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HOW SENSITIVE THE EFFECTS OF LATERAL HETEROGENEITY ON SEISMIC GROUND MOTION ARE ?

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ABSTRACT

This paper discusses site effects due to complex local geology in terms of seismic building codes. Our discussion is based on Euroseistest. The reasons for this choice is the very detailed information available on the subsoil structure at this shallow, alluvial valley, and the existence of a large database with earthquake records of small and moderate intensity, which makes Euroseistest one of the best documented cases of site effects studies. We take as our starting point previous studies of site effects at this valley (Raptakis et al., 2000; Chávez-García et al., 2000; Makra et al., 2001) that showed the large impact of the 2D valley structure on its site response. In this study, we pursue those ideas but extend the objectives along two lines. First, we quantify the additional amplification introduced by the complex geology relative to the predictions of a 1D model in terms of an "aggravation factor". Second, we check the sensitivity of the 2D/1D aggravation factor on the basis of a thorough parametric analyses on the most important parameters that condition the seismic response of 2D soil structures that is dynamic properties (shear wave velocity and attenuation distribution with depth) and shape of geometric characteristics of the basin.

Keywords: Euroseistest, complex site effects, lateral propagation, surface waves, 1D-2D simulations, aggravation factor

INTRODUCTION

Site effects accounting for 2D and/or 3D geometry play an important role in the manifestation of complex phenomena, which cause additional amplification and duration to the expected 1D response. The role of lateral heterogeneity in site effects, especially in small and shallow sedimentary basins, has been recently observed (e.g Coachella valley in California by Field, 1996; Parkway in New Zeland by Chavéz-García et al., 1999; Colfiorito in Italy by Caserta et al., 1998 and Rovelli et al., 2001). A striking example of this was observed during the Kobe earthquake (1995), where the damage belt has been attributed to focusing effects at the edge of the Osaka basin (Kawase, 1996).

The engineering community is well aware of the existence of this kind of complex site effects and of the need to taking them into account (Field, 1996; Rassem et al., 1997; Chávez-García & Faccioli, 2000; Makra et al., 2001, 2002, 2005; Raptakis et al., 2004a,b). However, modern seismic codes (UBC, EC8, NEHRP) and current microzonation practice have almost exclusively relied on the one-dimensional analysis to predict surface motions at a site, thus overlooking the effects of surface and buried topography (geometry of bedrock-sediment interface) and the finite lateral extent of soil in sediment filled valleys. Although there is an ongoing discussion on the need to improve seismic codes, attention is concentrated on aspects such as definition of soil classes and shape and amplitude of the design response spectra. Less effort is being directed to the possible influence of complex site effects.

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We believe that this issue should receive wider discussion, supported both by observations and numerical simulations.

This paper discusses site effects due to complex local geology in terms of seismic building codes. Our discussion is based on Euroseistest. The reasons for this choice is the very detailed information available on the subsoil structure at this shallow, alluvial valley, and the existence of a large database with earthquake records of small and moderate intensity, which makes Euroseistest one of the best documented cases of site effects studies. We take as our starting point previous studies of site effects at this valley (Raptakis et al., 2000; Chávez-García et al., 2000; Makra et al., 2001) that showed the large impact of the 2D valley structure on its site response. In this study, we pursue those ideas but extend the objectives along two lines. First, we quantify the additional amplification introduced by the complex geology relative to the predictions of a 1D model in terms of an "aggravation factor". Second, we check the sensitivity of the 2D/1D aggravation factor on the basis of a thorough parametric analyses on the most important parameters that condition the seismic response of 2D soil structures that is dynamic properties (shear wave velocity and attenuation distribution with depth) and shape of geometric characteristics of the basin.

DATA AND METHODS USED

Reference soil model

Euroseistest site is established on a 5.5 km wide and 200m deep sedimentary valley in the Mygdonian graben. This graben is located some 30km to the East of Thessaloniki in Northern Greece. The subsurface structure of the valley was explored extensively, with the aim of having an accurate description of the subsoil structure and of the mechanical properties of the sediments filling the valley (Jongmans et al., 1998; Pitilakis et al., 1999; Raptakis et al., 2000). A detailed determination of the geometry and dynamic properties of soil deposits was obtained using different and complementary prospecting techniques, including borehole seismic tests (cross-hole and down-hole), P and SH refraction, P reflection and surface wave (Rayleigh and Love) inversion and extensive geotechnical in-situ and laboratory testing programs (drillings, sampling, ground water table measurements, SPT and CPT, cyclic triaxial and resonant column tests). The result was the 2D model shown in Figure 1a (Raptakis et al., 2000) referred from now on as reference model (model I). Eight different soil layers (properties given in Table 1) and four faults were identified. The ability of this model to account for site effects in this basin was shown by Chávez-García et al. (2000).

Parametric analyses soil models

In order to check the sensitivity of the 2D/1D aggravation factor (i.e. the additional amplification introduced by the complex geology relative to the predictions of a 1D model), we, first, consider two alternative velocity structures for the sediments of the reference model while keeping the sediment/bedrock interface unchanged. In the first case (model II, Figure 1b), we have grouped soil layers according to their geological age. Formations A, B, C and D of the reference model, dated from the Quaternary, are grouped together, while formations E, F and G*, date from the Neogene, form a second layer. The shear wave velocity of each layer in model II is the average of the layers they replace, weighted by their thickness at the centre of the valley. The first layer is about 80 m thick, while the second about 120 m, at the centre of the valley. The second possible variation for the velocity structure of the sediments is to consider them homogeneous (model III, Figure 1c). Once again, the shear wave velocity taken for the sediments in this case is the weighted average (by their thickness) of the shear wave values at the centre of the valley. Q factors of the reference model were averaged in the same way to obtain the Q factors used in models II and III.

