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Site Effects and Design Provisions: The Case of Euroseistest

KONSTANTIA MAKRA,[1] DIMITRIOS RAPTAKIS,[2] FRANCISCO J. CHÁVEZ-GARCÍA,[3]
and KYRIAZIS PITILAKIS[4]

Abstract—Modern seismic codes usually include provisions for site effects by considering different coefficients chosen on the basis of soil properties at the surface and an estimate of the depth of bedrock. However, complex local geology may generate site amplification on soft soils significantly larger than what would be expected if we assume that the subsoil consists of plane soil layers overlaying a homogeneous half-space. This paper takes advantage of the large number of previous studies of site effects done at Euroseistest (northern Greece). Those studies have supplied a very detailed knowledge of the geometry and properties of the materials filling this shallow valley. In this paper we discuss the differences between site effects evaluated at the surface using simple 1-D computations and those evaluated using a very detailed 2-D model of the subsoil structure. The 2-D model produces an additional amplification in response spectra that cannot be accounted for without reference to the lateral heterogeneity of the valley structure. Our numerical results are extensively compared with observations, which show that the additional amplification computed from the 2-D model is real and affects by a significant factor response spectra, and thus suggests that some kind of aggravation factor due to the complexity of local geology is worthy of consideration in microzonation studies and seismic codes.

Key words: 1-D and 2-D modeling, observations, response spectra, aggravation factor, seismic codes, microzonation studies.

Introduction

It is widely recognized that local geological conditions have a pronounced impact on ground motion at a given site. The geometry of the subsoil structure, the variation of soil types and its properties with depth, the lateral discontinuities, and the surface topography are at the origin of large amplification of ground motion and have been correlated to damage distribution during destructive earthquakes (AKI, 1993; BARD,

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[1] Department of Civil Engineering, Aristotle University of Thessaloniki, P.O.B. 450, GR-54006 Thessaloniki, Greece. E-mail: makra@evripos.civil.auth.gr

[2] Department of Civil Engineering, Aristotle University of Thessaloniki, P.O.B. 450, GR-54006 Thessaloniki, Greece. E-mail: raptakis@evripos.civil.auth.gr

[3] Instituto de Ingeniería, UNAM, Apdo. Postal 70-472, Coyoacán, 04510 México, D.F. México
E-mail: paco@hermes.iingen.unam.mx

[4] Department of Civil Engineering, Aristotle University of Thessaloniki, P.O.B. 450, GR-54006 Thessaloniki, Greece. E-mail: pitilakis@evripos.civil.auth.gr

1994; FACCIOLI, 1991, 1996; CHÁVEZ-GARCÍA *et al.*, 1996). Site effects have been studied using both observations and numerical models. However, numerical studies are well in advance of observational ones as regards the understanding of the effects of complex geological settings. Thus, while most observational studies of site effects emphasize the effect of soft soils directly under the recording station, i.e., 1-D site effects (e.g., DIMITRIU *et al.*, 1998), detailed 2-D numerical studies were presented in BARD and BOUCHON (1980a, b, 1985), and today's modeling studies are concentrated on 3-D site effects (e.g., GRAVES, 1998; BIELAK *et al.*, 1998). This situation reflects the vast difficulties involved in evincing the effects of lateral heterogeneities in data sets that are obtained with an insufficient number of stations, or using arrays that are not dense enough for the dominating wavelengths. Numerical studies have shown clearly that the finite lateral extent of soil surface layers may generate surface waves at the edges of alluvial valleys. These locally generated wave trains may increase the amplitude and duration of ground motion. They may also contribute to the spatial variability of ground motion, which could have major significance in the seismic response of long structures such as dams, bridges or life-lines systems. Laterally inhomogeneous ground has repeatedly been signaled as a cause of severe damage (AKI, 1988; KAWASE, 1996).

The engineering community is well aware of the existence of this kind of complex site effects and of the need to consider them (RASSEM *et al.*, 1997; CHÁVEZ-GARCÍA and FACCIOLI, 2000). However, modern seismic codes (UBC97, EC8) and current microzonation practice have mostly 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 (see the papers presented at the special session on EC8 during the proceedings of the 11th ECEE, Paris 1998; AFPS/MSI Group Report, 1998). Less effort is being directed to the possible influence of complex site effects. 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 reason 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) that showed the substantial impact of the 2-D valley structure on its site response. Those papers were based on the analysis of one recorded event and a numerical simulation restricted to the low-frequency range. In this study we pursue those ideas but extend the objectives along two lines. First, a more thorough analysis of data recorded at Euroseistest is made, with the aim of evaluating a robust, observed, site response in terms of response spectra. Second, we compare the observations with numerical simulations of site effects in this valley, extending the domain of the computations up to 10 Hz. Both 1-D and 2-D numerical models are explored. Our results confirm that the effects of complex local geology have a large impact on ground motion. The additional amplification introduced by the complex geology relative to the predictions of a 1-D model is quantified in terms of an "aggravation factor." We propose that this additional amplification should be taken into account in seismic codes.

Data

Euro-seistest site is established on a 5.5-km-wide and 200-m-deep sedimentary valley between the Lagada and Volvi lakes in the Mygdonian graben. This graben is located some 30 km to the east of Thessaloniki in northern Greece (Fig. 1a). The subsurface structure of the valley was explored extensively, with the aim of generating an accurate description of the subsoil structure and of the mechanical properties of the sediments filling the valley (RAPTAKIS, 1995; 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. The seismic prospecting campaigns were followed by extensive geotechnical *in situ* and laboratory testing program (drillings, sampling, groundwater table measurements, SPT and CPT, cyclic triaxial and resonant column tests).

