Journal of Seismology **4:** 23–40, 2000.

Complex site effects and building codes: Making the leap

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Received 14 May 1998; accepted in revised form 9 December 1998

Key words: accelerograph array, alluvial valleys, design spectra, seismic response, site effects, wave propagation, 2D soil amplification, 2D seismic resonance

Abstract

The engineering community is aware of the importance of site effects, but it lags behind seismological studies when it comes to incorporating site effect considerations in design spectra for seismic norms. This lag is reflected in the conspicuous fact that current building codes make allowance for 1D site effects but ignore complex site effects. The purpose of this paper is to explore a way for including complex site effects in a building code environment. We take as example Eurocode 8, which is a modern code that exemplifies the current approach to site effect consideration. We examine the restrictions that we have imposed to make the problem of a feasible size and discuss the approach we have taken. We propose a strategy to incorporate a class of complex site effects in a design elastic spectrum.

Introduction

It has long been recognised that site effects are a significant component of earthquake ground motion on soft soil sites. Site effect studies 30 to 40 years ago emphasised ground motion amplification due to the impedance contrast of soft sediments overlying competent rock, the so-called 1D site effect. In more recent years there has been a large number of studies that have characterised 2D site effects on ground motion (e.g., Aki, 1993; Bard, 1994; Faccioli, 1991 and 1996a). It has been shown that the differences relative to the 1D case concern the appearance of different physical phenomena: propagation of locally generated surface waves and possible 2D resonance. This was clearly shown by the numerical studies of Bard and Bouchon (1980a, 1980b, 1985) for a large number of shapes, and parameters. More recent studies have confirmed those results (e.g., Moczo et al., 1996), showing that the conclusions of Bard and Bouchon really embrace all the different possible cases regarding 2D site effects. On the other hand, theoretical 3D site effects studies indicate that the differences relative to 2D are only of a quantitative nature. The third dimension increases somewhat ground motion amplification, and the additional lateral restriction shifts peak frequencies to higher values.

The engineering community is well aware of the existence of complex site effects and of the need of taking them into account (e.g., Rinne, 1994; Rassem et al., 1997). However, while the difficulties involved continue to spur a wealth of theoretical studies showing 3D calculations, current building codes only consider explicitly 1D site effects. Examples of this situation are the 1994 NEHRP Seismic Provisions (Martin and Dobry, 1994; Borcherdt, 1994; Rinne, 1994) or the current version of Eurocode 8 (Eurocode 8, 1994; Faccioli, 1996b; Davidovici, 1996). In these codes, site effects are defined through two amplification factors (NEHRP) or through the definition of spectral shapes specific for the soil classes defined (Eurocode 8). The classification of a site is based exclusively on the vertical soil profile. Figure 1 shows an example the elastic spectral shapes of Eurocode 8, for subsoil classes A (rock or other geological formation characterised by shear wave velocity of at least 800 m/s) and C (loose cohensionless soil deposits, characterised by shear wave velocities less than 200 m/s in the uppermost 20 m). This figure does not consider the soil amplification factor. Thus, the two design spec-

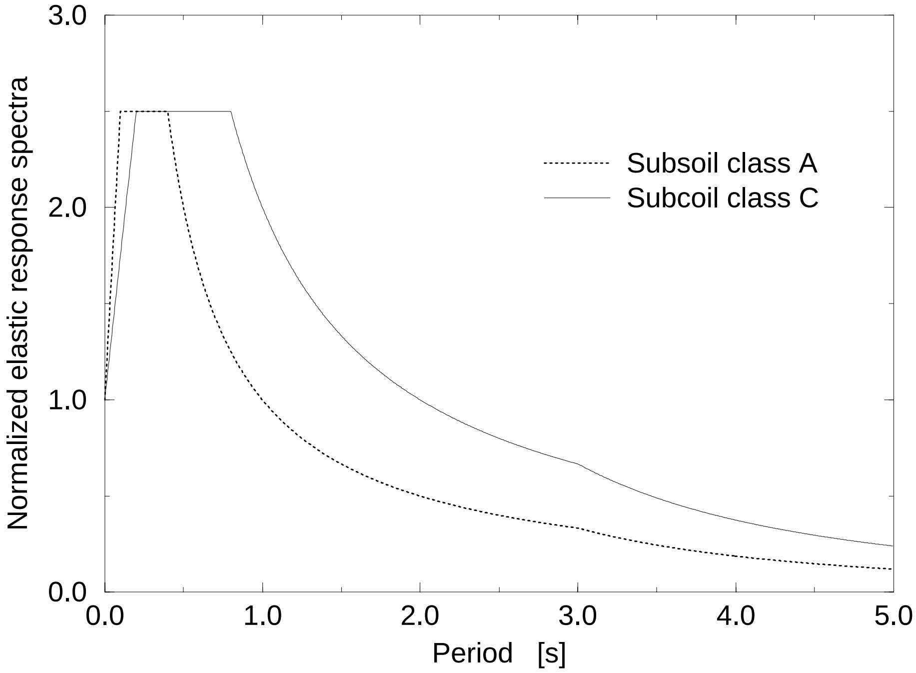


Figure 1. Elastic design spectra recommended in Eurocode 8 for the subsoil classes A and C. In addition to the difference in shape, site effects are taken into account through a constant factor S, yet to be defined.

tra may differ by a constant factor, which is not yet specified.

A seismic code involves a large number of different aspects that should be carefully considered. In particular, concerning the inclusion of site effects in code provisions, attention should be given to the adequate definition of soil classes, to the values of period that define the width of the plateau, etc. Eurocode 8 – which is presently undergoing a stage of final revision – has received large attention by the engineering and scientific community, given its importance as a European standard. An example of this attention are the 19 papers dealing with different aspects of this code that were presented in the 11th European Conference on Earthquake Engineering, held in Paris during September 1998. However, the possible influence of complex site effects is not mentioned. One of the purposes of this paper is to call attention to these effects and to encourage discussion regarding their possible inclusion in seismic codes.