The reference model not only has a complex velocity structure but also a very irregular shape. This shape was obtained from the synthesis of geologic data and the results of many different geophysical

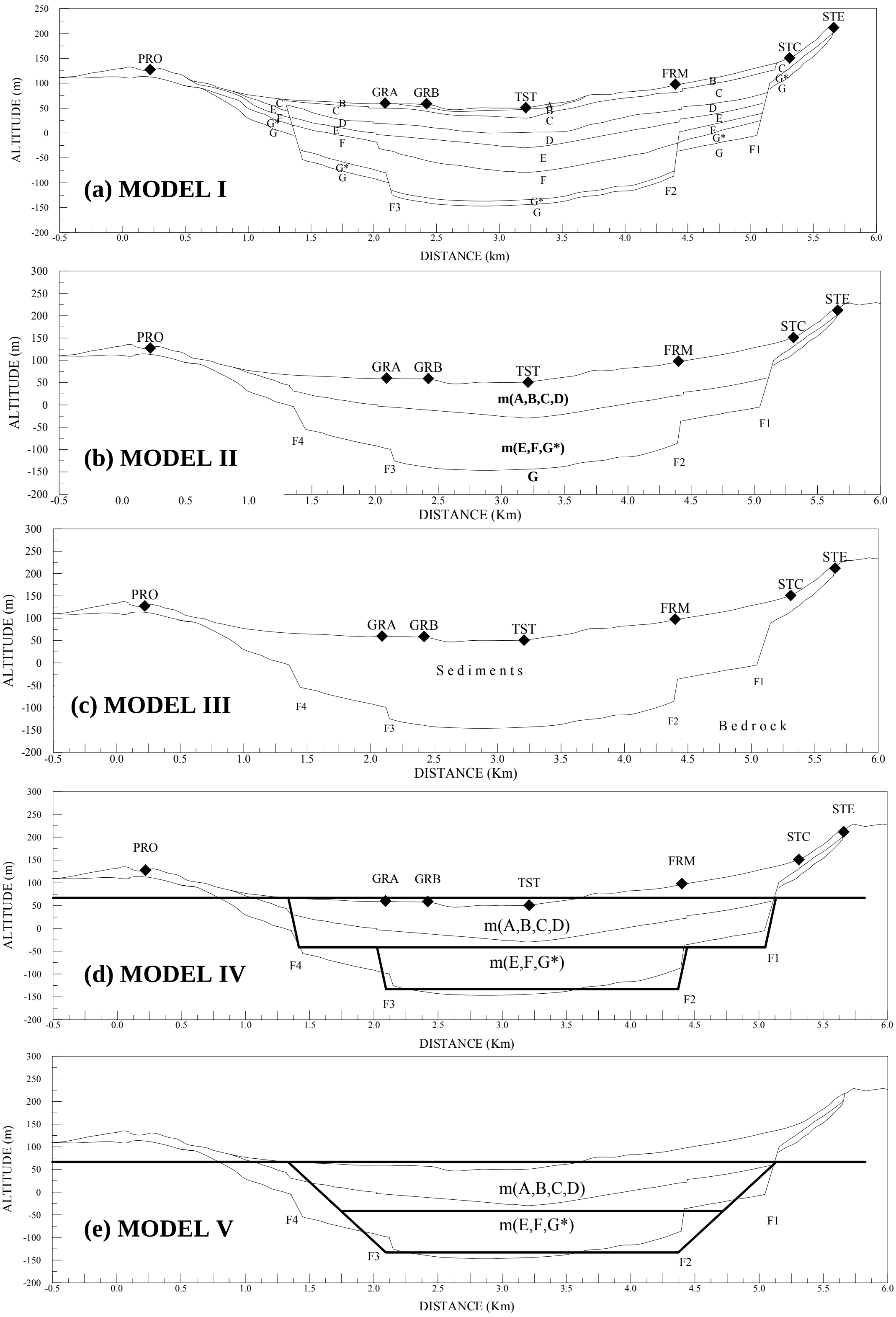

Figure 1. Five possible 2D models for Euroseistest valley. a) 2D cross section determined for Euroseistest valley by Raptakis et al. (2000). b) The shape of the interfaces of model I is kept, but the four topmost (A, B, C, and D) and the three lowermost formation (E, F, and G*) have each been replaced by a single homogeneous layer. c) The interface sediment/bedrock is the same as in model I but the sediments are considered homogeneous. d and e) Two possible simplifications of the geometry of the reference 2D model. We use the same two layers, averaged from the detailed profile, as in model II, together with a much simpler geometry. Properties of soil formations for all models are given in table 1.

Table 1. Dynamic properties of the soil materials included in the 2D models.

	Soil Formation	A	B	C	D	E	F	G*	G
MODEL I	Vs (m/sec)	130	200	300	450	650	800	1250	2600
	Qs (=1/2ξ)	15	25	30	40	60	80	100	200
	ρ (t/m^3)	2.05	2.15	2.075	2.10	2.155	2.20	2.50	2.60
MODEL II,IV,V	Vs (m/sec)	330				750			2600
	Qs (=1/2ξ)	33				75			200
	ρ (t/m^3)	2.10				2.20			2.60
MODEL III	Vs (m/sec)	590							2600
	Qs (=1/2ξ)	55							200
	ρ (t/m^3)	2.2							2.60
MODEL VI	Vs (m/sec)	123.5	190	285	427.5	617.5	760	1187.5	2600
	Qs (=1/2ξ)	14.25	23.75	28.5	38	57	76	95	200
	ρ (t/m^3)	2.05	2.15	2.075	2.10	2.155	2.20	2.50	2.60
MODEL VII	Vs (m/sec)	117	180	270	405	585	720	1125	2600
	Qs (=1/2ξ)	13.5	22.5	27	36	54	72	90	200
	ρ (t/m^3)	2.05	2.15	2.075	2.10	2.155	2.20	2.50	2.60
MODEL VIII	Vs (m/sec)	110.5	170	255	382.5	552.5	680	1062.5	2600
	Qs (=1/2ξ)	12.75	21.25	25.5	34	51	68	85	200
	ρ (t/m^3)	2.05	2.15	2.075	2.10	2.155	2.20	2.50	2.60
MODEL IX	Vs (m/sec)	104	160	240	360	520	640	1000	2600
	Qs (=1/2ξ)	12	20	24	32	48	64	80	200
	ρ (t/m^3)	2.05	2.15	2.075	2.10	2.155	2.20	2.50	2.60

as well as geotechnical studies (Pitilakis et al., 1999; Raptakis et al., 2000). Obviously, this effort is out of reach of standard site effect studies. For this reason, we assume now that our information is restricted to a good guess of the maximum thickness of the sediments. We have taken the two-layered structure of model II, and consider now two different shapes for the interface at the bottom of the basin shown in Figure 1d and 1e (models IV and V respectively).

Then in order to account, although crudely, for possible non-linear effects – implying degradation of shear modulus and increase of damping – in case of a strong earthquake or introducing uncertainties in the determination of Vs and Qs values of the initial model, we assumed an incremental decrease of Vs values and increase of attenuation for the soil formations of the reference model (model I) while the shape of the interfaces of this model is kept. Thus, we have computed site response for 95%, 90%, 85% and 80% of the initial Vs and Qs values (models VI – IX, Table 2) considering for shear modulus, G, values from G_0 to $0.64G_0$ and damping from ξ_0 (=1/2Qs) to 1.25 ξ_0.