The more recent evaluation of those measurements (RAPTAKIS *et al.*, 2000) refined previous models as it concentrated on the determination of shear-wave velocities for each soil formation, since it is foreseen that this parameter plays the most important role in seismic response due to incident shear waves. The result was the 2-D model shown in Figure 1b. The mean values of material properties assigned to each soil formation are given in Table 1.

Earthquake observation at Euroseistest has been a major goal of this test site. In this paper the records obtained by the permanent accelerograph network that has operated since 1993 have been used. This network consists of 7 surface and 3 downhole three-component accelerographs with force balance accelerometers, capable of measuring acceleration from 0.001 g (trigger threshold) to 1.0 g in the frequency band 0 to 50 Hz. The digital resolution of the Instruments ranges between 12 and 19 bits (Fig. 1b, RAPTAKIS *et al.*, 1998).

Sixty seven earthquakes have been recorded at this network since its installation (EUROSEISMOD Final Scientific Report). Twelve of them have been selected for use in

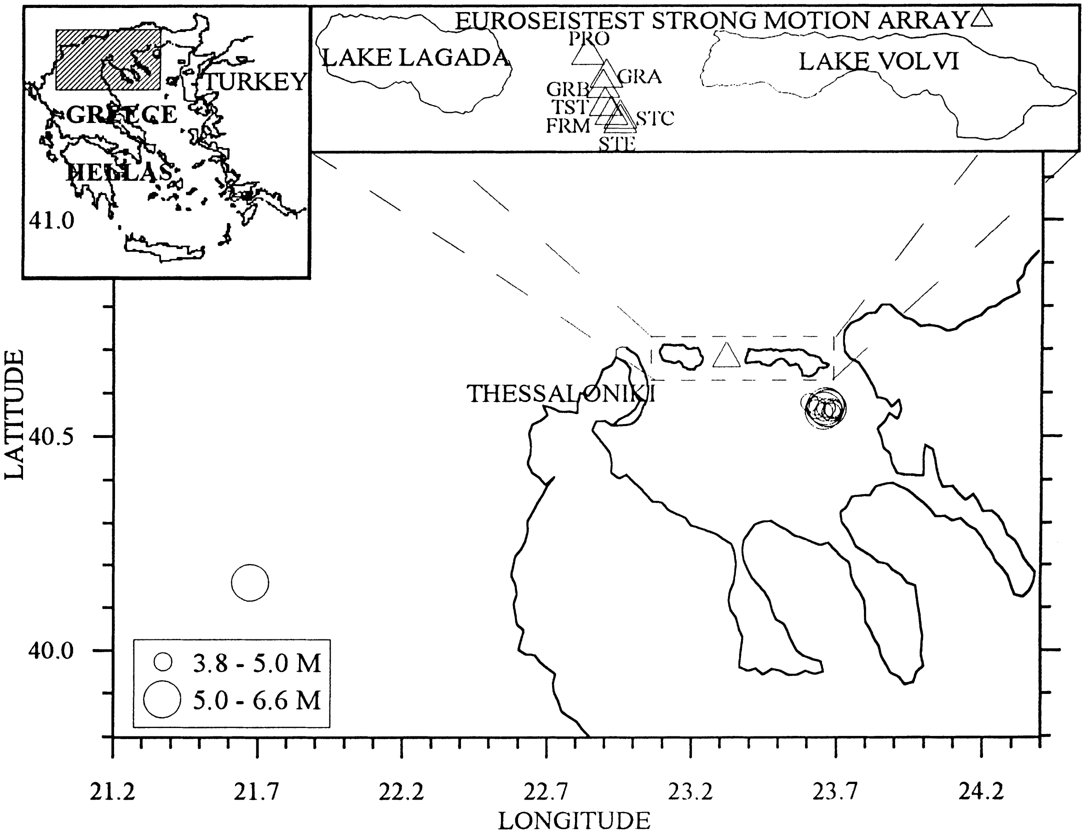

Figure 1

(a) Map of the Mygdonian Graben with the earthquakes' epicenters (open circles) recorded at the stations of the Euroseistest strong-motion network (open triangles). (b) NNW-SSE 2-D model of the Euroseistest soil structure. The solid diamonds show the location of the permanent strong-motion network. Four faults (F1–F4) and eight different strata (layers A to G) are identified. Properties of the material are given in Table 1. [After RAPTAKIS *et al.* (2000).]

this study (Table 2) because they were recorded at all stations. The largest peak-ground acceleration of the data that was used is 0.03 g, while the majority of the recordings have peak acceleration between 0.003 and 0.02 g. Thus it is anticipated that linear models may be adequately compared to this database. The records were rotated with respect to the axis of the valley. In this paper, we have limited ourselves to site effects evaluated in the horizontal component directed along the axis of the valley, perpendicular to Figure 1b (*SH* motion). In a later paper we will present results for the in-plane component (*SV* motion).

These data were used to evaluate site effects at Euroseistest. Moreover, we have used the standard spectral ratio technique relative to a reference station. We will also show results of spectral ratios using smoothed amplitude Fourier spectra, and