In this paper we explore how we should modify seismic spectra in order to take into account site effects of a two-dimensional (2D) nature on a sedimentary valley. Our work is similar to that of Okawa et al. (1996) and Rassem et al. (1997). However, we do not restrict ourselves to evaluation of site effects in response spectra, but try to shape our results in a form that could be useful for seismic norms. For the sake of illustration, we will refer to the framework of Eurocode 8 (Part 1–1), although we are aware that other recent codes, for instance UBC97, provide for a more refined treatment of site conditions. We have chosen simple examples of alluvial basins (symmetrical, homogeneous) for the purpose of limiting the number of free parameters. For this simple configuration, we have explored the influence of the most obvious parameters, including sediment properties and shape ratio. We concentrate on evaluating the additional amplification that 2D site effects produce on ground motion. That is, we assume that 1D site effects are correctly taken into account in Eurocode 8, and use extensively ratios between 2D results relative to the 1D case. Now, the relation between site effects transfer functions and response spectra is not linear. Although the synthetic accelerogram computed on the surface of an alluvial valley from a given input results from a linear operation (convolution), the calculation of its response spectrum implies convolution with a series of SDOF systems (linear operation) and taking absolute and maximum values (nonlinear operations) of the resulting time series. For this reason, we need to compute results for several input motions (see

Table 1. Data of the acceleration records considered as input

Recording station	Date of the event	M	Epicentral distance [km]	Duration of the record [s]	Notes
Tolmezzo EW	07 May 76	6.5	24.2	15.29	Friuli mainshock
Tolmezzo NS	07 May 76	6.5	24.2	15.37	same
Tarcento EW	15 Sep 76	5.9	9.5	20.08	Friuli aftershock
Tarcento NS	15 Sep 76	5.9	9.5	20.10	same
Bagnoli EW	23 Nov 80	6.8	23.0	24.99	Irpinia mainshock
Bagnoli NS	23 Nov 80	6.8	23.0	24.99	same
Sturno EW	23 Nov 80	6.8	34.1	34.99	same
Pietralunga EW	29 Apr 84	5.6	19.6	26.12	Umbria earthquake
Pietralunga NS		5.6	19.6	26.10	same
Aegion O.T.E. EW	15 Jun 95	6.4		30.09	Large damage in Aegion
Aegion O.T.E. NS	15 Jun 95	6.4		30.09	same
kpi-83 EW	17 Jan 95	7.2	15.5	40.01	Kobe Port Island at 83 m depth
kpi-83 NS	17 Jan 95	7.2	15.5	40.01	same

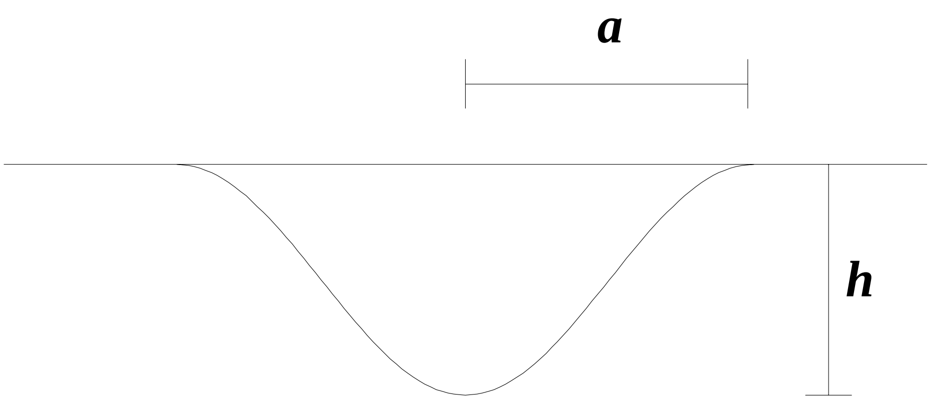


Figure 2. A sine-shaped sedimentary valley.

Table 1). To simplify the problem, we rule out nonlinear behaviour of sedimentary materials during wave propagation. Hence, the characterisation of the source need only account for the different spectral content of the excitation, and effects of input amplitude can be neglected.

Method

We have selected a symmetrical, sine-shaped valley as a 'representative' model (Figure 2), and we want to quantify the influence of the two physically different phenomena that occur in alluvial valleys (lateral propagation and 2D resonance) on the response at the surface. The sine-shaped valley has two significant advantages: it can be characterised simply by its shape ratio, h/a (where a is the valley half-width, and h its maximum depth), and a thorough investigation of its response was provided in a previous study (Bard and Bouchon, 1985). In that study, it was shown that there is a 'critical shape ratio', depending on the velocity contrast, that controls whether the response of the valley is governed by lateral propagation or by 2D resonance. We have chosen different sine-shaped valleys, that emphasise one or the other phenomenon.

The properties of the materials are not crucial because we want to determine 2D site effects relative to 'equivalent' 1D site effects. However, the sediment/bedrock velocity contrast controls the shape ratio

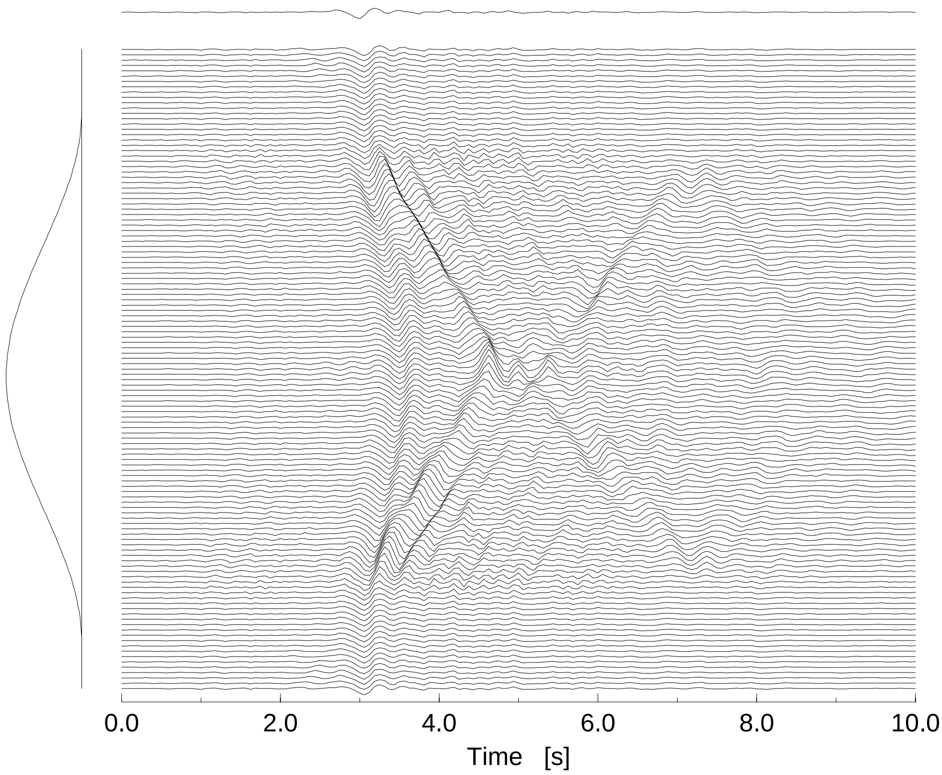


Figure 3. Acceleration synthetics computed at the surface of a shallow (shape ratio = 0.23), high velocity contrast (C_v = 5.25) alluvial valley. Input motion was the record obtained at Aegion O.T.E., NS component (Table 1) pre-processed as described in the text. The topmost trace shows input motion. To the left of the section the shape of the valley is indicated.