Earthquake observation

The records obtained by the permanent accelerograph network that has operated since 1993 have been used. Twelve (12) of them have been selected to be used in this study (Table 2) because they were recorded simultaneously at all stations along the 2D cross section and already used in previous studies. The records were rotated with respect to the axis of the valley to obtain transversal and radial components of motion. Our reference station was PRO located on a very thin sediment layer overlying the gneiss basement. Thus, in order records at station PRO to be used as input motion, we deconvolved the recorded records at station PRO by its transfer function as suggested in Chávez-García et al. (2002a).

Computational method

The 2D computational method we use is finite differences, in the version coded by Moczo (1989) (see also Moczo and Bard, 1993; Moczo et al., 1996) and accounts for linear anelastic with constant damping behavior of soil materials. In this paper we have modeled site response for SH waves, which allow a simpler discussion. The excitation to the finite difference grid was vertically incident plane waves. The time signal used for the excitation was a Gabor pulse with parameters chosen so that it had an almost flat amplitude spectrum in the frequency range 0-10 Hz. The spatial sampling step was of 1.3 m, allowing computing accurately ground motion up to 10 Hz (model I) to 8Hz (model IX) with the lowest Vs value). Models IV and V have higher than 10 Hz frequencies for which the results present numerical stability, but for reasons of uniformity, their results were low passed filtered at a corner frequency of 10 Hz. Synthetic ground motion was computed at 155 equally spaced receivers on the free surface. 1D site response was computed for the corresponding vertical soil profile for each one of the 155 receivers of 2D modeling using Kennett's reflectivity-coefficient method (Kennett, 1983).

Table 2. Data of the earthquakes used in this study.

NO	DATE	TIME (GMT)	M	LATITUDE	LONGITUDE
1	950404	17:10	4.6	40.562	23.626
2	950404	17:27	4.3	40.565	23.661
3	950503	14:16	4.4	40.555	23.679
4	950503	15:39	4.7	40.565	23.685
5	950503	18:56	4.3	40.556	23.653
6	950503	21:36	5.0	40.565	23.667
7	950503	21:47	5.1	40.569	23.660
8	950503	22:33	3.8	40.561	23.687
9	950504	00:34	5.8	40.558	23.653
10	950504	00:43	4.1	40.570	23.628
11	950504	01:14	3.8	40.577	23.605
12	950513	08:47	6.6	40.158	21.673

RESULTS

Figure 2a shows the synthetic seismograms computed for vertical incidence of SH waves on model I (Figure 1a). At the centre of the valley, multiples of the direct S-wave arrival were observed, however, the whole cross-section is dominated by laterally propagating Love waves. These surface waves are generated mainly by the lateral discontinuities at the location of faults F1, F3, and F4, and correspond to the fundamental and first higher modes for the soil structure at the centre of the valley. These locally generated Love waves have large amplitude and govern the duration of ground motion on the sediments; the closer to the centre of the basin, the larger the duration of ground motion due to those contributions. These synthetics will serve us to evaluate the results computed for the other models.

Figure 2b shows, similarly, the synthetic seismograms on model II (Figure 1b). The results are very similar to those for the reference model. The simpler stratigraphy of model II, however, allows discriminating more clearly the 1D reflections from the lateral propagation. Again, 1D resonance controls ground motion for a short time at the centre of the basin; with surface waves taking over at about 2 sec. Synthetics for model III (Figure 2c) are still simpler. At the centre of the valley, for example, we may readily identify three reflections from the bottom interface of the valley, before the arrival of surface waves. In all three cases (models I, II, and III), the amplitude of the diffracted surface waves is significantly larger than that of the vertically propagating pulses. The group velocity of those Love waves is larger in model II, relative to model I and is largest in model III. This is expected from the dispersion curves that can be computed at the centre of each basin model. The consequence is that the increment in the duration is smallest for model III, given that in all three cases, Q factors are small enough to attenuate the reflection of surface waves at the edges of the basin.

In order to compare the models in more detail, we have chosen the locations of the strong motion stations as representative (Figure 1a). The left column of Figure 3 shows the 2D synthetic seismograms at the 4 central sites (GRA, GRB, TST, and FRM). The degree of heterogeneity is