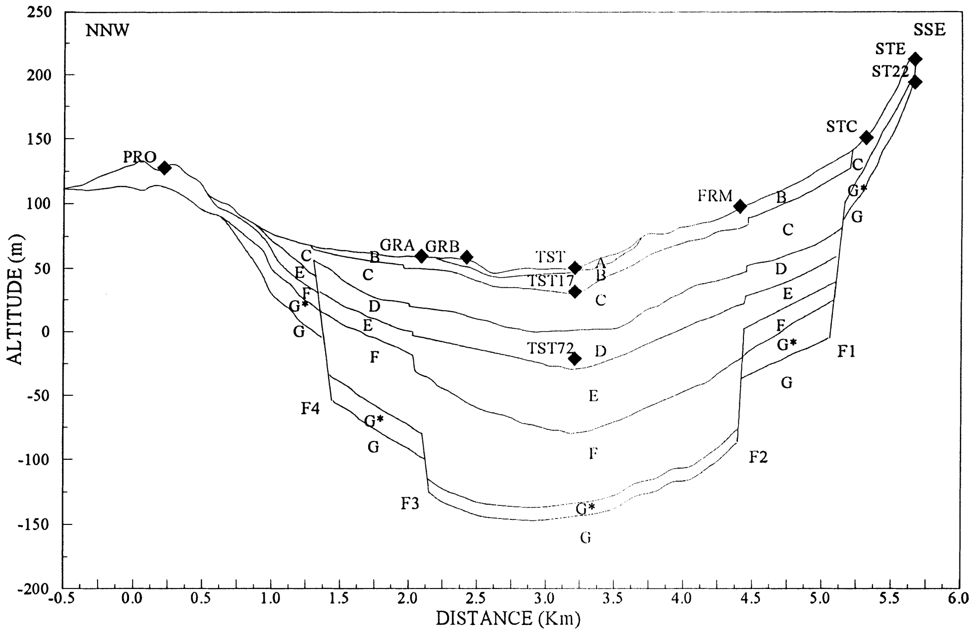

Figure 1b

Table 1

Properties of the materials in the model

Layer	Description	*S*-wave velocity, V_s (m/s)	Density, ρ (t/m^3)	Quality fator, Q_s
A	Silty, clayey sand	130	2.05	15
B	Silty sand and sandy clay	200	2.15	25
C	Marly silt and silty sand	300	2.075	30
D	Marly, sandy clay and clay silt	450	2.100	40
E	Alternating sublayers of clayey, silty sand and sandy clay with stones and gravels	650	2.155	60
F	Alternating sublayers of clayey, silty sand and sandy clay with stones and gravels	800	2.20	80
G*	Weathered schist bedrock	1250	2.50	100
G	Gneiss basement	2600	2.60	200

spectral ratios of 5% acceleration response spectra. Our reference station was PRO (Fig. 1b) located on a very thin sediment layer overlying the gneiss basement.

Numerical Modelling

We have modeled site response using 1-D and 2-D numerical models. Only linear behavior was considered for all the soil types. In all cases, excitation was given by vertical *SH* waves. 1-D site response was computed for the corresponding vertical soil profile at each station using Kennett's reflectivity-coefficient method (KENNETT, 1983). The 2-D response of the model of Figure 1b was computed applying the finite-difference method of MOCZO (1989), refined in MOCZO and BARD (1993), and MOCZO *et al.* (1996). This finite-difference method allows modeling of a non-flat free surface, if it is constrained to pass through nodes of the grid. This restriction does not apply for any other irregular interfaces in the model, which allows, including in the model, the precise shape of the soil interfaces. Attenuation is taken into account through three relaxations mechanisms which ensure approximately constant quality factors in the frequency range of validity of the computations (MOCZO, 1989; MOCZO and BARD, 1993). The grid model is bounded laterally and at the bottom with transparent, Reynolds' type, non-reflecting boundaries (REYNOLDS, 1978) to avoid unwanted artificial reflections.

The 2-D valley of Figure 1b was extended laterally and at the bottom up to a total length and height of 6,453.2 m and 403 m, respectively. The model is covered by a grid using a constant grid step of 1.3 m in the horizontal and vertical directions. This model is similar to the one used in CHÁVEZ-GARCÍA *et al.* (2000), however, we have decreased the horizontal grid step in order to extend the frequency of validity of

Table 2

Seismological information of the strong motion data used (Euroseismod Final Scientific Report)

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

the computations up to 10 Hz. The excitation to the model is a vertically incident, plane *SH* wave with a time dependence of a Gabor pulse given by the equation:

$$s(t) = \mathrm{e}^{-\alpha} \cos\left[\omega_p (t - t_s) + \psi\right]$$

where

$$\alpha = \left[\frac{\omega_p (t - t_s)}{\gamma}\right]^2, \; f_p = 2\omega_p = 4.0, \; \gamma = 1.5, \; \psi = 0.0 \text{ and } t_s = 0.169 \; .$$

Figure 2 depicts this signal in time and frequency domains. The pulse has non-negligible frequency content extending 15 Hz (Fig. 2b). Thus the synthetic time histories are low-pass filtered in order to eliminate contribution of frequencies that cannot be propagated correctly by the grid.

So as to compare with the observations, synthetic response spectra were also computed for the 1-D and 2-D numerical results. The procedure was as follows. For each of the 12 selected events (Table 2), the transverse component of the record obtained at PRO was convolved with the numerical 2-D *SH* transfer function relative to station PRO and with the 1-D transfer function computed at the locations corresponding to each of the accelerograph stations. Station PRO is not located on bedrock (the gneiss basement), however site effects at this station are small, and they occur at high frequencies. Moreover, this procedure allows a direct comparison with the observations, since site effects at PRO are already present in the observed record. Then, synthetic accelerograms are obtained at each strong motion station for the transverse component of motion, for each selected event, and for each of the two models considered (1-D or 2-D). In order to compare observations to synthetics, average response spectra were computed. Before averaging, response spectra were normalized relative to the observed peak ground accelerations at station PRO.

