from 100 m/s at the surface to 400 m/s at about 30 m depth. At this depth there is the contact with the bedrock (marl limestone). This velocity profile comes from the analysis of a linear array (Mucciarelli et al., 2004). The two buildings have been represented as rectangles with equal base (21 m) and different height. Taking into account also the foundation, the two buildings are 12 and 15 m high. The density values of the bedrock, the clayey soil and the buildings are respectively equal to 2500, 1500 and 300 Kg/m<sup>3</sup>. Fig. 4 represents the mesh used for the modelling. It is possible to note how the shape and dimension of the elements changes with depth: the mesh is denser near the surface where the velocity decreases. The buildings have been discretised using a regular grid with 3 m interspace, corresponding to inter-storey height. At the outer limits of the model we applied an absorbing boundary where the waves are attenuated in order to avoid reflections. The model is composed by 5500 elements.

The seismic excitation is simulated with a vertical incident plane wave. It is generated with a horizontal alignment of sources at 200 m below the surface (Fig. 5, right). The source time history is a

Ricker pulse with peak frequency at 4 Hz (Fig. 5 left). The seismograms are calculated for a duration of  $T=10.24$  s and then low pass filtered with a cut-off frequency equal to 10 Hz.

## RESULTS

The analysis has been performed using both wave field snapshots and synthetic seismogram calculated for different free field lithologies and for different positions inside the buildings.

First of all we verify the correspondence between the behaviour of the first 30 m and the resonance frequency obtained by Mucciarelli et al. (2004). The ratio between the spectra of the synthetic seismogram simulated for the soil and those for the bedrock calculated for model 0 (Fig. 6) shows both for the P-SV and the SH component a peak at 2.6 Hz. This value is in good agreement with the HVSRR peak obtained for noise and aftershocks by Mucciarelli et al. (2004).

Fig. 7 shows acceleration time histories calculated at the surface with and without the two buildings. The red line represents the seismogram calculated atop the two buildings in order to highlight the variations in the wave field caused by the presence of the structure. The different characteristic of the wave field can be observed also in the wave field snapshots plotted in Fig. 8. When one or both buildings are present the wave field is trapped within the structure and in the soil. The energy is gradually released, lengthening the duration of the time histories close to the buildings when they are present.

Fig. 9 reports the wave field snapshots for the buildings and their surroundings. It is possible to visualise the different modes and phases of the vibrating structures.

The spectral characteristic of simulated motions are highlighted using the ratio between the Fourier spectra obtained atop the buildings for model 2 and those obtained at the surface in model 0 (without buildings). Fig. 10 shows for the small building a peak at 3 and 4 Hz while the ratio shows a peak at 3.6 Hz for the radial component and one at 3.9 in the transversal component. The tallest building shows in the amplitude spectra a clear peak at 2.4 Hz, very close to the fundamental frequency of the soil, while in the spectra ratio the peak is at 2.4 Hz for the radial component and at 3.7 for the transverse component.

To evaluate the building-building interaction we can compare the ratio between the Fourier spectra obtained atop the 4-storey building for model 2 and at the surface in model 0 (Fig. 10 right) with the ratio of the Fourier spectra for the same building in model 1 and the surface in model 0 (Fig. 11 left). The comparison shows that for both components in model 1 the 4 Hz peak is missing, while this peak is visible for model 2. This suggests the presence of the interaction between the two buildings: the peak at about 4 Hz in the tallest building is a consequence of the oscillation of the smaller one. This can be confirmed comparing the spectral ratio calculated for the same building in model 2 and model 1 (Fig. 11 right). The spectral ratios show for both components a peak at about 4 Hz. It is worth noting that this 4 Hz peak appears as a transient sometimes after the beginning of the shock in the wavelet analysis performed by Mucciarelli et al. (2004).

Fig. 12 compares the seismograms obtained for model 0 and 2 at receivers located on soil close to the buildings. Spectral ratios show peaks at different frequencies: at 4-5 Hz left of the 3-storey building and at 3.5 -3.9 Hz right of the 4-storey building. The same analysis for sites left and right to the buildings but located on bedrock (Fig. 13) shows spectral ratios that are flat and close to unity, indicating that for those distances ( $>100$  m) and that lithology the presence of the buildings does not change the seismic wave field.