Table 2. Material properties used in the high velocity contrast case

Material	V_s [m/s]	V_p [m/s]	Density [gr/cm^3]	Q_S	Q_P
Soft soil	200	300	2.0	20	40
Bedrock	1050	1818.7	2.0	200	400

value for which the main phenomenon shifts from lateral wave propagation to 2D resonance. The examples we have studied correspond to the solid circles in Figure 4. Many examples were computed for the high velocity contrast, i.e., a propagation velocity ratio C_v = 5.25. This value would correspond, for example, to soft sediments with shear wave velocity, V_s, of 200 m/s overlying bedrock with V_s = 1050 m/s. This contrast is very large, and it is unlikely that homogeneous sediments would be resting directly on bedrock. The previous V_s value for the bedrock corresponds to an average of sites SC-Ib in the classification of Borcherdt (1994). The V_s for soft soil would place these sediments at the limit between subsoil classes SC-IVa and SC-III of the same classification. Table 2 gives the complete properties of the (non-saturated) materials used in this study, in the high velocity contrast case. Different values of velocity contrast were obtained by keeping the velocity of the bedrock constant, and varying V_s for the sediments. Only shear wave velocity was varied, while density was kept constant. The chosen properties of bedrock and sediments in the high velocity contrast case correspond to conditions of subsoil classes A and C of Eurocode 8. For simplicity we have considered only vertical incidence of SH and SV waves, and we performed the 2D response calculations with the well-known Aki-Larner method (Aki and Larner, 1970) whose reliability is solidly established.

The adopted strategy is as follows. We have calculated the response at the surface of each sine-shaped valley analysed, for vertical incidence of SH and SV waves at 512 frequencies, equispaced in the frequency range 0 to 8 Hz. A total of 121 receivers equally spaced on the surface was used. We have chosen 13 hori-

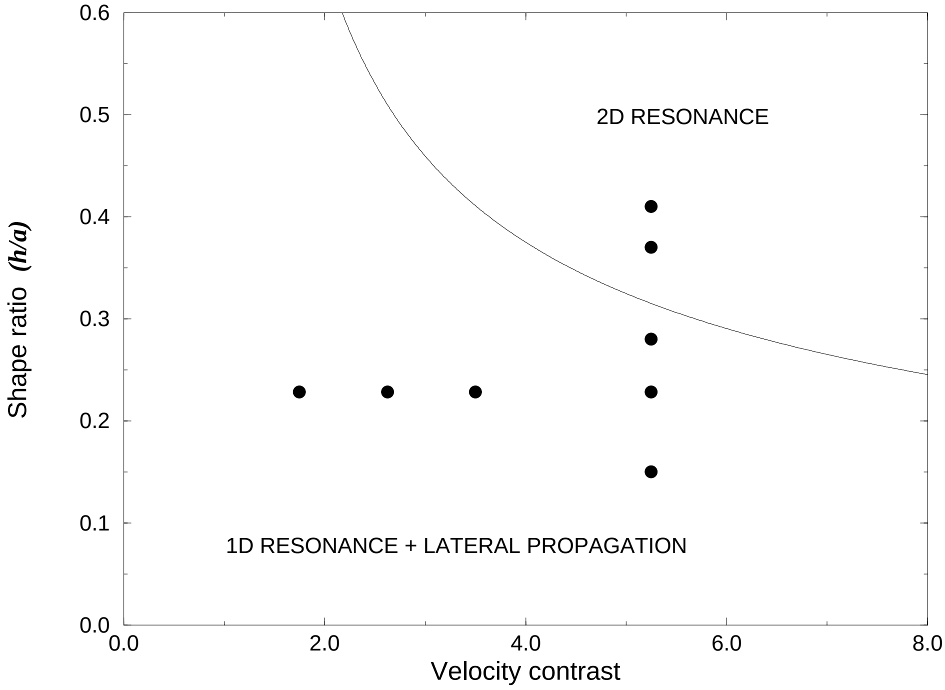


Figure 4. Existence condition of the 2D resonance in alluvial valleys for the SH case. Valleys with combination of parameters falling above the delimiting curve exhibit predominantly 2D resonance, while the region below the curve corresponds to valleys characterised by 1D resonance plus lateral propagation of surface waves. The curve was determined empirically by Bard and Bouchon (1985). Solid circles show the particular alluvial valleys analysed.

zontal accelerograms recorded on rock as excitation (Table 1). The pre-processing of these signals involved application of a low-pass, Butterworth filter with 6.5 Hz frequency cut-off. The input signals were also re-sampled to a common rate of 16 Hz, and padded with zeros to obtain 1024 points time series. Surface synthetic accelerograms were computed by convolution with the frequency transfer function determined for each model of the valley. An example of the results is shown in Figure 3, which was obtained using as input the record Aegion O.T.E., NS component (Table 1), shown in the figure by the isolated trace on top. The shape of the valley is shown to the left of the seismic section. The properties of the valley correspond to a shallow, high contrast valley (shape ratio = 0.23, C_v = 5.25). The predominance of locally generated surface waves is evident for all receivers within the valley.

These synthetic accelerograms were used to compute response spectra for 5% of critical damping. Finally, the response spectra thus obtained were normalized by the results for an ‘equivalent’ 1D model. For each case, this was done by taking as equivalent 1D model the single-layer model with the soil profile of the centre of the valley. We have explored a shape ratio range from 0.15 to 0.41, and velocity contrast values between 1.75 and 5.25, as shown in Figure 4.

Results

An example of the procedure used is given in Figure 5, for a shape ratio value of 0.23, velocity contrast of 5.25, and SH wave incidence. In this calculation, anelastic attenuation was neglected. Figure 5a shows average and average $\pm$ one standard deviation of the response spectra at the surface of a horizontal medium consisting of a single layer, with thickness equal to maximum depth of the valley. Scatter about the average value results from the different way in which each of the input signals excites shear wave resonance. Figure 5b shows the same results for the receiver at the centre of the corresponding sine-shaped alluvial valley; note that the maximum value of the average of the response spectra is significantly larger than the 1D value. Also, the scatter about the average has increased considerably, although the input signals are the same in the two cases. This increased variability is a con-