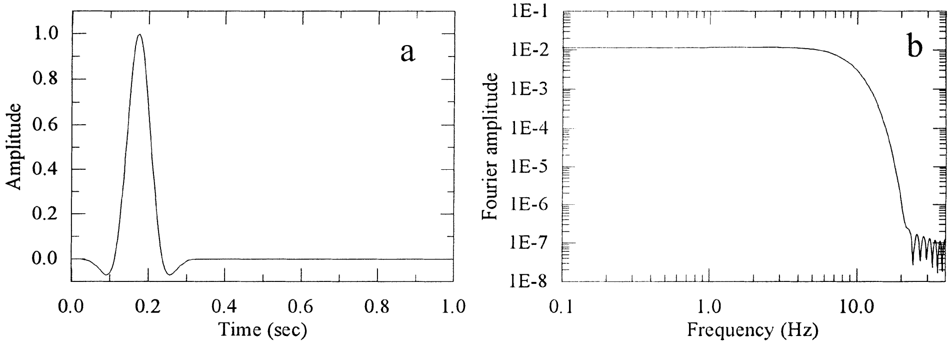

Figure 2
The Gabor pulse used as incident signal in the 2-D finite-difference simulation. (a) Signal in time domain. (b) Fourier amplitude spectrum of the time signal.

Scatter is measured using standard deviation. Finally, ratios of average response spectra were computed.

Results

2-D Numerical Modeling in Time and Frequency Domains

Figure 3 shows the displacement time-histories of 155 receivers distributed every 41.6 m along the free surface of the 2-D soil profile. They have been low-pass filtered with a Butterworth filter with 10 Hz cut-off frequency. The results are similar to those presented in CHÁVEZ-GARCÍA *et al.* (2000). The most important feature of the synthetics is the surface wavetrains generated at fault F4 (northern edge), fault F3 and at fault F1 (southern edge). Two additional surface wavetrains are observed in Figure 3. The first one is generated below station STE at the southern edge of the valley. The second is generated at the northern edge of the valley. These wavetrains have dominating frequencies larger than 4 Hz and therefore were not present in previous computations. All these surface waves converge towards the center of the valley,

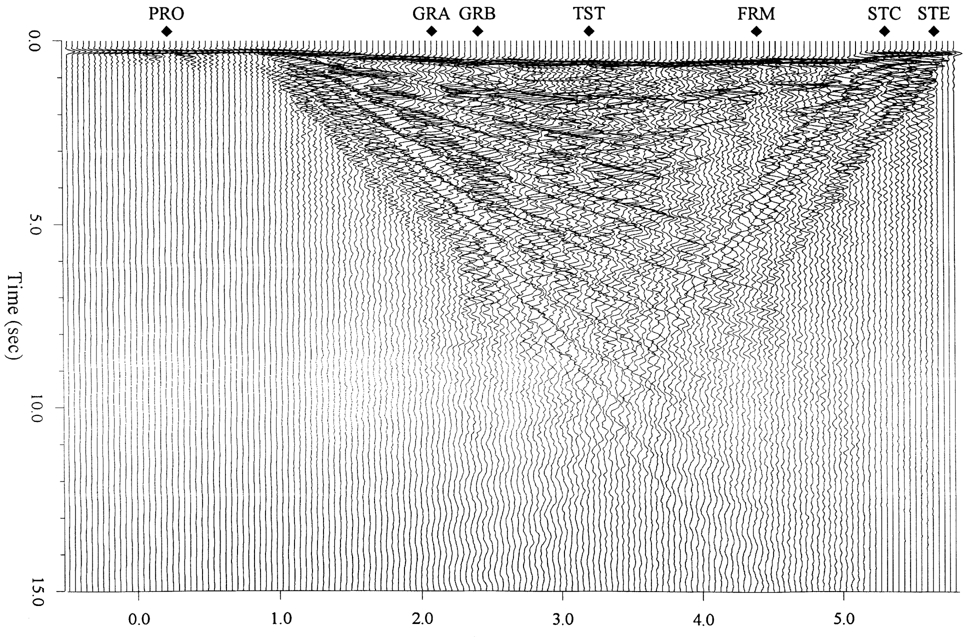

Figure 3
Seismic section computed at the surface of the 2-D model of Figure 1b for vertical incidence of *SH* waves. The positions of the surface accelerographs of the permanent network have been indicated for reference. Traces have been low-pass filtered with a 10.0 Hz cut-off frequency.