## CONCLUSIONS

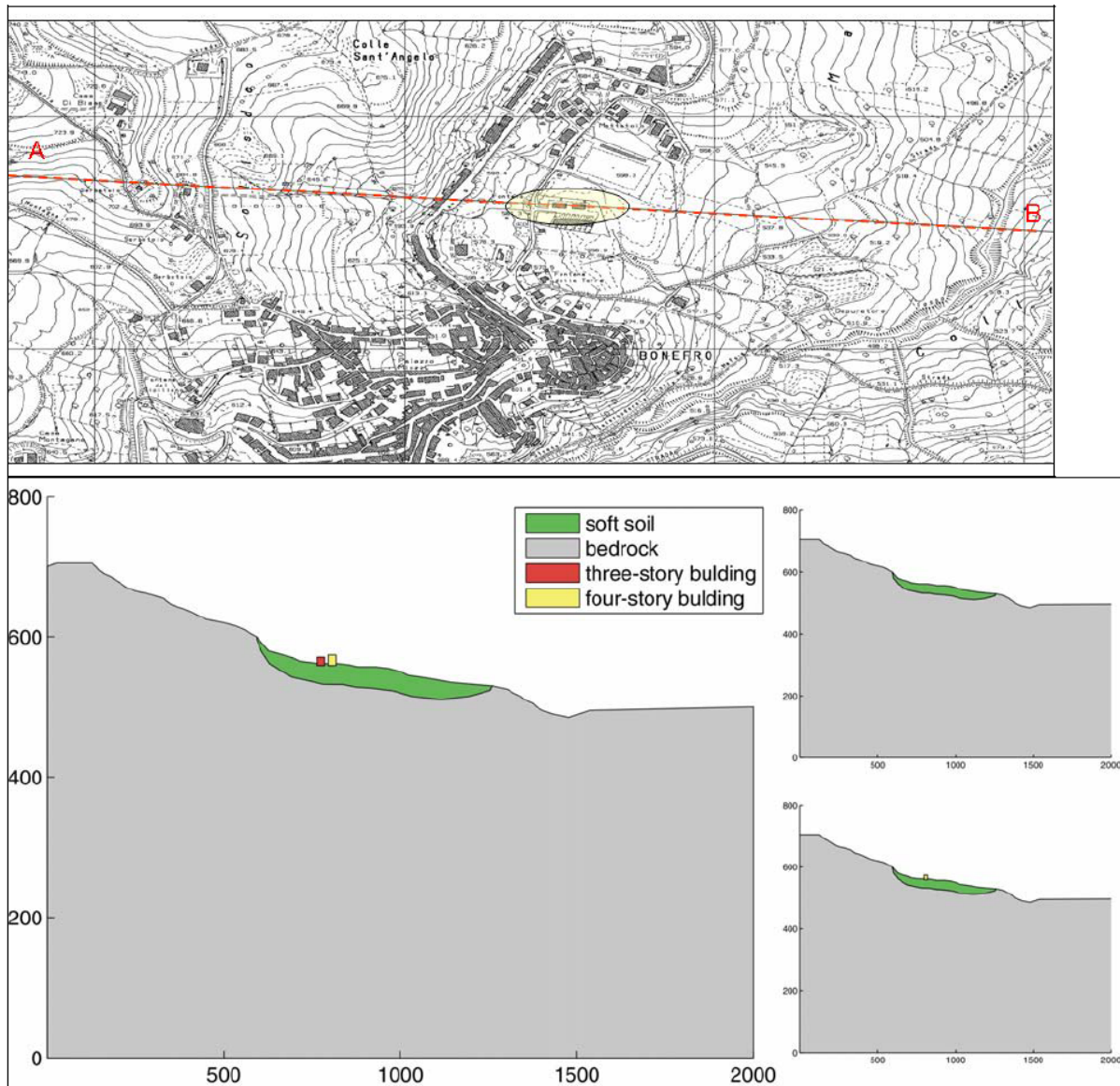
We performed 2-D numerical simulations to analyse the effect on ground motion due to the soil-building and city-site effects for the real case of two buildings located in Bonefro (Italy). The case history is interesting because atop the taller of the two buildings a time history was recorded while a strong shock was severely damaging the structure. Our study confirms that the most damaged building suffered a resonance with the soil, both having a fundamental frequency  $f_0=2.5$  Hz. The less damaged building has a much higher frequency. Moreover, the numerical model demonstrates that there is a spectral amplification effect due to the presence of the buildings and to their interaction during the seismic excitation. This effect is greater close to the buildings and becomes negligible at distance and on the bedrock.

## ACKNOWLEDGEMENTS

This work was supported by a grant in the framework of project DPC-INGV S3.

## REFERENCES

- Bard, P.-Y., Gueguen, P. and A. Wirgin (1996). A note on the seismic wavefield radiated from large building structures into soft soils, in Proc. of the Eleventh World Conference on Earthquake Engineering, Acapulco, Mexico, Paper No. 1838.
- Cornou, C., Guéguen, P., Bard, P.-Y. and E. Haghshenas (2004). Ambient noise energy bursts observation and modeling: Trapping of harmonic structure-soil induced-waves in a topmost sedimentary layer, *Journal of Seismology*, 8, 4, 507–524, 2004.
- Gallipoli, M.R., Mucciarelli, M., Castro, R.R., Monachesi, G. and P. Contri (2004). Structure, soil-structure response and effects of damage based on observations of horizontal-to-vertical spectral ratios of microtremors, *Soil Dyn. Earthq. Eng.*, 24, 487-495.
- Gallipoli, M. R., M. Mucciarelli, F. Ponzio, M. Dolce, E. D'Alema, M. Maistrello (2006) Buildings as a seismic source: analysis of a release test at Bagnoli, Italy, *Bull. Seism. Soc. Am.*, 96, 6
- Guéguen, P., Bard, P.-Y. and C.S. Oliveira (2000). Experimental and numerical analysis of soil motion caused by free vibration of a building model, *Bull. Seism. Soc. Am.*, 90, 6, 1464-1479.
- Guéguen, P., Bard, P.-Y. and F.J. Chavez-Garcia (2002). Site-city seismic interaction in Mexico City-like environments: An analytic study, *Bull. Seism. Soc. Am.*, 92, 2, 794- 811.
- Guéguen, Ph. and P-Y Bard (2005). Soil-structure and soil-structure-soil interaction: experimental evidence at the Volvi test site, *Journ. Earthq. Eng.*, 9, 5, 657–693.
- Jennings P.C. (1970). Distant motion from a building vibration test, *Bull. Seis. S.Am.*, 60, 2037-2043.
- Kanamori, H., Mori, J., Anderson, D.L. and T.H. Heaton (1991). Seismic excitation by the space shuttle Columbia, *Nature*, 349, 781-782.
- Kham M. J.-F. Semblat, P.-Y. Bard and P. Dangla (2006); Seismic site-city interaction: main governing phenomena through simplified numerical models, *Bull. Seism. Soc. Am.*, 96, 1934-1951
- Mucciarelli, M., Masi, A., Gallipoli, M.R., Harabaglia, P., Vona, M., Ponzio, F., and Dolce, M. 2004. Analysis of RC building dynamic response and soil-building resonance based on data recorded during a damaging earthquake (Molise, Italy, 2002). *BSSA*, 94 (5), 1943-1953.
- Priolo, E., 2001. Earthquake ground motion simulation through the 2-D spectral element method. *J. Comp.Acoustics*, 9 (4), 1561-1581.
- Priolo, E., 2002. Ground Motion Modelling Using the 2-D Chebyshev Spectral Element Method. Numerical Analysis and Modeling in Geomechanics. Editor Dr. John W. Bull Spon Press. Taylor and Francis Group Ltd., London
- Wirgin, A. and P-Y Bard (1996). Effects of building on the duration and amplitude of ground motion in Mexico City, *Bull. Seism. Soc. Am.*, 86, 914-920.
- Wong, H.L. and M.D. Trifunac (1975). Two dimensional antiplane building-soil-building interaction for two or more buildings and for incident plane SH waves, *Bull. Seism. Soc. Am.*, 65, 1863-1885.