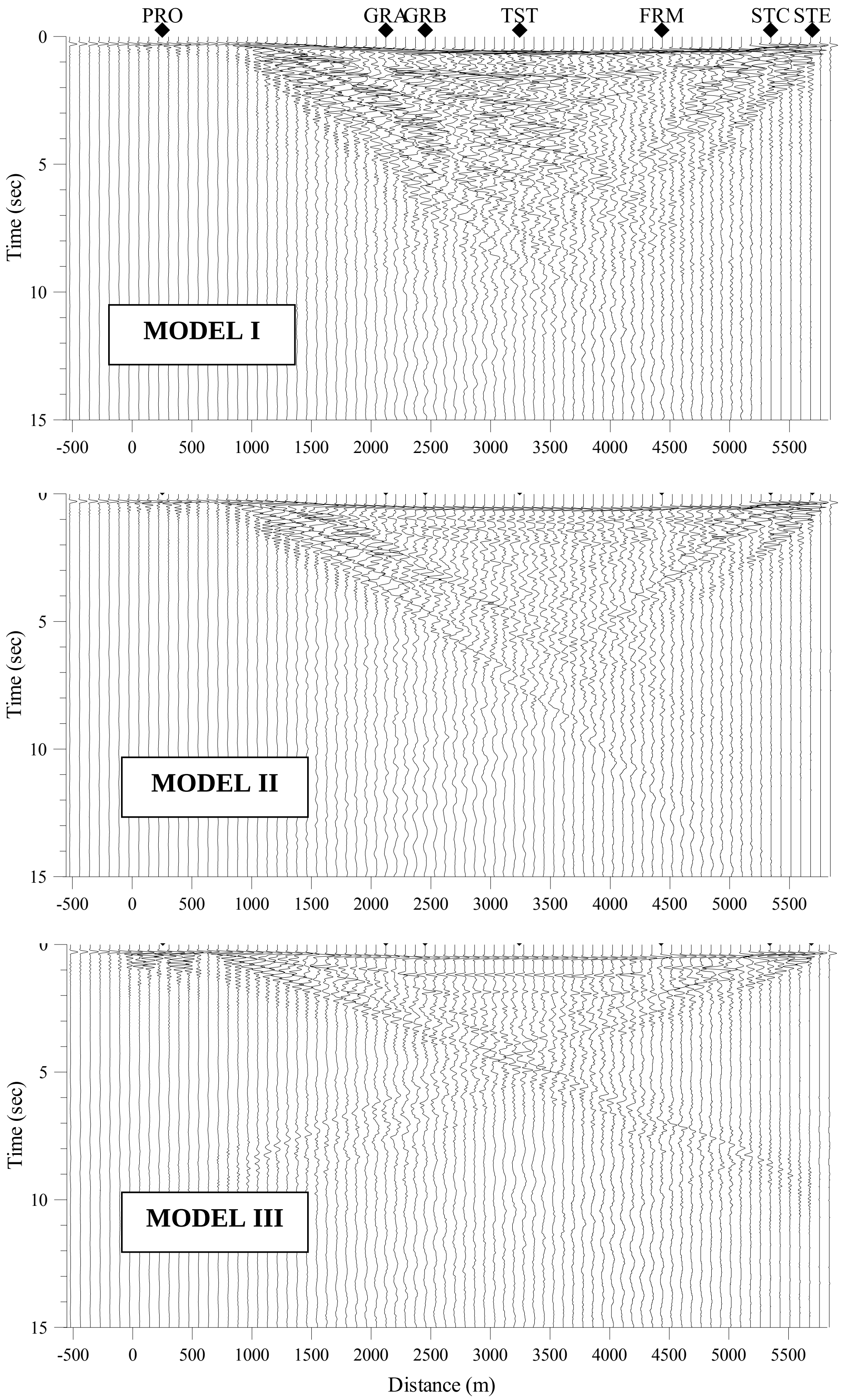

Figure 2. Synthetic seismograms computed at the surface for vertical incidence of SH waves on the 2D models I, II and III shown in Figure 1a,b,c. The traces have been low passed filtered with a cutoff of 10 Hz.

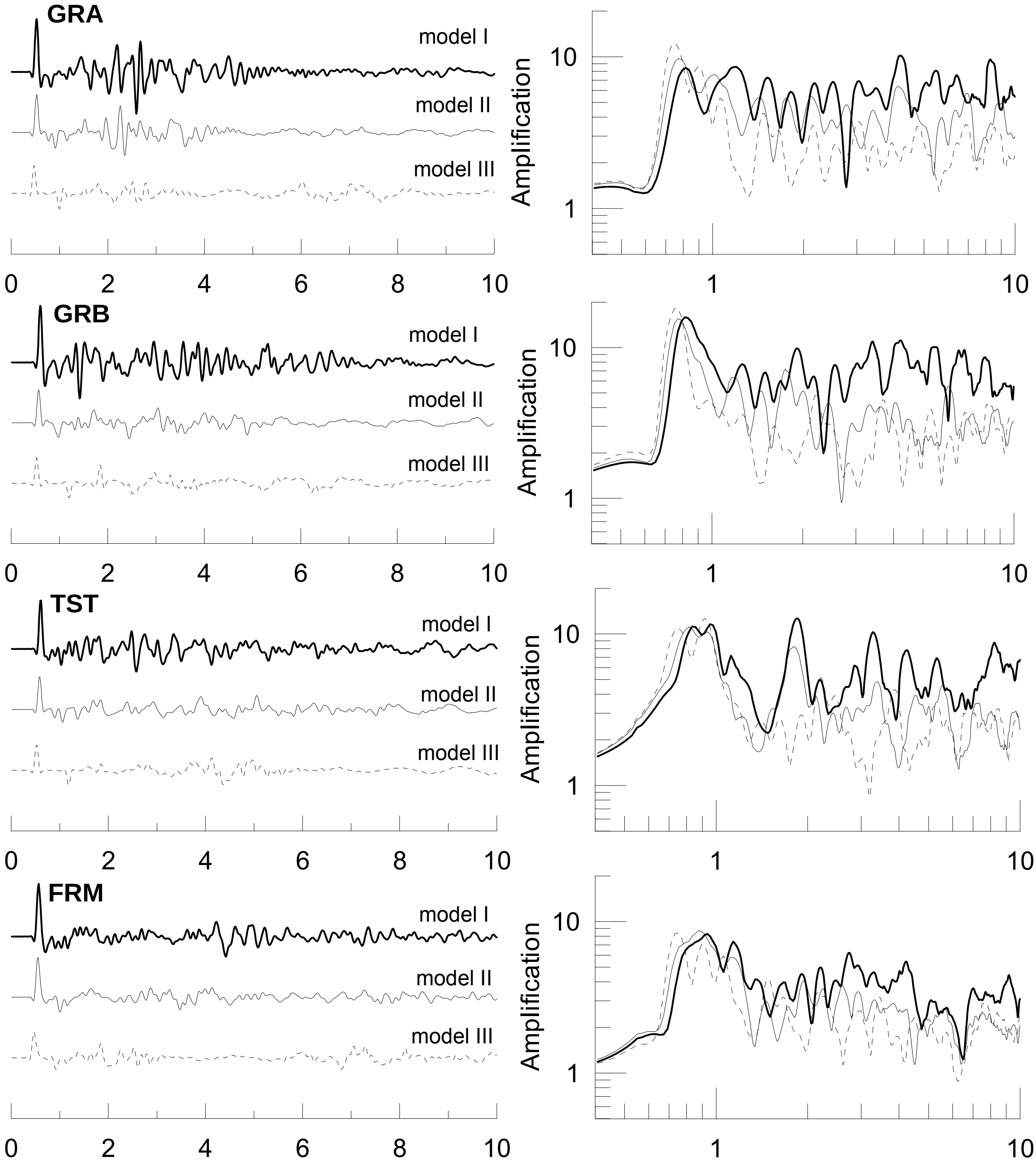

Figure 3. Left column: synthetic seismograms computed using finite differences at the sites where the permanent array of strong motion stations is installed (Figure 2a) for the three different 2D models (I, II, and III) shown in Figure 2. Right column: corresponding transfer functions for each synthetic seismogram.

directly related to the maximum amplitude of the signals, which decreases between model I and II and between model II and III. An interesting feature, however, is that that decrease of amplitude is almost the same between the direct arrivals and the late arrivals of surface waves. This means that, even if the absolute amplitudes depend strongly on the particular model chosen, the energy carried by the locally generated surface waves is related by an almost constant factor with the amplitude of the direct arrivals. At TST, for example, the ratio of the peak-to-peak amplitude between the first arrival and the larger amplitude surface waves is 1.4 for model I, 1.6 for model II, and 1.0 for model III. Thus, the progressive simplification of the 2D reference model changes the maximum amplification, but does not change the relative amplitude of the locally generated surface waves, i.e., all three models generate the same amount of surface waves relative to the amplitude of the input motion. The right column in Figure 3 shows the corresponding frequency transfer functions of the synthetics. For all three models, and for the 4 stations with significant amplification around 1 Hz, the amplitudes and shapes of the transfer functions are similar below 1 Hz. It is at frequencies larger than 1.5 Hz that the results from the three models become different, with model II coming in between models I and III.