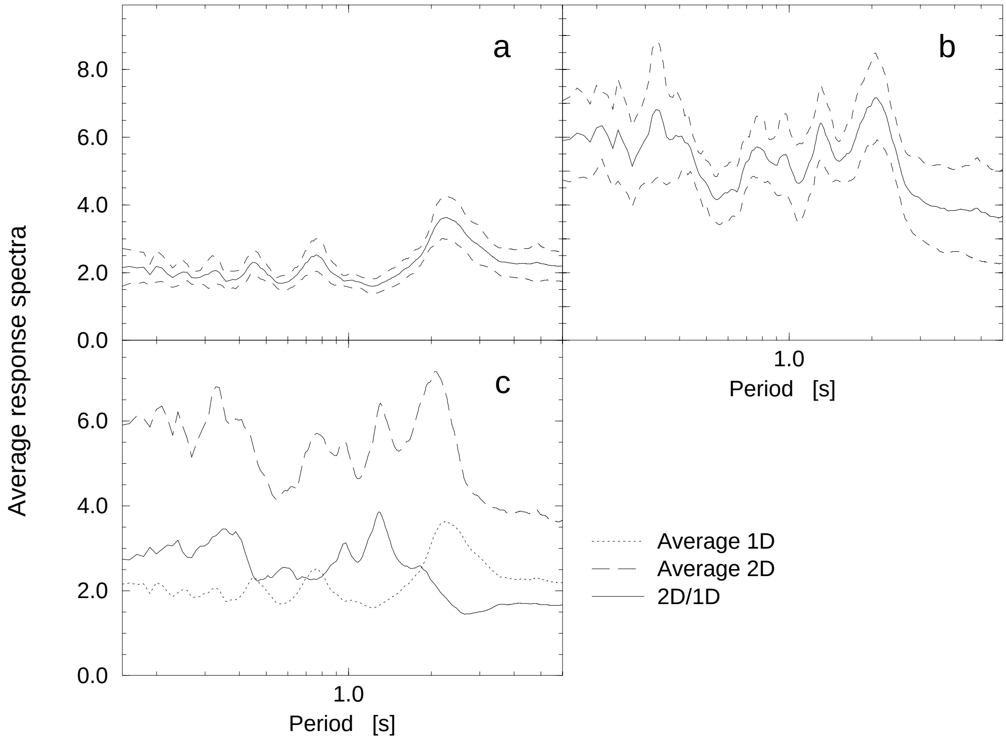


Figure 5. Summary of results for a shallow valley (shape ratio = 0.23) with high velocity contrast and no anelastic attenuation. Excitation is given by the 13 selected accelerograms of Table 1. (a) Average and average ± one standard deviation of the response spectra computed at the surface of a single layer over half-space. (b) Same, computed at centre of the sine-shaped valley for vertical incidence of SH waves. (c) Average curves shown in (a) and (b), plus the ratio between them.

sequence of the larger complexity of the 2D transfer function.

Finally, Figure 5c compares the two average curves and shows the ratio between them. We observe that lateral restriction in the 2D model moves the largest resonant peak of the response towards shorter periods. The ratio between the two average curves attains values larger than 3. For this particular valley, this ratio is a measure of the extent at which site effects in the 2D configuration exceed those in the 1D configuration, as seen in the response spectra domain.

It is clear that anelastic attenuation cannot be neglected in evaluating site effects on sediments with such low shear wave velocity. Figure 6 illustrates how a Q factor value of 20 for the sediments affects the response at the surface. This time we show only the ratio between average 2D response spectra, relative to the ‘equivalent’ 1D model. The average 2D response spectra were computed for the receiver at the valley centre, and we show results both for incident SH and SV waves. As expected, the large values at shorter periods decrease drastically when including attenuation. We may note that anelastic attenuation affects 2D site response to a larger extent than 1D response. This is shown by the decrease of the 2D/1D ratio for the peak due to the fundamental mode. This is natural as the larger 2D peaks result from the contributions of laterally propagating waves, which travel longer paths than vertically propagating waves in the 1D model. This figure also shows that an SV wave incidence leads to smaller 2D effects than an SH incidence, and that 2D effects occur at similar periods for both types of wave. Again, the largest peak tends to occur at shorter periods in the 2D case than in 1D.

We examine now the influence of the shape ratio. We have explored shape ratios in the range 0.15 to 0.41, while keeping a constant velocity contrast C_v = 5.25. Attenuation was considered through a Q factor of 20 for the sediments, and 200 for the bedrock. Since the resonance frequency for the sediments changes with the shape ratio, we have normalized the period by the 1D resonance period of the soil column at the valley centre. The results are shown in Figure 7, again, only for the receiver at the centre. Normalisation of the period by the 1D resonance period appears to be quite correct, since all the curves tend to group to-

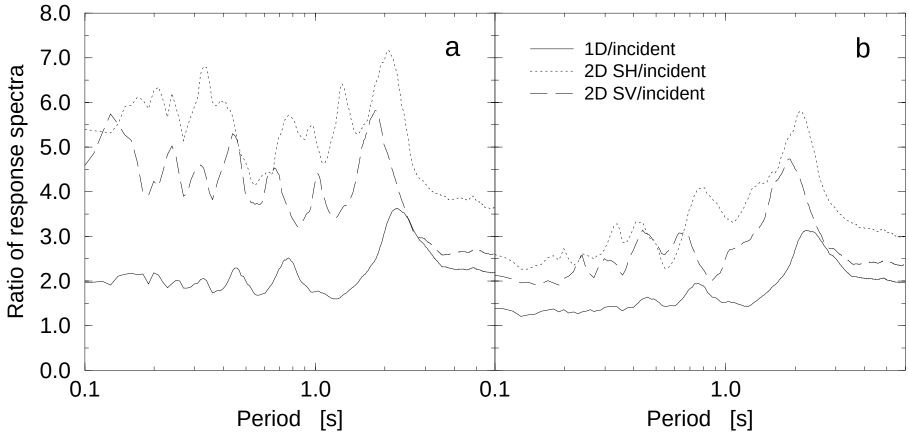


Figure 6. Average response spectra on the surface of a single-layer flat model (1D), and at receiver at the centre of a shallow (shape ratio of 0.23), high contrast valley. For the 2D case we show results for incidence of SH and SV waves. (a) Without attenuation. (b) Including a Q factor of 20 for the sediments.

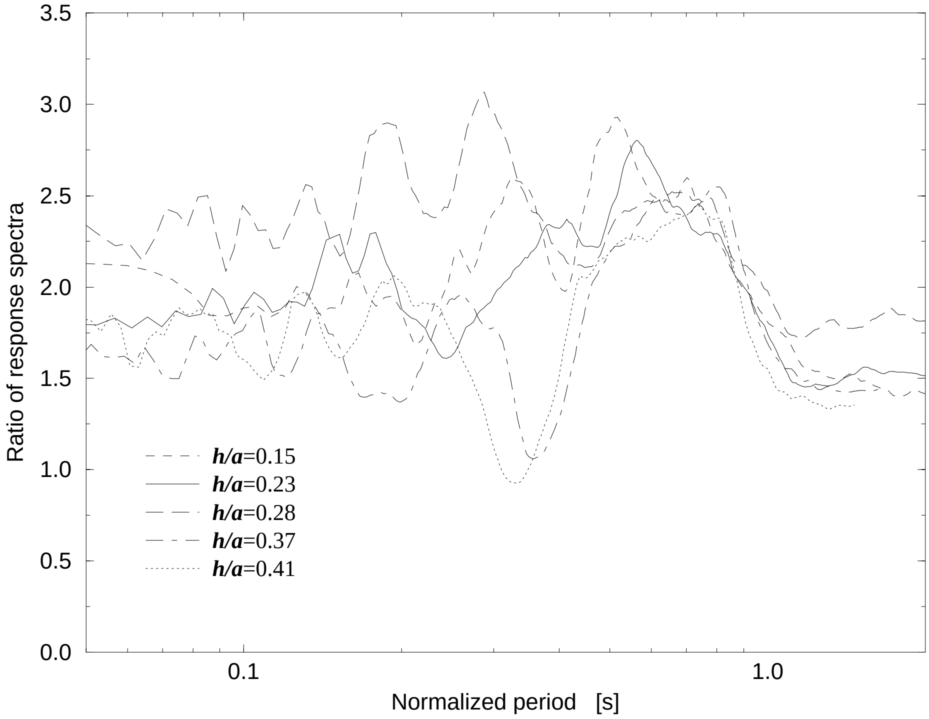


Figure 7. Ratio of average response spectra for receiver at the centre of a valley relative to the average spectra at the surface of the 'equivalent' 1D model for each case. Each curve corresponds to the given shape ratio. Velocity contrast is constant (C_v = 5.25), and attenuation included (Q = 20).

gether. A large, wide maximum of the ratios is seen to occur for normalized periods between 0.4 and 1, with amplitudes around a factor 2.5.