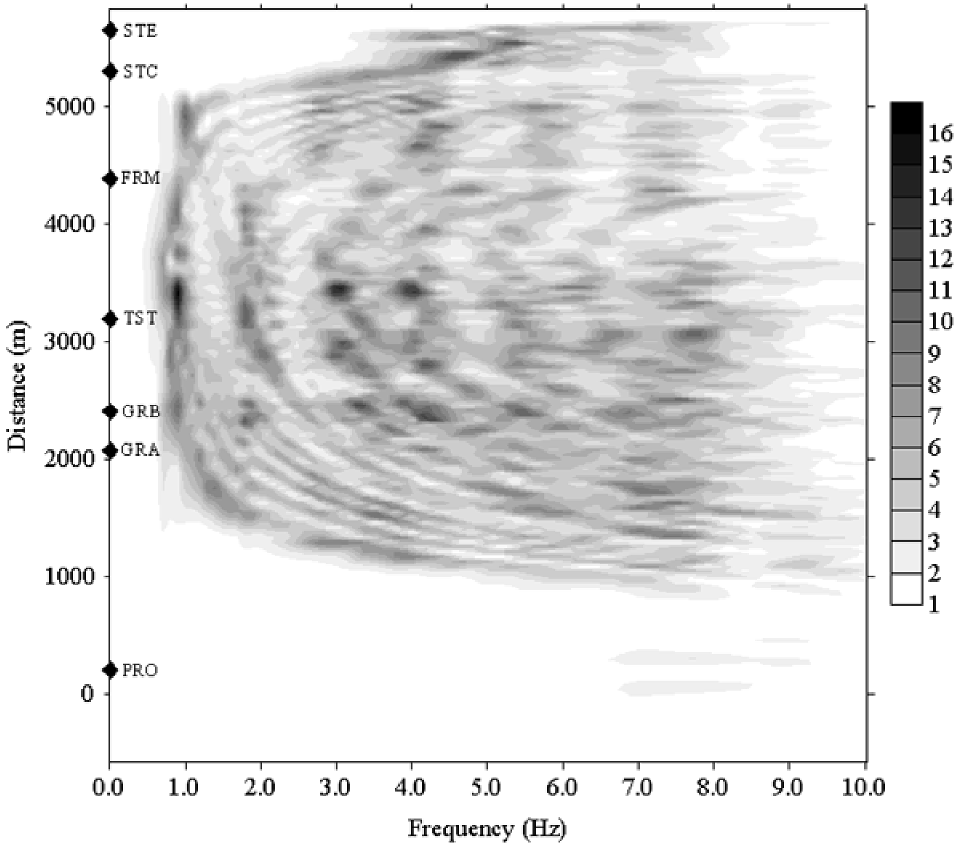

Figure 4
Numerical transfer function for vertical incidence of *SH* waves with respect to the receiver at the location of station PRO of the 2-D model shown in Figure 1b. This result was computed from the synthetics of Figure 3.

resulting in large amplitudes of ground motion for more than 10 s in sharp contrast to ground motion duration outside the central part of the valley. Synthetics around PRO confirm that the topography at this station modifies slightly ground motion.

Transfer functions of the synthetics relative to the synthetic at station PRO are presented in Figure 4. Station PRO is also considered as a reference for the 2-D transfer functions. This serves the requirement to compare similar transfer functions relative to the observed ones. The center of the valley shows peaks of amplification at about 0.8–1.0 Hz, at 1.8–2.0 Hz, and at 3 and 4 Hz. The regular succession of amplification peaks suggests 1-D site effects, however the spacing in the frequency domain of these peaks is too small, ruling out resonance of vertically propagating waves. CHÁVEZ-GARCÍA *et al.* (2000), using borehole records from TST site, demonstrated that ground motion at low frequencies is dominated by locally generated surface waves. Figure 4 confirms that those results are valid in a larger frequency range. This figure shows that the main amplification peaks observed at the center of the valley are very discontinuous. None of them, not even the fundamental, remains continuous over the central part of the valley, where soil layering is approximately flat and without geological discontinuities. This lateral variability increases with frequency. The peaks follow the pattern corresponding to the dominance of locally generated surface waves, as identified by BARD and BOUCHON (1980a).

Comparison of Observations with Synthetics, in Frequency and Time Domains

Empirical and numerical transfer functions are compared in Figure 5. This figure shows average spectral ratios with respect to station PRO (thick lines) for each strong motion station. The thin, solid line indicates the numerical transfer function (computed with respect to the synthetic at PRO) for the 2-D simulation, and the dotted line indicates the corresponding amplification computed for the vertical soil profile at each station. The differences in shape between the predictions of the 1-D model and those from the 2-D simulation are quite large. The 2-D transfer functions do not have the simplicity and regularity of the 1-D transfer functions, and in this sense are closer to the observations. In general, the synthetic transfer functions have amplitudes similar to those of the observations in the low frequency range, and larger than the observations in the higher frequency range (higher than 3 Hz). This suggests that the shear-wave velocity contrast is correctly estimated in the model, but that Q factors in Euroseistest may be lower than the values assigned in Table 1. In detail, there is similarity between observed and predicted transfer functions with the 2-D model, with the exception of station GRA and GRB, where quite good agreement is observed up to 3 or 4 Hz. The complexity of the observed curves and the level of amplification are well predicted, but the precise location of peaks and troughs is missed. The results for stations STE and STC show major disagreements between observations and results from modeling, suggesting that the subsoil structure in the southern edge of the valley should be revised.

We now compare the observations with the synthetics in the time domain. To this end the event occurred on May 4, 95 (No. 9 in Table 2), whose epicenter was located 32 km to the southeast of Euroseistest. Figure 6 shows, on the left column, the transverse component of the records obtained at the strong motion stations. All traces in this figure have been low-pass filtered with a 2.5 Hz cut-off frequency, in order to reveal the contribution of locally generated surface waves both in amplitude and duration at this frequency band. The amplitude scale is common to all traces. It is observed that, in addition to the large differences in amplitude between PRO and the stations on sediments, there are pronounced differences in the duration of ground motion. Indeed, the records obtained at stations GRB and most clearly at TST for