Figure 4a,b shows the synthetic seismic sections computed for vertical incidence of SH waves on the models shown in Figure 1d and e. The response is very similar to that of model II, with which they share the velocity structure of the sediments. Figure 4 shows clearly that the details of the interface between sediments and bedrock may affect the relative amplitude of the different waves generated by the lateral irregularities. However, the site response is still the result of the combination of 1D resonance and locally generated surface waves. 1D resonance dominates ground motion at the centre of the basin for model IV (Figure 4a), while the very simple structure generates very simple Love wavetrains that contribute little to ground motion at the center of the basin (at the edges they significantly change the 1D picture). The synthetic seismic section for model V (Figure 4b) shows a very similar picture, only that now it is the Love waves that have the largest amplitudes. The duration of ground motion due to 1D site effects is small in both models, the larger contribution form the effects of lateral irregularities. The results in frequency domain are not significantly different from those shown in Figure 3. The first and largest peak is correctly reproduced in both models IV and V for all stations. The differences among the models appear for frequencies larger than 1.5 Hz. The first peak, at frequencies slightly below 1 Hz, corresponds both to the direct arrivals and the surface waves, i.e., the frequency of the locally generated surface waves coincides with that of 1D resonance, making it difficult to separate both effects (a similar observation was made using data from another shallow alluvial valley in Chávez-García et al., 2002b).

Figure 5 shows the synthetic seismograms computed at TST for vertical incidence of SH waves on 2D models I (reference), VI, VII, VIII and IX in order to check the effect of the absolute values of dynamic properties (Vs and Qs). The traces have been low passed filtered with a cutoff of 8 Hz. As it was expected, the decrease of Vs values in the 2D model affects the arrival of different wave trains at the surface. The largest the decrease is, the slower the arrivals are, although the slowness is larger for surface waves than for direct S wave arrivals that is attributed to the fact that surface waves travel longer paths than body waves. It is also observed that the longer the path that surface wave travel is the larger the slowness is. The amplitude, however, either of body or of surface waves is not that much affected by the, as much as 20%, decrease of initial Vs and Qs values. At the left part of figure 6, 2D transfer functions at TST for models I (reference), VI, VII, VIII and IX are presented. No significant changes in the level of the amplification ratio at fundamental frequency are observed, however, a slight incremental decrease of the amplification ratio is depicted at larger frequencies. The decreases of Vs values resulted, as it was expected to be, in decreases of fundamental resonant frequency. The shape of the transfer function is similar for all cases. Difference is, however, observed around the normalized fundamental frequency (fig.6 right). A clear double peak is depicted at the 2D transfer function of model I, while for the other models it seems that the second peak presents smaller amplification.

AGGRAVATION FACTOR

We have shown the similarities and differences between different possible models for Euroseistest basin in terms of time domain synthetics and frequency domain transfer functions. It is clear that site response at Euroseistest basin owes to its 2D shape, and that no 1D model is able to satisfactorily characterize it. However, in terms of engineering applications and in terms of code compatible specifications, it is not the detailed response of each valley that is of interest. We would rather like to estimate in a simple way the effects of each structure in terms of response spectra, and to be able to quantify the differences between the different 2D models in those terms.