**Figure 1. Above: Topographic map of Bonefro. The line AB is the section chosen for the model. Below: Structure of the models; with both buildings (model 2, left); without building (model 0, top right); with the 4-storey building alone (model 1, bottom right). The units are meters. Note that the studied buildings are far from other structures**



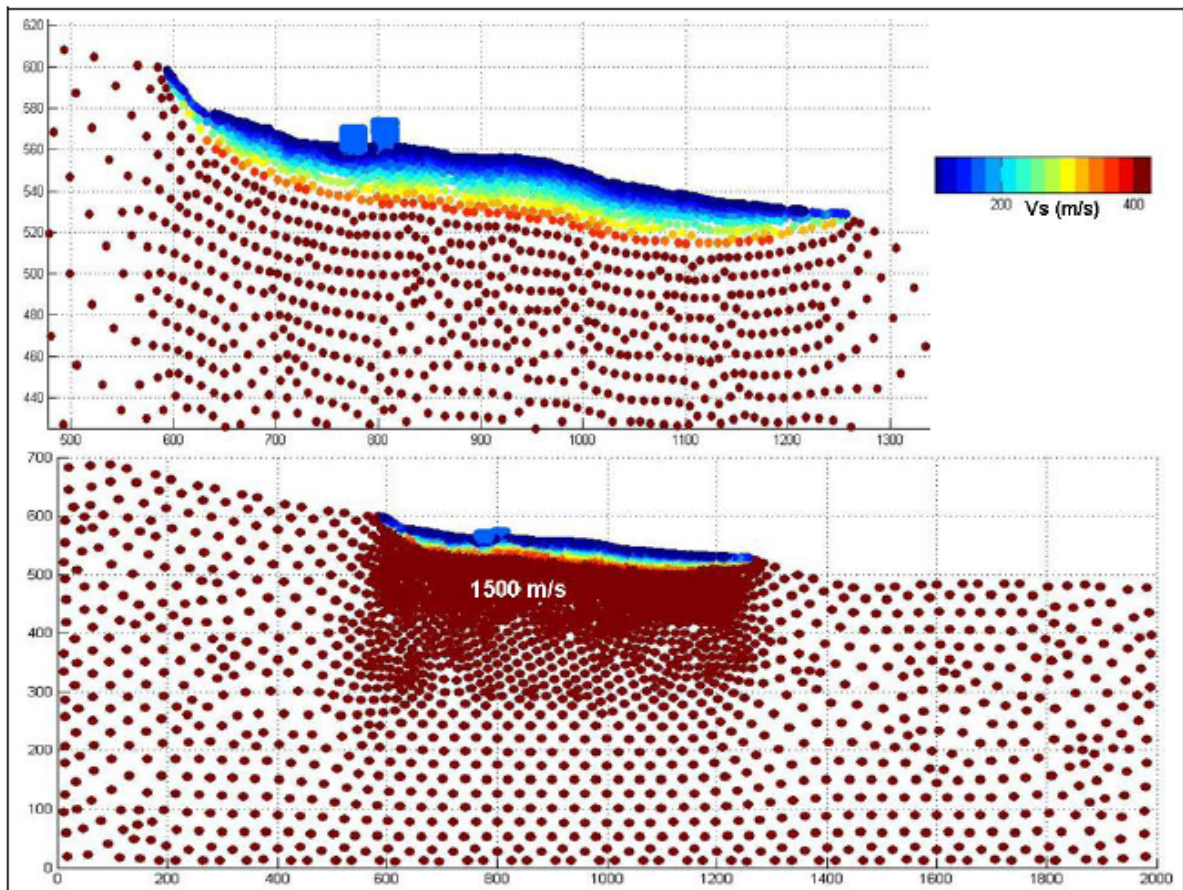


Figure 2. Vs values for model 2. Below, the whole model. Above, close-up near the surface.