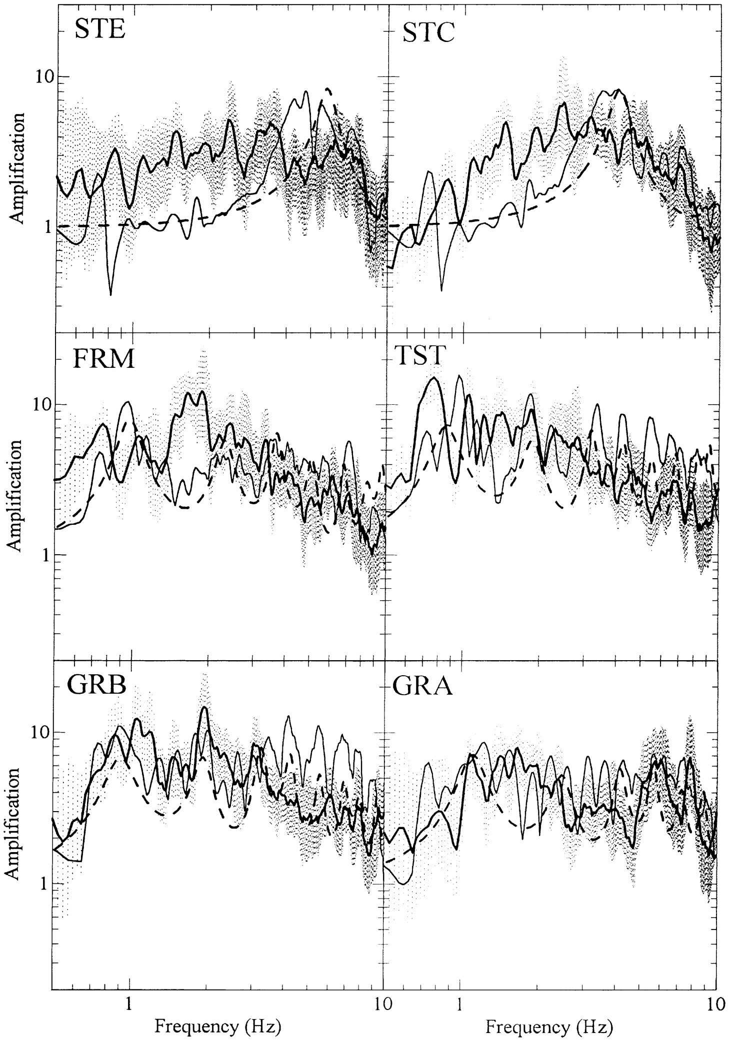

Figure 5
Comparison of observed and computed transfer functions. Thick, solid lines: average ratios of the transversal component of motion, relative to the corresponding component recorded at PRO, for the 12 events analyzed. The shaded area shows the average plus or minus one standard deviation. Thin, solid line: numerical transfer function, relative to the receiver at the location of PRO, obtained from the 2-D, finite-difference computations. Dotted line: numerical transfer function, relative to the receiver at the location of PRO, obtained from the 1-D vertical profile at each location.

this event show late arrivals with amplitude comparable or larger than the *S* wavetrain (which arrives at 4 s). This characteristic is well reproduced by the synthetics shown in the central column of Figure 6. They correspond to synthetic accelerograms obtained by convolution of the observed record at PRO with the

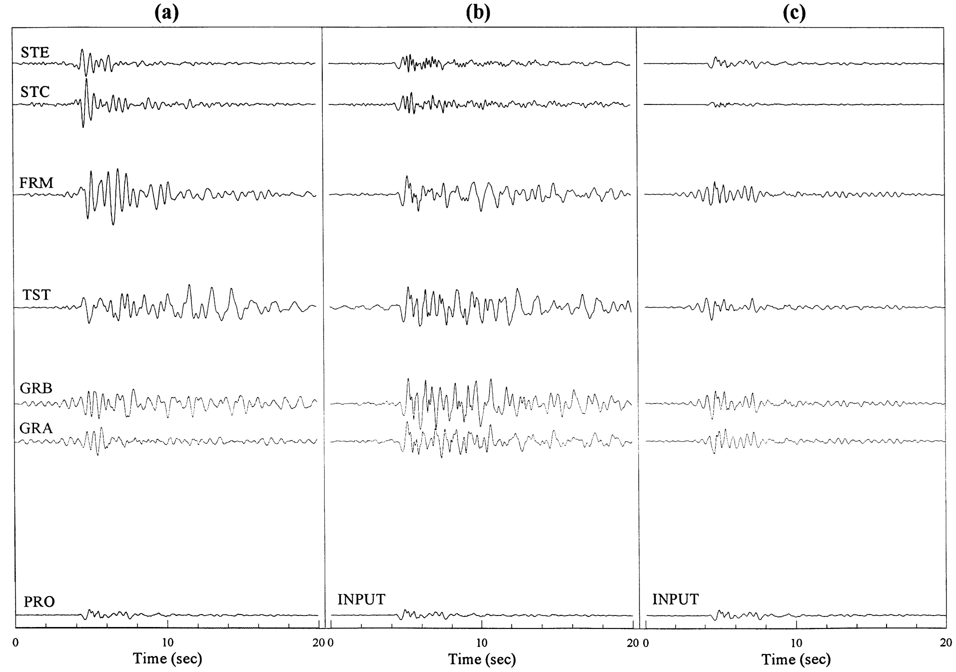

Figure 6
Comparison in time domain between observations and synthetics, for the event which occurred on May 4, 95 (No. 9 in Table 2). All traces were low-pass filtered with a 2.5 Hz frequency cut-off in order to reveal the contribution of locally generated surface waves. Amplitude scale is common to all traces in the figure. (a) Accelerograms recorded at the permanent array. (b) Synthetic accelerograms obtained by convolution of the observed record at PRO with the corresponding 2-D transfer function at each location. (c) Synthetic accelerograms obtained by convolution of the observed record at PRO with the corresponding 1-D transfer function for the vertical soil profile at each location.

corresponding 2-D transfer function at each location. As in the observations, in addition to the large amplitude increase, the duration of the record and the importance of the late arrivals are well reproduced, especially at the center of the valley. In contrast, the synthetic accelerograms obtained by convolution of the observed record at PRO with the corresponding 1-D transfer function for the vertical soil profile at each location, shown on the right column of Figure 6, manifest very poor approximations to the observations. The duration is too short and similar in all the stations, and amplitudes are smaller than observed.