This maximum does not depend on the shape ratio. For shorter periods, the ratio between 2D and 1D response spectra does depend on shape ratio, and is more related to the troughs of the 1D spectra than to maxima of the 2D spectra. Note that, in spite of anelastic attenuation, the ratio does not tend to unity, i.e., 2D amplification does not tend to 1D amplification at shorter periods, but remains substantially larger.

We now look at the influence of the velocity contrast between sediments and bedrock. Figure 8 depicts the ratio of the average spectra at the centre of the

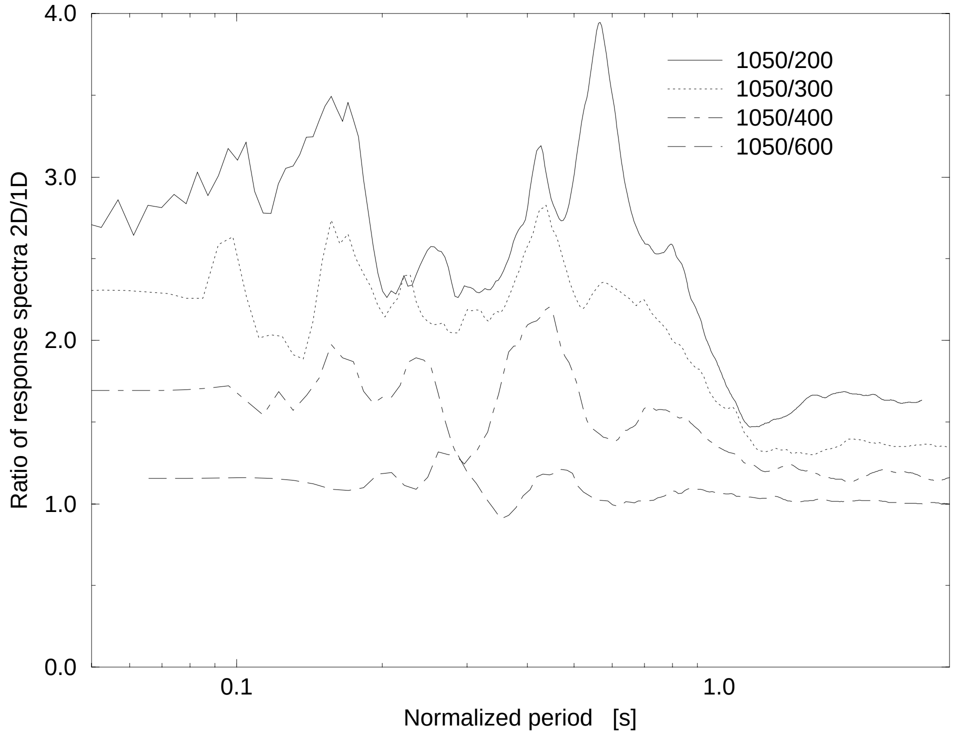


Figure 8. Ratio of average response spectra at the receiver at the centre of a shallow alluvial valley (shape ratio 0.23) relative the average spectra at the surface of the ‘equivalent’ 1D model for each case. Each curve corresponds to the given values of shear wave velocities (bedrock/sediments). Attenuation is not included.

valley relative to the average 1D result. Each curve corresponds to a prescribed velocity contrast. Abscissae are again given in terms of period normalized to the 1D resonant period, which now varies with the shear wave velocity of the sediments. This time anelastic attenuation was not considered, since a different *Q* value would have been required each time the shear wave velocity of the sediments was changed. It is evident that the velocity contrast has a very large impact on the 2D/1D average spectra ratio. The value at the resonant period can change by a factor larger than 3.

Figure 8 suggests that 2D site effects are more important for large velocity contrast, i.e., in the case of softer sediments which roughly correspond to subsoil class C of Eurocode 8. It appears that 2D amplification need not be considered in the case of subsoil class B, where velocity contrast is smaller.

Up to this point we have only considered the receiver at the centre of the valley. We now examine the spatial variation of ground motion across the surface of the valley. Let us first discuss a very usual parameter in Earthquake Engineering, peak ground acceleration (PGA). We have computed synthetic accelerograms at 121 receivers at the surface of our models, for each one of the 13 selected input motions. Figure 9 shows the average and the standard deviation band of peak ground acceleration across the surface of a shallow, high velocity contrast alluvial valley. PGA was normalized by its value outside the valley for each record. A large dispersion characterises the PGA amplification within the valley, and similar results were observed for different valley configurations. The dispersion in Figure 9 is due to the different way in which each input motion excites the 2D transfer function at each site. These results seem to corroborate the well established observation that PGA alone is not an adequate measure of site effects.

We now look at spatial variation in terms of our preferred measure of motion. For this purpose, we extended the procedure described for the receiver at the centre of the valley to all the 121 receivers at the surface, i.e., we computed the synthetic accelerogram at the surface for each of the 13 selected input motions. For each synthetic record, the 5% damping response spectrum was calculated and then divided