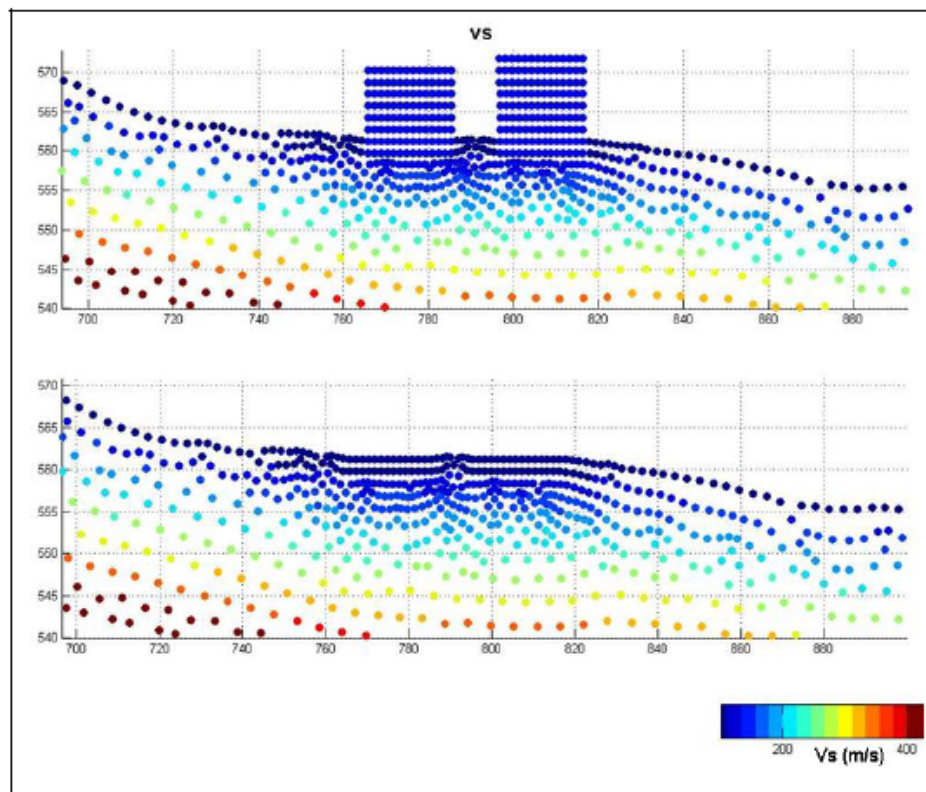
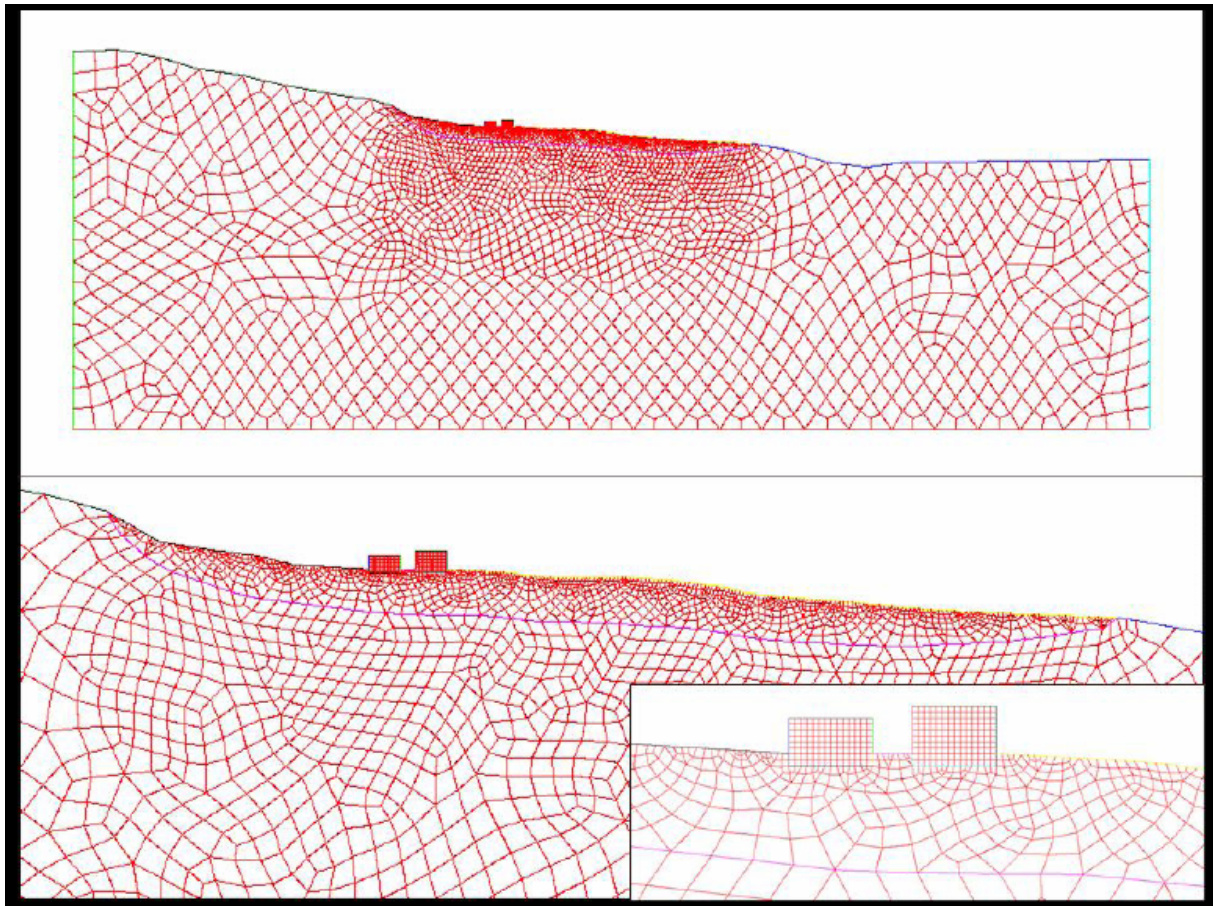
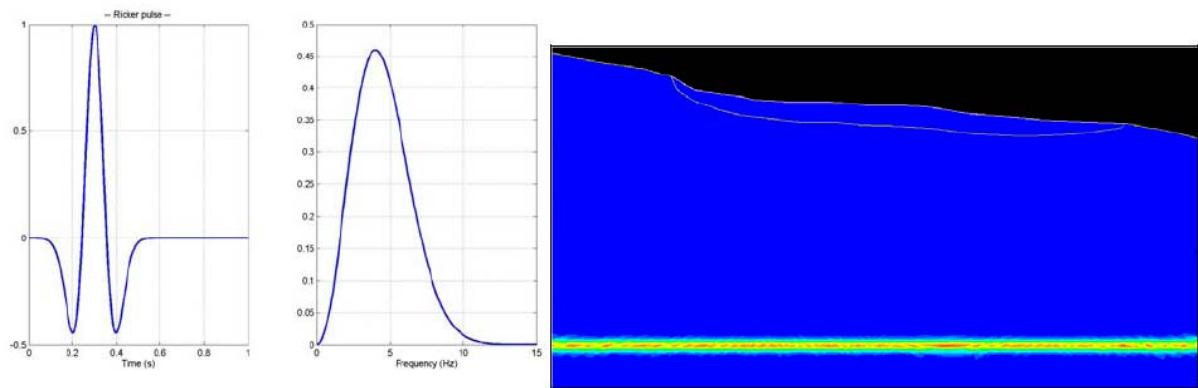