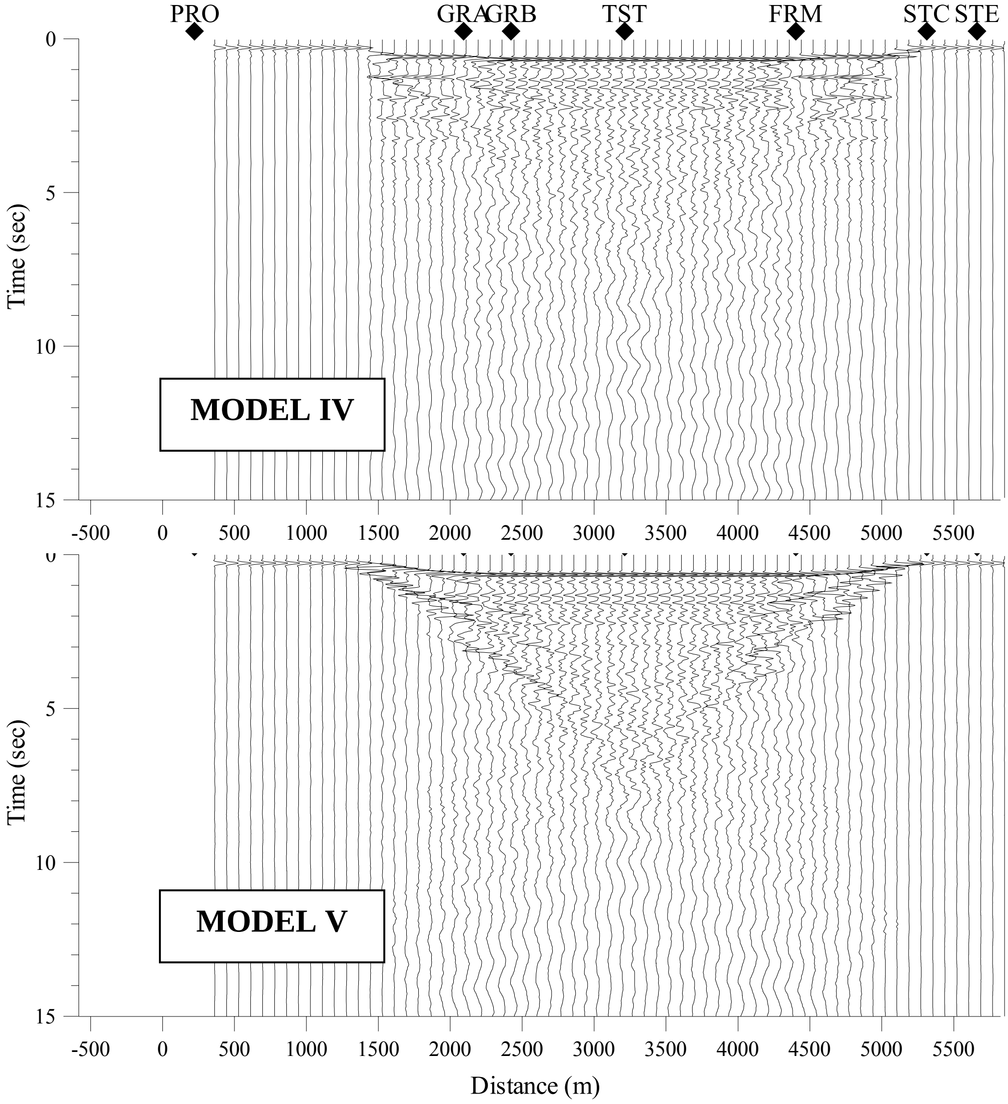

Figure 4. Synthetic seismograms computed at the surface for vertical incidence of SH waves on the 2D models IV and V shown in Figure 1d and e. The traces have been low passed filtered with a cutoff of 10 Hz.

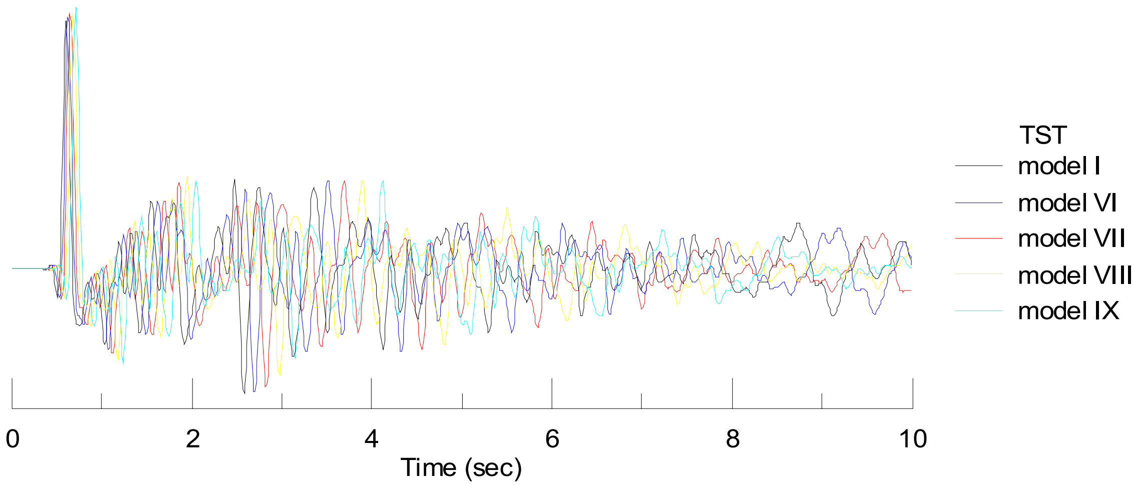

Figure 5. Synthetic seismograms computed at TST for vertical incidence of SH waves on the 2D models I (reference), VI, VII, VIII and IX. The traces have been low passed filtered with a cutoff of 8 Hz.

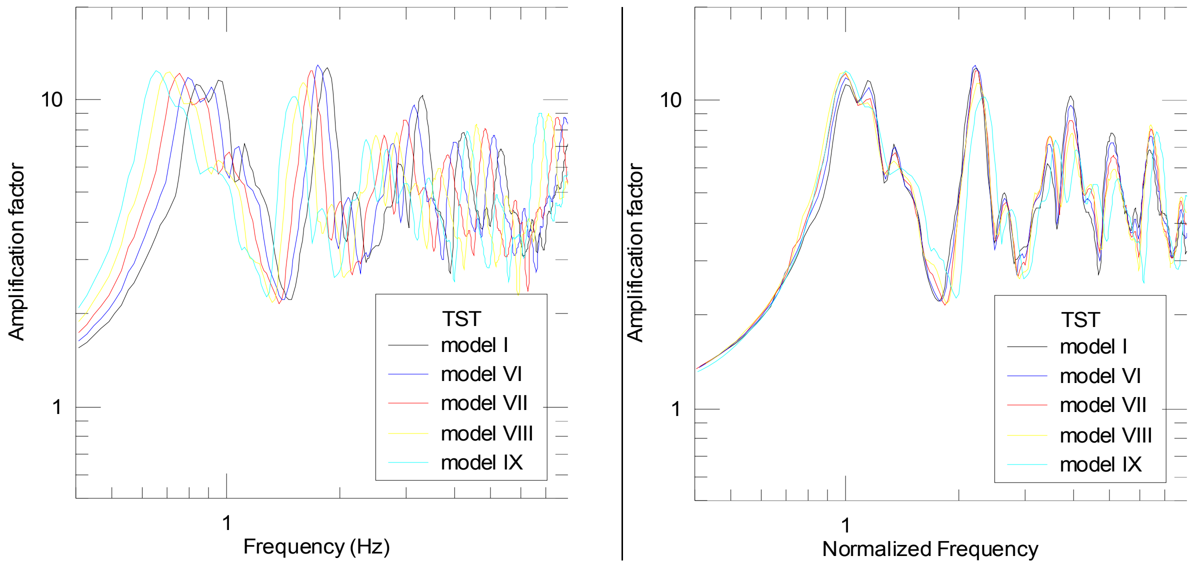

Figure 6. Left: 2D transfer functions at TST for models I (reference), VI, VII, VIII and IX.

In order to compare the different models in the terms that are relevant to the usual specification of ground motion in building codes, we have quantified for each of our models the "aggravation factor" (af) for 2D site effects, introduced by Chávez-García and Faccioli (2000). This factor was defined as the average ratio between response spectra computed at the surface of the 2D model and the response spectra computed at the surface of the equivalent 1D model. The idea behind this factor is that 1D site effects may account for amplification related to impedance ratio. Geometric effects due to lateral irregularity introduce an additional amplification factor. We will now consider the similarities and differences among our models in terms of the af..

The input motion obtained from the deconvolution described in paragraph "Earthquake recordings" was convolved by the transfer function at each receiver in the different 2D models, and by the transfer function of the 1D profile at the location of that receiver in the corresponding 2D model. Then, response spectra were computed from the simulated records, corresponding to each 2D model and the corresponding profile at each site. Finally, we computed the ratio of response spectra at each site between the one from the 2D synthetic divided by the one from the 1D synthetic.