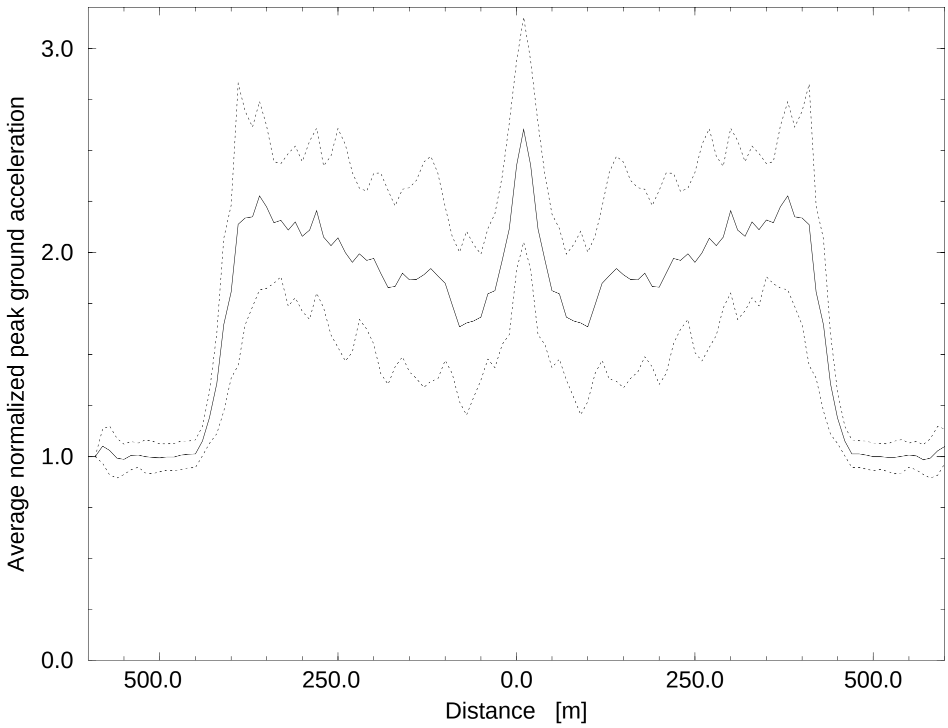


Figure 9. Normalised peak ground acceleration (PGA) across a model of a shallow, high velocity contrast alluvial valley. Results correspond to: Continuous line: average normalized PGA computed for the 13 input motions. Dashed lines: average ± one standard deviation.

by the response spectrum calculated at the surface of the single-layer, flat model *at the centre of the valley*. Finally, the average ratio between those response spectra ratios was determined, for each receiver and each period. An example of the results is shown in Figure 10, for the case of a shallow, high velocity contrast alluvial valley. The surface shown in this figure is a measure of how much larger 2D site effects are relative to the 1D motion at the centre of the valley for the particular configuration chosen.

2D site effects are significantly larger in a large band of periods and at all receivers more than 50 m from the edge of the valley. Despite the significant amplitude variations across the surface (for example between 1 and 1.5 s period) maximum values are close to what we had observed for the receiver at the centre of the valley. For shorter periods, the difference between 2D and 1D amplification diminishes, but stays larger than 1, as previously observed. We have computed this surface for other configurations with similar results; maximum values do not change significantly across the valley, nor do the periods at which maxima occur. This result is significant in terms of our objective. If there were significant variations of the 2D basin amplification factor, we would be facing a cumbersome alternative. In fact, one possibility would be to propose a different site classification scheme in the Eurocode 8, but this could become very complicated because it would be necessary to specify the position of the site of interest relative to the lateral structure of the sedimentary deposit. The alternative could be too conservative because we would assign the worst basin amplification factor at any point at the surface to all the points at the surface of the soil deposit. Our results indicate, in first approximation, that it would not be over conservative to use a single basin amplification factor for all points at the surface of a particular soil deposit, except perhaps close to the edges. Note however, that, close to the edges of the valley, differential motion rather than absolute amplification may be the most important effect of lateral heterogeneity on strong ground motion (e.g., Moczo and Bard, 1993). This subject, however, is beyond the scope of this paper.

Comparisons with real data

An adequate data set to compare our results proved difficult to find. We have computed a measure of increased amplification due to 2D configuration of sed-

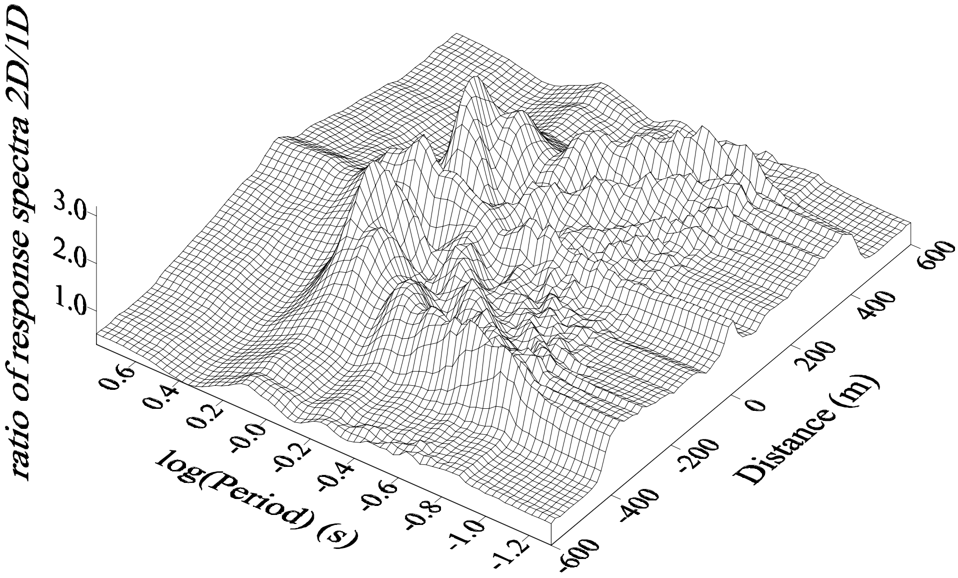


Figure 10. Example of spatial distribution of the 2D basin amplification factor. The surface shows ratio between average response spectra at each of the 121 receivers on the surface of the 2D model, relative to average spectra of the 1D model at the valley centre. This average was computed from the results for the 13 input accelerograms. The valley extends from –500 m to 500 m distance.

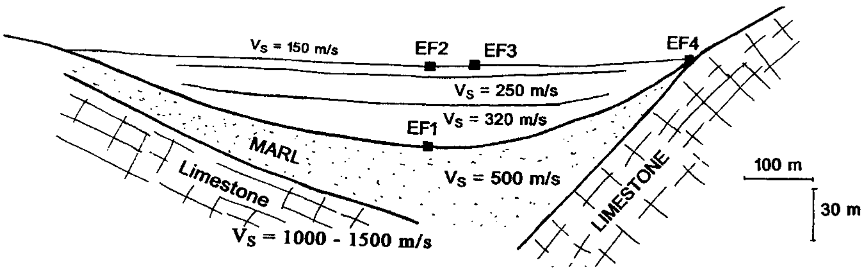


Figure 11. Geological cross-section of the Kefalonia accelerograph array site. Solid squares show the position of the accelerographs (three at the surface, one at depth). From Gazetas (1997).

iments, compared with an ‘equivalent’ 1D situation. However, in a real situation, there are no distinctions of records obtained over a 1D or 2D configuration. Rather, there are only records obtained on soil sites and records obtained on rock sites. However, we have found some records of two test sites where a limited comparison could be attempted. These are Kefalonia valley, in Kefalonia island in Greece, and the Euroseistest site near Thessaloniki, also in Greece. At each of these alluvial valleys an accelerograph array is installed and simultaneous earthquake recordings on rock, and near the centre of the valley are available. Additionally, a geotechnical profile under the soft soil site is known there (albeit with a different detail for the two arrays), allowing evaluation of 1D site effects for this station in both cases. This will in principle allow to determine how well the computed 1D site amplification function explains the differences between the observed soil and rock motions.