Comparison in the Response Spectra Domain

We consider now one of the favorite measures of site response in the engineering community: response spectra for 5% damping. We computed average acceleration response spectra from the 12 transverse acceleration record obtained for the events of Table 2, as well as for the synthetic accelerograms obtained from the convolution of

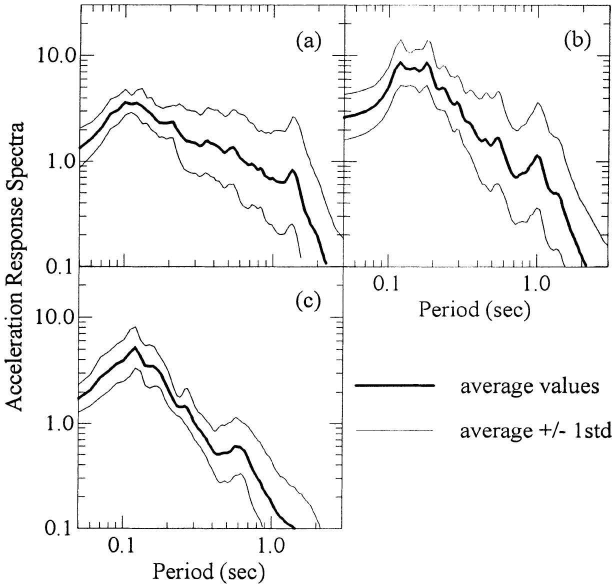

Figure 7
Average and average plus or minus one standard deviation response spectra computed for the transverse component of motion at station TST at the center of the valley. Response spectra were normalized with respect to the peak ground accelerations recorded at station PRO. (a) Observations. (b) 2-D synthetics (response spectra of the synthetics obtained with the convolution of the 2-D transfer function and the observed record at PRO). (c) 1-D synthetics (response spectra of the synthetics obtained with the convolution of the 1-D transfer function and the observed record at PRO).

PRO record and the 2-D and 1-D transfer functions corresponding to each strong motion site. Before averaging, response spectra were normalized with respect to the observed peak ground accelerations at station PRO. This normalization is chosen so as to compare shapes of response spectra obtained for events with different relative amplitudes. Scatter is measured with the standard deviation. The results obtained for station TST are shown for reference in Figure 7. Scatter about the average 1-D value results from the different way in which each of the input signals excites shear-wave resonance. It is observed that scatter about the average 2-D response spectra has increased considerably relative to the 1-D value, although the input signals are the same in both cases. The same also applies for the scatter of the observed values. This increased variability is a consequence of the larger complexity of the 2-D and observed transfer functions.

Figure 8 displays average values of observed response spectra, as well as average values of response spectra for the synthetic accelerograms obtained from the convolution of PRO record and the 2-D and 1-D transfer functions corresponding to each strong motion site. It is observed that the largest amplitudes of the observed response spectra occur at short periods, decaying steadily at longer periods. There are fewer differences among the stations, as the computation of response spectra is not

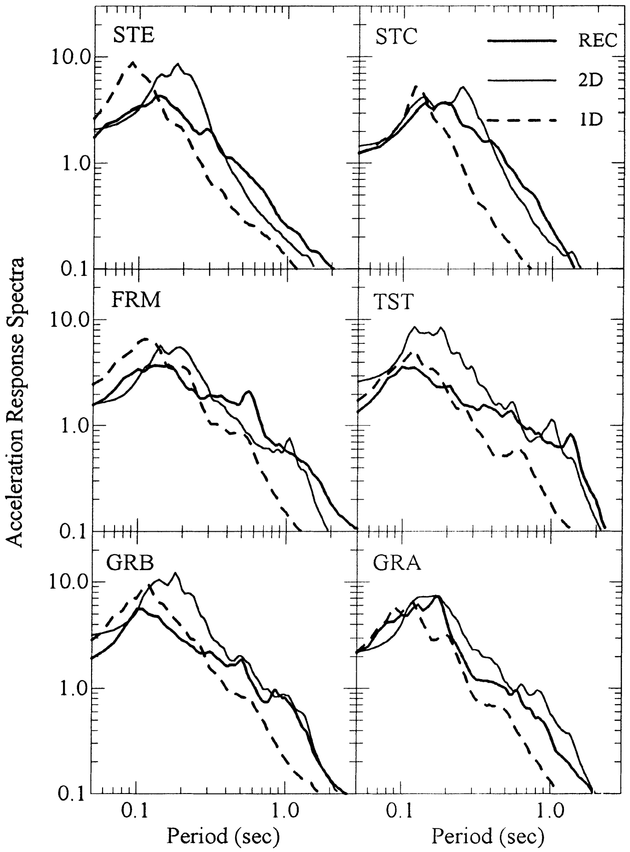

Figure 8
Average response spectra computed for the transverse component of motion (parallel to the axis of the valley) obtained at each station for the 12 events analyzed. Thick, solid lines: Observations. Thin, solid lines: 2-D synthetics (response spectra of the synthetics obtained with the convolution of the 2-D transfer function and the observed record at PRO). Dashed lines: 1-D synthetics (response spectra of the synthetics obtained with the convolution of the 1-D transfer function and the observed record at PRO).

very sensitive to the duration of ground motion. TST, FRM and GRB exhibit significant amplitudes at longer periods than the other stations. There is a good agreement in the shape and amplitude of the average 2-D response spectra with the observed ones. The longer period amplitudes in the stations at the center of the valley are nicely reproduced by the 2-D synthetic response spectra. It is immediately apparent that results using the 1-D transfer function at each location present a lack of longer period energy in the response spectra and significant differences with the observations. This comparison indicates clearly that the differences in the physical nature of site effects between 1-D and 2-D models translate into significant differences in the response spectra domain and that results from 2-D modeling are closer to a robust average of observations at this site.

Aggravation Factors

We have shown that, in the response spectra domain, results from 2-D numerical simulations are closer to the observations than results from 1-D models. Another way to show this is using ratios of average response spectra, which we discuss in this section, following the proposal of CHÁVEZ-GARCÍA and FACCIOLI (2000). Consider initially the ratio between response spectra obtained from the 2-D model relative to that obtained from the 1-D computation for each site. This ratio is shown with thin lines in Figure 9. This ratio is larger than unity in almost the whole period range considered. This indicates that 2-D site effects are significantly larger than 1-D site effects. We have validated this result only for the model of Figure 1b, nonetheless it coincides with many previous studies of 2-D site effects. We note that the additional amplification observed in the results for the 2-D model come only from the geometry of the soil formations, and that it appears at all the stations.