Figure 3. Vs values for model 2 (above) and 0 (below), close-up near the surface.

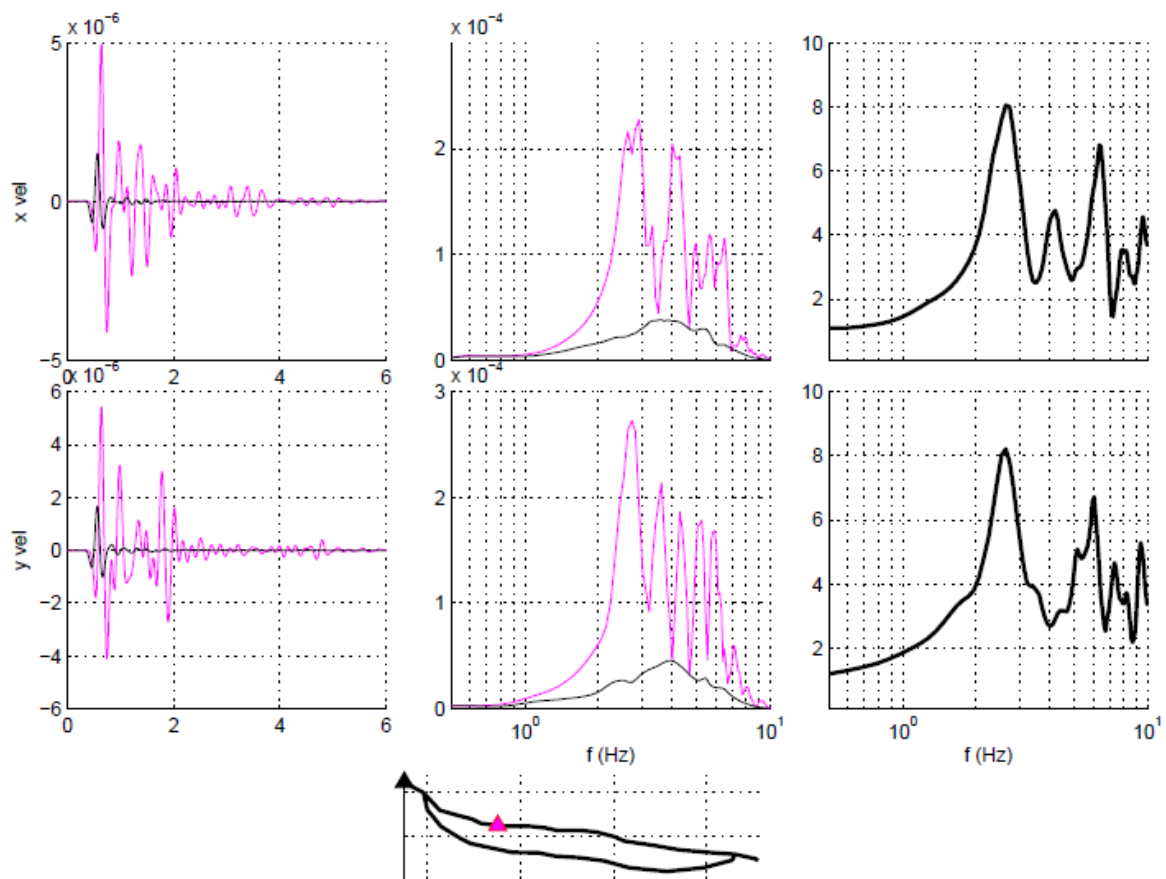


**Figure 4. Different levels of details of the mesh used for the discretisation of model 2.**

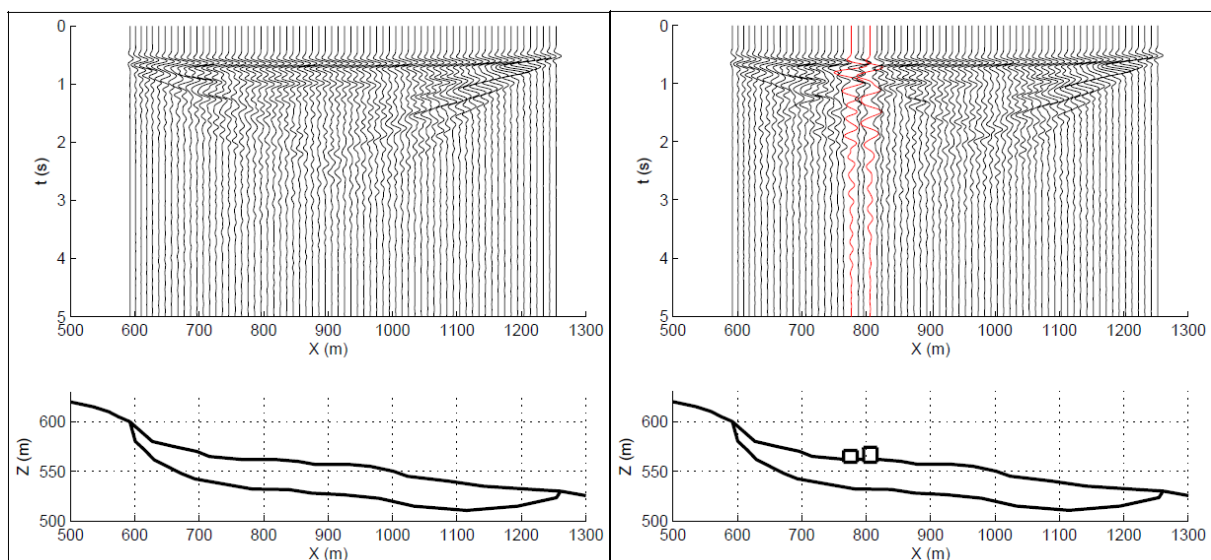


**Figure 5. Left: source time history and its