The results computed for the locations of the permanent strong motion stations are shown in Figure 7 for models I (reference), II, III, IV and V and in Figure 8 for models I (reference), VI, VII VIII and IX. These figures show how much larger is, in average for the 12 considered earthquakes, the synthetic ground motion on the surface of the 2D model relative to the amplification predicted by the 1D profile at each location, measured in terms of response spectra at 5% damping. The very large amplification factors and differences among the models have been largely smoothed by the procedure of taking ratios of 5% damping response spectra. Most of the curves have values between factors 2 and 3 in the considered period range (0.1 to 3 sec). This indicates that 2D effects do contribute significantly to the surface ground motion, imposing a large amplification additional to that due to impedance contrast alone. It is, also, worth noticing that the af is rather constant with values also around 2 and 3 for the models with decreased dynamic properties assigned to represent soil formations (figure 8) compared to af for the reference model, while it is more discrepant for those models with different geometrical characteristics (figure 7, models IV and V). Aggravation factor for models of simplified dynamic properties with depth (figure 7, model II and III) seems to stand in between the aforementioned cases. The variations of af, although depend on frequency, are not very large and could be disregarded in favor of simplicity. These figures show that, at least as a first step, we could consider the af to be constant throughout the basin, because specifying the location of each site relative to the significant lateral boundary, then the general usefulness of the af in terms of building codes decreases.

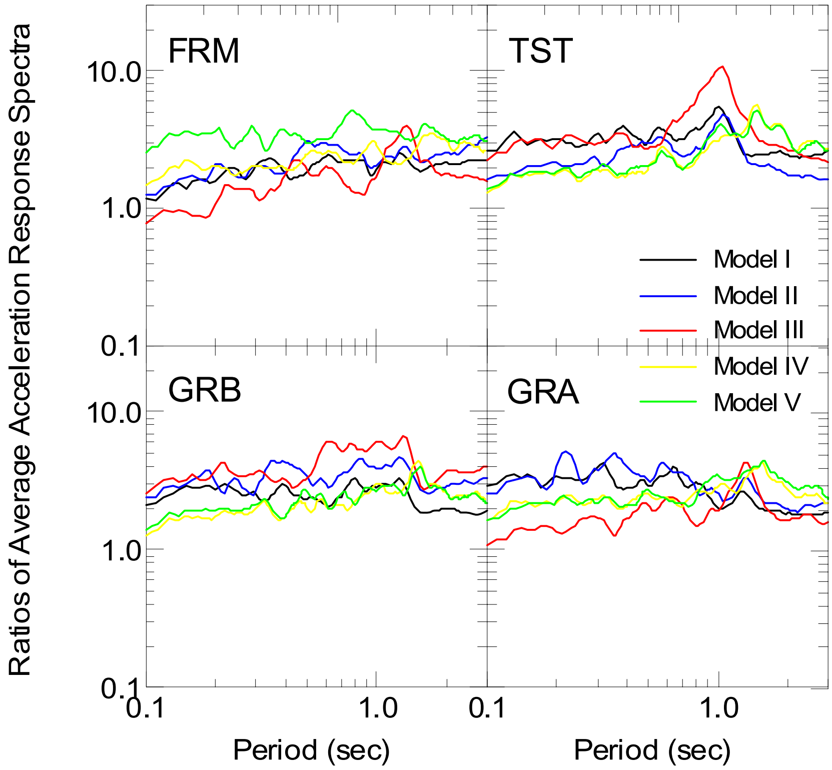

Figure 7. Ratios of response spectra for 5% damping between simulated ground motion at the locations of the permanent strong motion stations for the 2D models I (reference), II, III, IV and V and the 1D response spectra computed using the 1D profile at the location of each receiver of the corresponding 2D model.

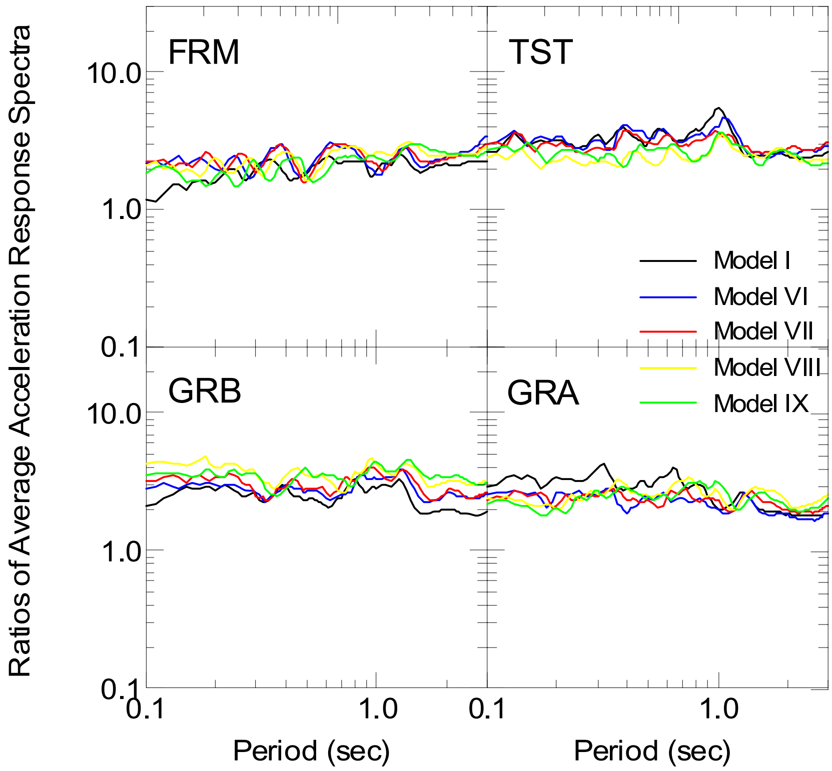

Figure 8. Ratios of response spectra for 5% damping between simulated ground motion at the locations of the permanent strong motion stations for the 2D models I (reference), VI, VII, VIII and IX and the 1D response spectra computed using the 1D profile at the location of each receiver of the corresponding 2D model.

CONCLUSIONS AND DISCUSSION

We have presented a parametric study of the site response at Euroseistest valley near Thessaloniki, in northern Greece. The detail with which this valley has been studied has allowed the construction of a detailed 2D model of its structure. This model has been validated previously through comparison with recorded data (Chávez-García et al., 2000). In this paper we have explored the differences between the computed ground motions for different models of the valley's structure, for SH waves. We considered variations in the velocity structure within the sediments, and variations of the shape between sediments and bedrock as well as decrease of the initial values of dynamic properties.