In order to now include the observations, the ratio between average observed response spectra at each site relative to average response spectra obtained from the 1-D model is computed. This ratio is shown with the thick lines in Figure 9. The marked similarity between the thin and thick lines in this figure is immediately apparent. This shows, first, that in the response spectra domain, observations are consistently larger than the predictions that could be made with the 1-D model, especially for periods longer than 0.2 s. Second, the differences between observations and the 1-D model are very similar to the differences between the 2-D and the 1-D models, strongly supporting the idea that at Euroseistest, a 2-D model is required to explain the observations.

We will call "aggravation factor" the additional amplification introduced in response spectra by the 2-D nature of the response at this valley, relative to the amplification that could be predicted using a 1-D model. In the case of Euroseistest, the aggravation factor is comprised between 2 and 5, and does not seem to depend strongly on the location of the station relative to the valley edge. We insist that seismic codes emphasize 1-D site response, as the parameters that govern the seismic coefficient at a given site are shear-wave velocity of the uppermost layers and depth to bedrock. Our results indicate that an aggravation factor, due solely to the geometry of the soil formations, may affect response spectra by a factor between 2 and 5, in a period range of interest in engineering. We propose that such aggravation factors may not be safely neglected in the elaboration of seismic codes.

Conclusions

In this study we have tried to evaluate the additional amplification introduced by the irregular lateral geometry of the soil formations at Euroseistest. This additional amplification comes besides that due to the impedance contrast between soil layers. Our purpose has been to stimulate discussion among the engineering community of

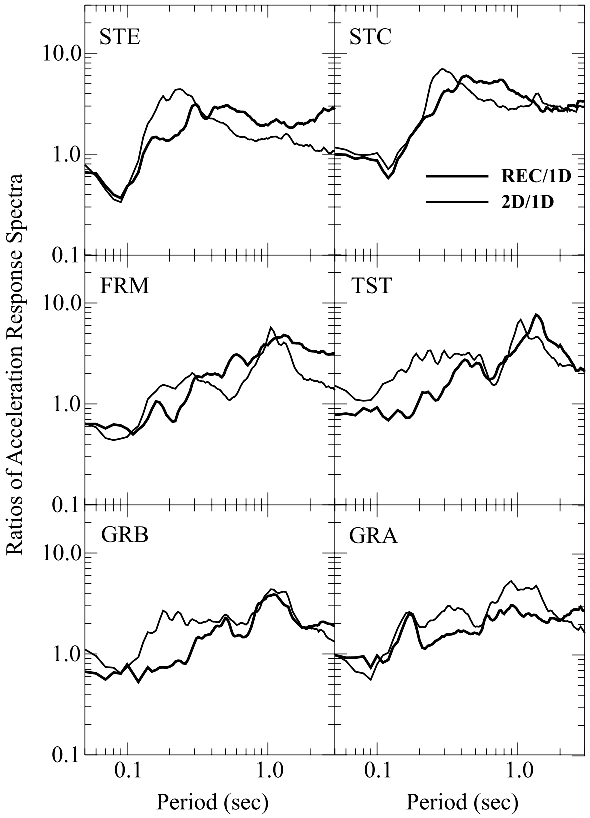

Figure 9
Ratios of average response spectra for each station. Thick line: ratio between average observed response spectra at each station relative to average response spectra computed at each site using the 1-D transfer functions. Thin line: ratio between average response spectra computed at each station using the 2-D transfer function relative to average response spectra computed at the same site using the 1-D transfer functions.

the possibility of including some manner of provision for such complex site effects in terms of a modern seismic code.

To that end we have presented results of 2-D and 1-D numerical modeling for the sedimentary valley of Euroseistest. The numerical results have been compared with observations in time, frequency and response spectra domains. This comparison was possible thanks to the detailed information available on the subsoil structure and mechanical properties of the sediments filling this valley. We have shown that in Euroseistest, site response is dominated by locally generated surface waves, even at the center of the valley, where layering could be approximated as flat. Lateral heterogeneity thus increases the duration of ground motion, in addition to increasing its amplitude.

In the case of Euroseistest, we have defined an aggravation factor that measures the additional amplification in the response spectra domain caused by the 2-D geometry of this valley, relative to site effects measured using a 1-D model. This aggravation factor does not depend strongly on the location of the station relative to the valley edge, and attains a value of 5 for periods longer than 0.3 s. It is clear that these results apply only to this site. One limitation of our study is that all our computations are based on the linear behavior of soil material. Thus, it could be argued that our results are not applicable to the case of damaging earthquakes. This objection, however, does not hold in regions of moderate seismicity, such as Europe. For example, BARD (1997) proposes that a PGA between 0.1 to 0.2 g is required before nonlinear deformations of soft sandy soils becomes apparent. The threshold is larger (0.3 to 0.4 g) for soils of medium stiffness or stiff soils. It is thus very likely that ground motion behavior will be linear during the future damaging events in Europe where expected PGA on rock is less than 0.3 g (taking into account that maximum expecting pga in Europe is 0.36 g – according to the Greek Seismic Code 2000 – independent of soil category), then our aggravation factors are likely to apply. This is not intended to minimize the research that is still required to understand nonlinear soil behavior phenomena and their consequences on ground motion. We rather would like to call attention to the importance of the aggravation factor introduced in this paper and the need of similar studies elsewhere. If the amplitude of this aggravation factor is confirmed, it can be used to incorporate the effects of complex geology in seismic codes and microzonation studies.

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