spectrum. Right: snapshot of the wave field at the beginning of propagation.**



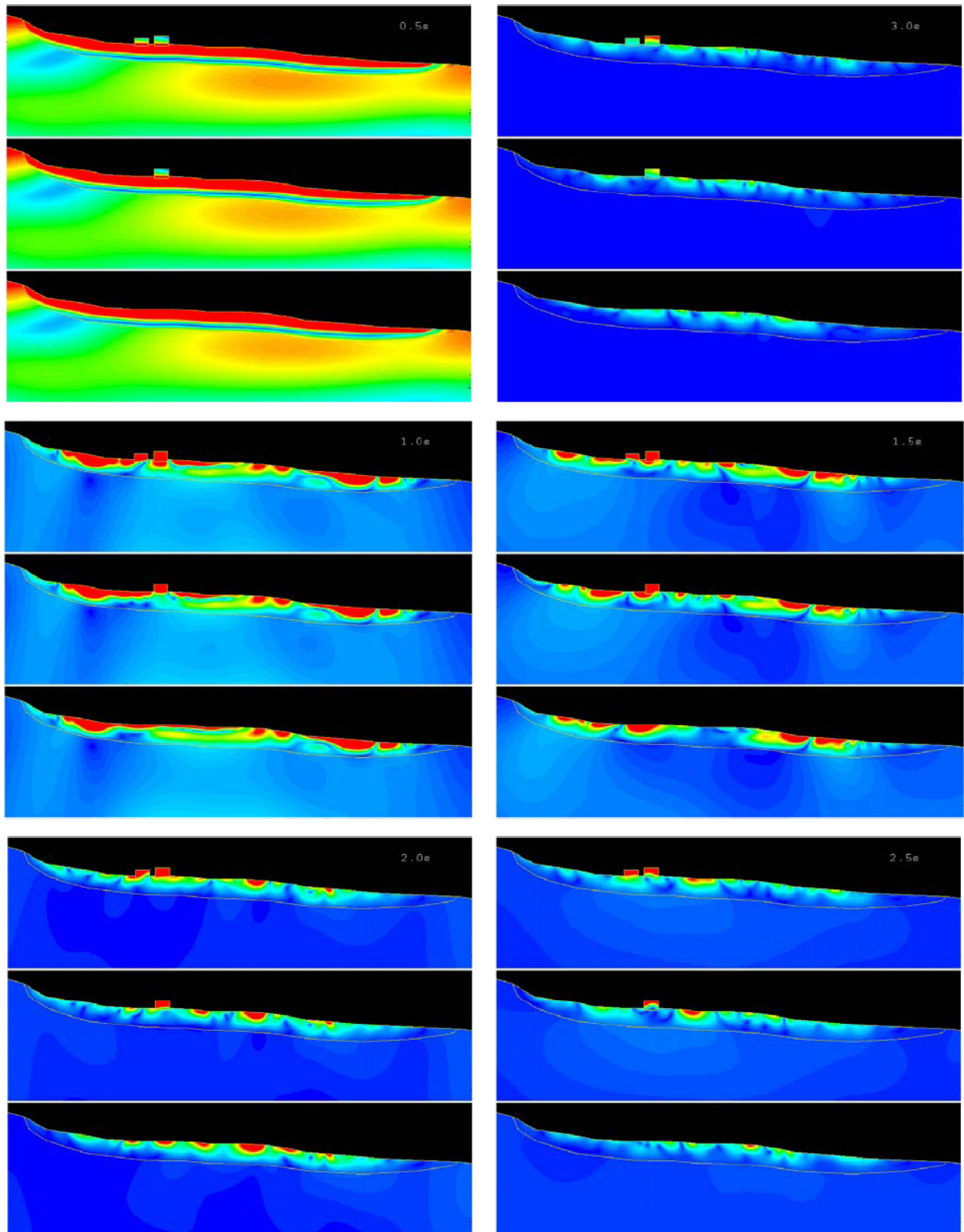


**Figure 6. Synthetic seismograms for model 0 at bedrock (black) and soil (red). Left to right: time histories, Fourier spectra and spectral ratio (radial above and transverse below).**