Kefalonia valley

A small seismic field laboratory was installed in an alluvial valley in the island of Kefalonia, Greece (Gazetas, 1997). The valley is approximately 800 m wide, and of the order of 100 m deep. The shear wave profile was interpreted from SPT measurements. In this valley there are two accelerographs at the surface, one on rock, and one at the bottom of the surface sediments (Figure 11). We had available only one earthquake of M_L = 3.8 for which these four instruments produced simultaneous records (event of 06.03.97 at 11:09:25, GMT). The epicentre was located 11.1 km due South

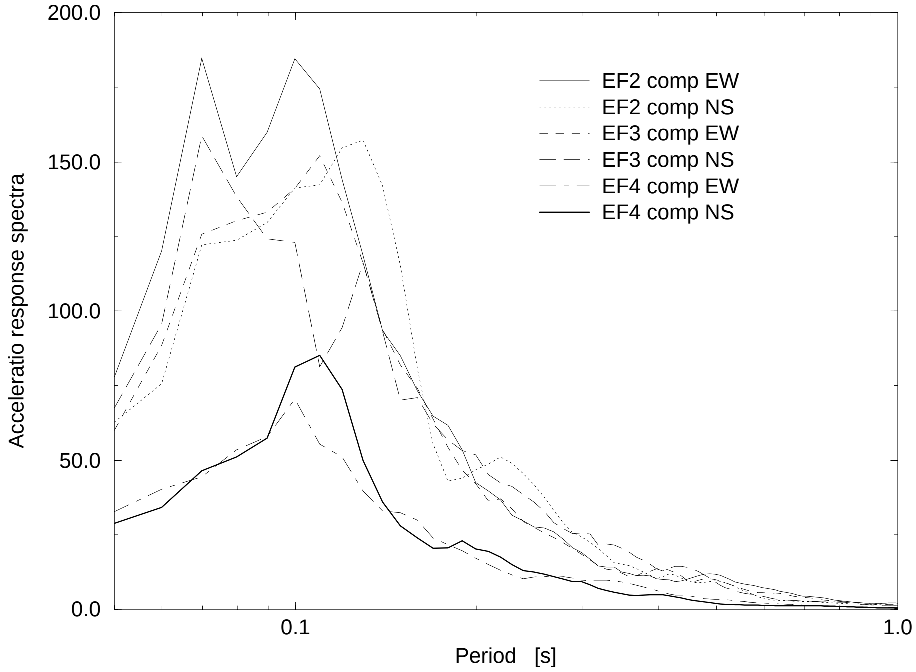


Figure 12. Acceleration response spectra for 5% damping of the records at stations EF-2, EF-3 and EF-4 of Kefalonia array.

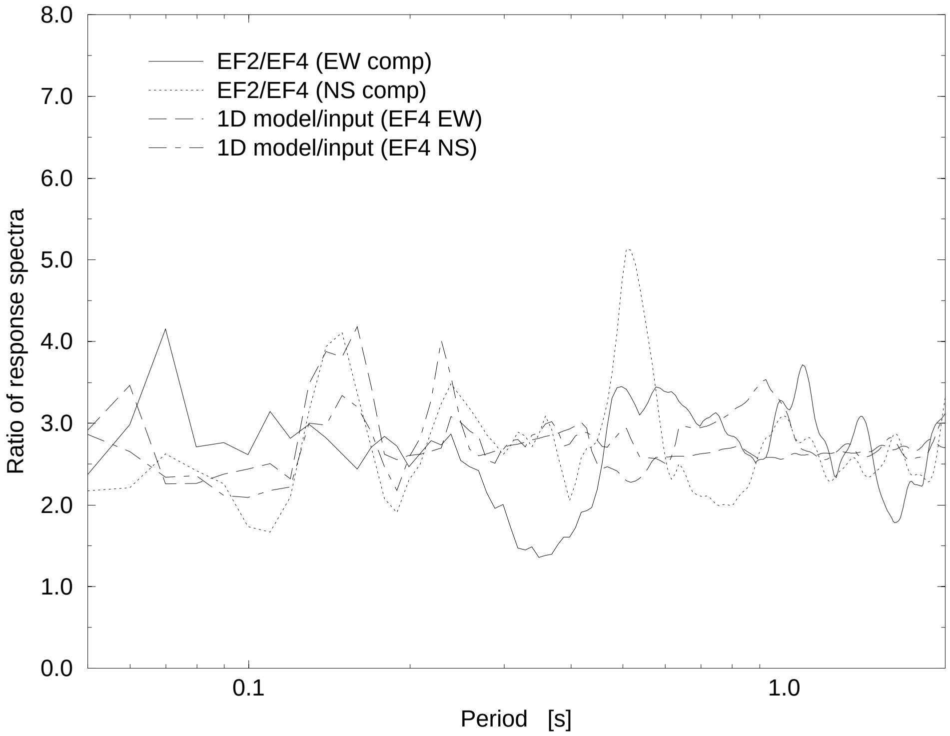


Figure 13. Ratio of response spectra for Kefalonia array data. Solid lines show the ratio of response spectra of the two horizontal components of station EF-2 relative to the spectra of EF-4 records. Dashed lines show the ratio between response spectra of the synthetic record at the surface of the 1D soil profile at station EF-2 relative to input motion (EF-4 record).