Our results show clearly that, in the case of Euroseistest, site response owes fundamentally to its closed basin shape because it is largely controlled by locally generated surface waves. Thus, in terms of predicting site response, a rough idea of its shape ratio and of the average mechanical properties of the sediments are better than a very detailed 1D profile at the central site. Although the details of ground motion may vary significantly between the models, the relative amount of surface waves generated in the 2D models seems to be relatively constant. Moreover, if we quantify the additional amplification caused by the lateral heterogeneity in terms of the "aggravation factor" introduced by Chávez-García and Faccioli (2000), a roughly constant factor between 2 and 3 seems to appropriately take into account the effects of lateral heterogeneity. This aggravation factor seems to mostly depend on the geometrical characteristics of the valley than on variations of the velocity structure or absolute values of dynamic properties (Vs and Qs). Our results suggest that, in order to improve current schemes to take into account site effects in building codes, the more to be gained comes from consideration of lateral heterogeneity. If we assume that the seismic response of Euroseistest is representative of that for shallow alluvial valleys where 1D resonance and lateral propagation of surface waves dominate, then we believe that our results may apply to a large number of sites.

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REFERENCES

Caserta, A., Rovelli, A., Marra, F. and Belluci, F. (1998). Strong diffraction effects at the edge of the Colfiorito, central Italy, basin. Proceedings of the Second International Symposium on the effects of Surface Geology on Seismic Motion, Yokohama, Balkema, Vol. 2, 435-440.

Chavez-Garcia, F.J., Stephenson, W.R. and Rodriguez, M. (1999) Lateral propagation effects observed at Parkway, New Zealand: a case history to compare 1D versus 2D side effects. Bulletin of the Seismological Society of America, 89(3), 718-732

Chávez-García, F.J. and E. Faccioli (2000). Complex site effects and building codes: making the leap, J. of Seismology 4, 23-40.

Chávez-García, F.J., D. Raptakis, K. Makra, and K. Pitilakis (2000). Site effects at Euroseistest – II. Results from 2D numerical modeling and comparison with observations, Soil Dyn. Earthq. Engrg. 19, 23-39.

Chávez-García, F.J., D. Raptakis, K. Makra, and K. Pitilakis (2002a). The importance of the reference station in modeling site effects uo to larger frequencies. The case of Euroseistest, Proc. 12th European Conf. on Earthq. Engrg., Sept. 9-13, London, CDROM edited by Elsevier Science Ltd., paper 682, 10 pp.

Chávez-García, F.J., J. Castillo, and W.R. Stephenson (2002b). 3D site effects: a thorough analysis of a high quality dataset, Bull. Seism. Soc. Am. 92, 1941-1951.

Field, E.H. (1996) Spectral amplification in a sediment filled valley exhibiting clear basin-edge-

induced waves. Bulletin of the Seismological Society of America, 86, 991-1005.
Jongmans, D., K. Pitilakis, D. Demanet, D. Raptakis, J. Riepl, C. Horrent, G. Tsokas, K. Lontzetidis & P.-Y. Bard, 1998. EURO-SEISTEST: Determination of the geological structure of the Volvi graben and validation of the basin response. Bull. Seism. Soc. Am., 88:473-487.
Kawase, H. (1996). The cause of damage belt in Kobe: “the basin effect”, constructive interference of the direct S wave with the basin induced diffracted Rayleigh waves, Seism. Res. Lett. 67, 25-34.
Kennett, B.L.N. 1983. Seismic Wave Propagation in Stratified Media, Cambridge Univ. Press, Cambridge.
Makra, K., D. Raptakis, F.J.Chávez-García, and K. Pitilakis (2001). Site effects and design provisions: the case of Euroseistest, PAGEOPH 158, 2349-2367.
Makra, K., D. Raptakis, F.J.Chávez-García, and K. Pitilakis (2002). How important is the detailed structure of a 2D soil structure for site response evaluation, Proc. 12th European Conf. on Earthq. Engrg., Sept. 9-13, London, CDROM edited by Elsevier Science Ltd., paper 682, 10 pp.
Makra K., F.J. Chávez-García, D. Raptakis & K. Pitilakis, 2005. Parametric analysis of the seismic response of a 2D sedimentary valley: Implications for code implementations of complex site effects. Soil Dynamics & Earthquake Engineering, 25, 303-315.
Moczo, P. (1989). Finite difference technique for SH waves in 2-D media using irregular grids: application to the seismic response problem, Geophys. J. Int. 99, 321-329.
Moczo, P. and P.-Y. Bard (1993). Wave diffraction,amplification and differential motion near strong lateral discontinuities, Bull. Seism. Soc. Am. 83, 85-106.
Moczo, P., P. Labák, J. Kristek, and F.Hron (1996). Amplification and differential motion due to an antiplane 2D resonance in the sediment valleys embedded in a layer over the half-space, Bull. Seism. Soc. Am. 86, 1434-1446.
Pitilakis, K., D. Raptakis, K. Lontzetidis, Th. Tika-Vassilikou & D. Jongmans, 1999. Geotechnical & geophysical description of EURO-SEISTEST, using field, laboratory tests and moderate strong motion recordings. J. of Earthq.Eng., 3(3): 381-409.
Raptakis, D., F.J. Chávez-García, K. Makra, and K. Pitilakis (2000). Site effects at Euroseistest – I. Determination of the valley structure and confrontation of observations with 1D analysis, Soil Dyn. Earthq. Engrg. 19, 1-22.
Raptakis D., K. Makra, A. Anastasiadis & K. Pitilakis, 2004. Complex site effects in Thessaloniki (Greece): I. Soil structure and confrontation of observations with 1D analysis. Bulletin of Earthquake Engineerin, 2(3), 271-300
Raptakis D., K. Makra, A. Anastasiadis & K. Pitilakis, 2004. Complex site effects in Thessaloniki (Greece): II. 2D SH modeling and engineering insights. Bulletin of Earthquake Engineering, 2(3), 301-327
Rassem, M, A. Ghobarah & A.C. Heidebrecht, 1997. Engineering perspective for the seismic site response of alluvial valleys. Earthq. Eng. Struct. Dyn., 26: 477-493.
Rovelli, A., Scognamiglio, L., Marra, F. and Caserta, A. (2001) Edge-diffracted 1-sec surface waves observed in a small-size intramountain basin (Colfiorito, central Italy). Bulletin of the Seismological Society of America, 91(2), 313-334.