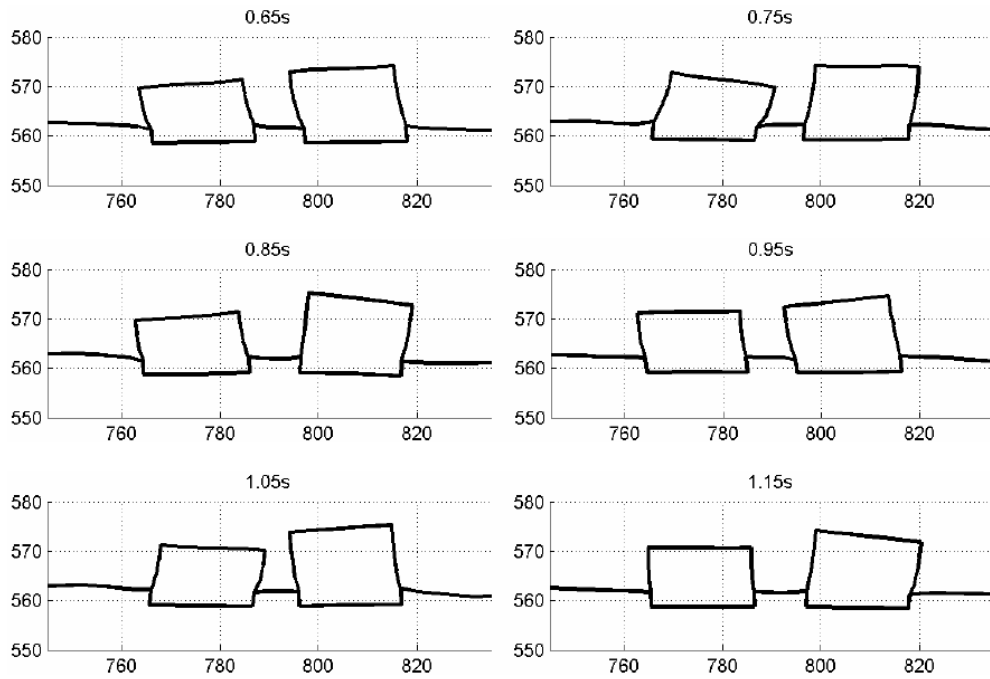


**Figure 7. Synthetic seismograms at the surface along the section for model 0 (left) and model 2 (right, with red lines relevant to buildings).**

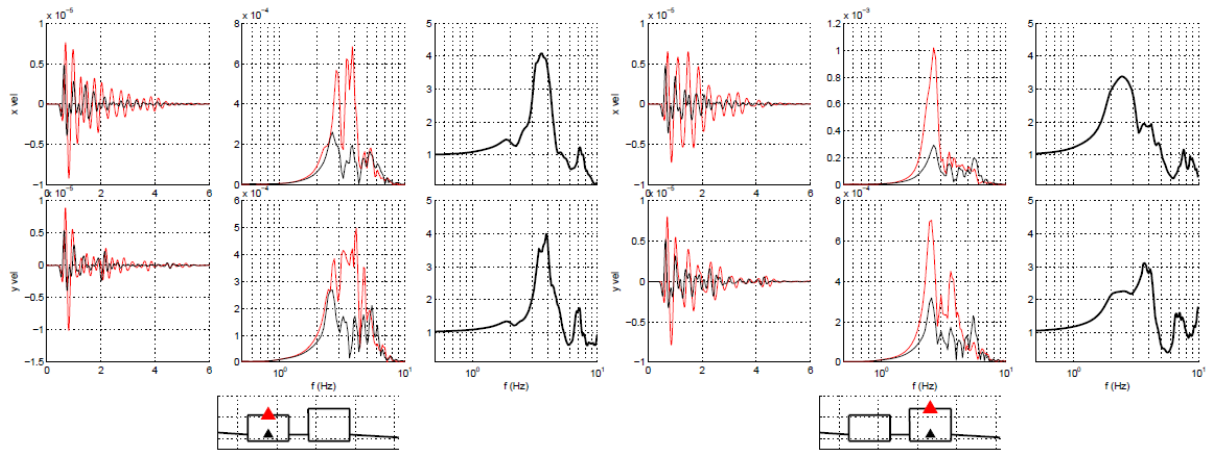




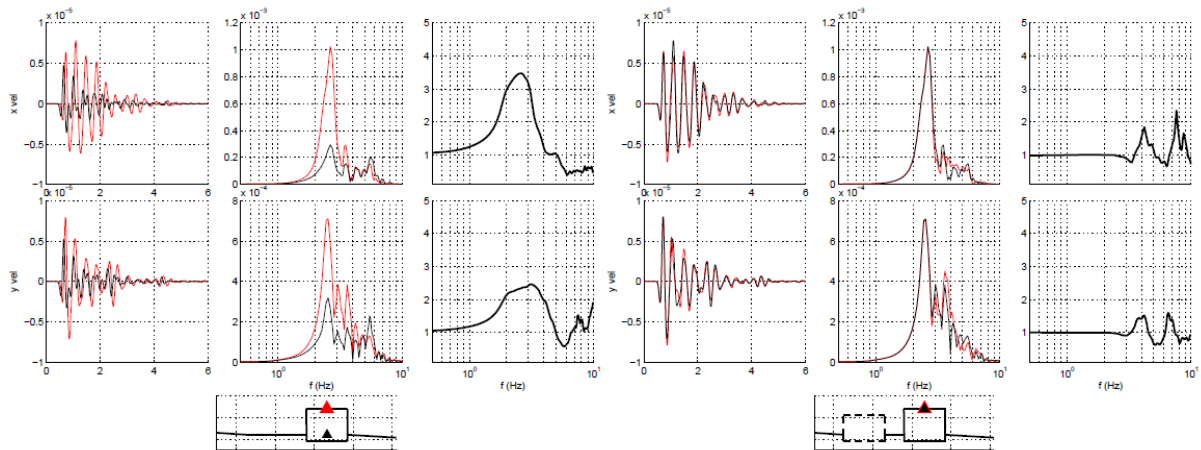
**Figure 8. Snapshots at different propagation times for the P-SV wave field. For each panel top to bottom model 2, 1 and 0.**



**Figure 9. Snapshots at different propagation times for the P-SV wave field, model 2. Close up to buildings.**



**Figure 10. Comparison between model 2 (red) and model 0 (black). Triangles indicate synthetic receivers. Panels as in Fig. 6.**



**Figure 11. Left: comparison between model 1 (red) and model 0 (black) for the 4-storey**

building. Triangles indicate synthetic receivers. Panels as in Fig. 6. Right: comparison between model 2 (red) and model 1 (black) for the 4-storey building.

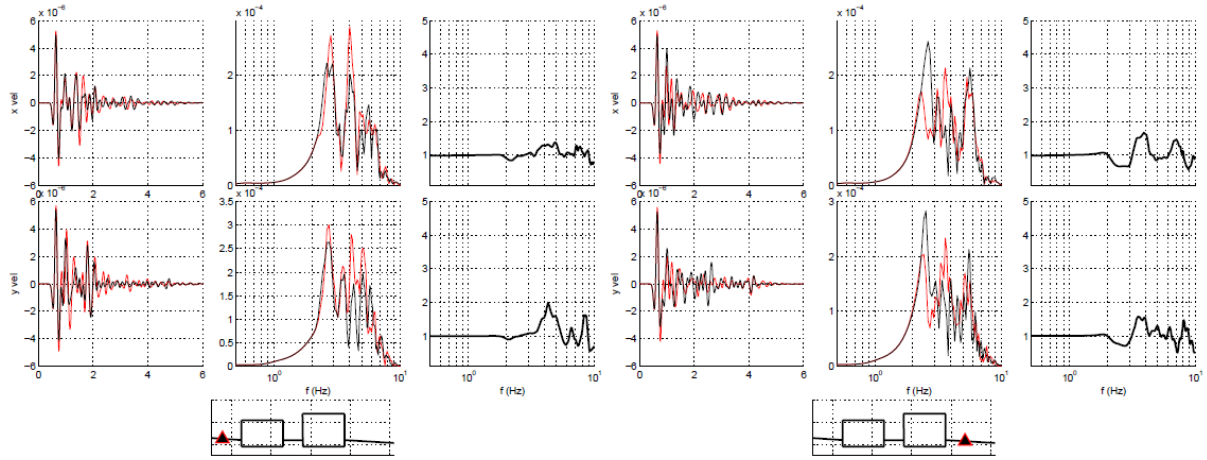


Figure 12. Comparison between model 2 (red) and model 0 (black) for clayey soil. Triangles indicate synthetic receivers. Panels as in Fig. 6.

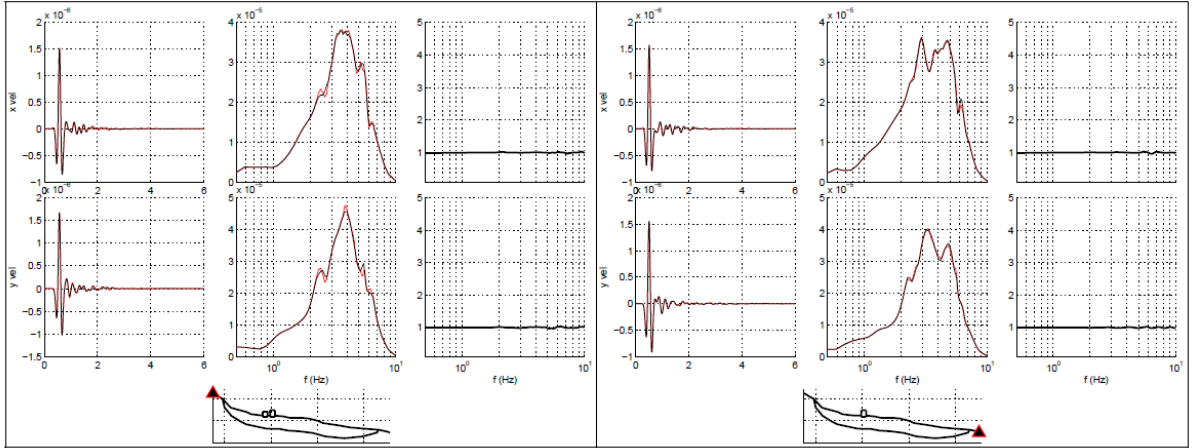


Figure 13. Comparison between model 2 (red) and model 0 (black) for bedrock at 200 m (left) and at 400 m (right). Triangles indicate synthetic receivers. Panels as in Fig. 6.