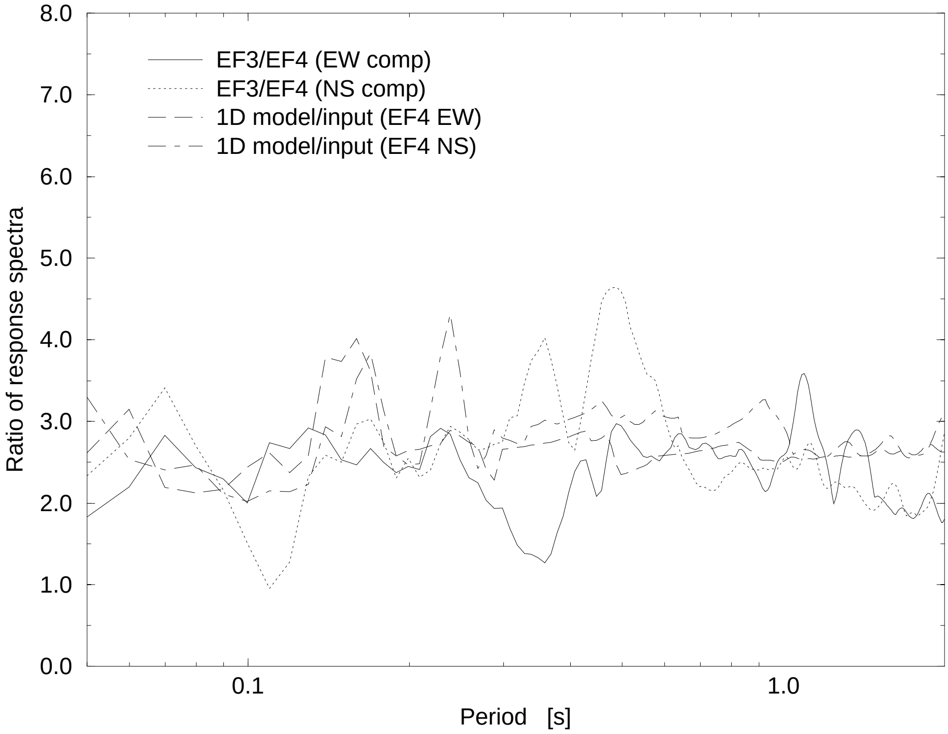


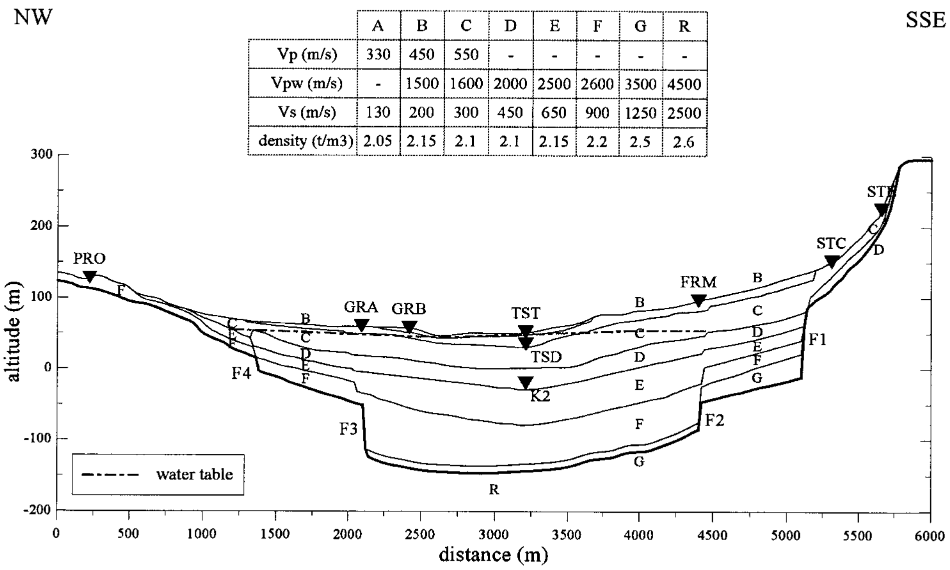
Figure 14. Ratio of response spectra for Kefalonia array data. Solid lines show the ratio of response spectra of the two horizontal components of station EF-3 relative to the spectra of EF-4 records. Dashed lines show the ratio between response spectra of the synthetic record at the surface of the 1D soil profile at station EF-3 relative to input motion (EF-4 record).

of the instrumented site. Figure 12 shows the acceleration response spectra computed for the two stations on soft soil and the station on rock. As we expect for a small, close-by event, the largest amplitudes occur at periods below 0.2 s, with the peak at 0.1 s (10 Hz). The response spectra of the records on soft sediments are larger (by a factor between 2 and 3) in the period band 0.05 to 0.2 s. Thus, these records show significant site effects only at very low periods.

We have computed synthetic accelerograms for the soft soil sites using the 1D soil profile under each station and the horizontal records on rock as input. We have then computed response spectra for those synthetic accelerograms. Finally, Figure 13 shows the comparison in terms of ratios of response spectra for station EF-2. The narrow peaks in this figure are due to small values of the denominator response spectrum. We observe a good overall agreement between the computed amplification using the 1D model, and the observed amplification between the rock and soft soil sites. In the calculation of the 1D transfer function, we assumed no anelastic attenuation, because we have no useful data for this purpose. Thus, the good agreement obtained at low periods indicates that our velocity model underestimates the velocity contrast; a larger velocity contrast is required to offset the effect of anelastic attenuation at shorter periods. As shown in Figure 12, ground motion amplitudes are very small for periods above 0.5 s.

The results for station EF-3 are shown in Figure 14, and are similar to those of EF-2. We observe again agreement between the amplification computed with the 1D model and the observed amplification. Again, amplification of ground motion by the soft sediments, as measured by the ratio of observed response spectra is small. As for station EF-2, observed amplification has similar amplitudes to those computed using a 1D profile without anelastic attenuation. Thus, a larger velocity contrast model is called for.

The results observed for the data from Kefalonia array are not very helpful for our purpose. Site effects are overall small, and only significant for frequencies higher than 5 Hz, a range where clearly our deterministic modelling is not very useful. Site effects are small and clearly related to the amplification of the topmost surface layers. Therefore, dominant wavelengths are



	A	B	C	D	E	F	G	R
Vp (m/s)	330	450	550	-	-	-	-	-
Vpw (m/s)	-	1500	1600	2000	2500	2600	3500	4500
Vs (m/s)	130	200	300	450	650	900	1250	2500
density (t/m3)	2.05	2.15	2.1	2.1	2.15	2.2	2.5	2.6

Figure 15. Geological cross-section of the Euroseistest valley. Solid triangles show the location of the strong motion recorders. The subsoil profile data are also shown. (After Raptakis et al., 1998).

of the order of tens of m, and 2D site effects can be safely ruled out. The network is still in operation, and a larger earthquake, with more energy at longer periods could effectively elicit a 2D response of this sedimentary basin. Additionally, our results suggest that a direct measurement of shear wave velocities in the soil layers is needed.

Euroseistest

This site is located on a 5.5 km wide and 200 m deep alluvial valley, between the Lagada and Volvi lakes in the Mygdonian graben, some 30 km to the East of Thessaloniki in Greece. Within this valley, a strong motion network of 7 surface accelerographs was installed (Raptakis et al., 1998). We will be concerned only with two of them, TST and PRO (Figure 15). TST was installed near the centre of the valley, and detailed geotechnical information is available on the soil profile to bedrock beneath this station while PRO is located on rock at one side of the valley. We have analyzed records of two events at these two stations. The first event occurred on 04.05.95 at 00:34:11, with a magnitude of 5.8. The epicentre was located at an azimuth of 110°, 32.3 km away from the instrumented site. The second event occurred on 13.05.95 at 08:47:14 with a magnitude of 6.6. The epicentre was located at an azimuth of 247°, 150 km away from the instrumented site.

Figure 16(a) shows response spectra of the horizontal motion for the two stations for the first event. Ground motion at TST is amplified by a large factor (between 3 and 4) in the period band 0.3 to 2 s. At shorter periods, the records still have significant energy, but clearly some additional effects come into play. This is evident in the EW component recorded at PRO, which attains amplitudes larger than the EW component at TST, and much larger than the NS component at PRO. Thus, near field or directivity effects seem to control ground motion below 0.3 s. For longer periods, the two horizontal components are similar for each of the two stations.

Ground motion for the second event shows similar characteristics. However, as the epicentre is far away, high frequency energy has been attenuated. We observe similar amplitudes for both horizontal components at each station. TST shows larger amplitudes than PRO by a factor similar to that observed in the first event, with two bumps of energy below and above 1 s period, similar to those of the first event. Thus, both events show a rather consistent picture of site effects at Euroseistest.

A detailed soil profile is available under station TST, better constrained than that of Kefalonia valley, as it is derived from in situ geophysical measurements. Attenuation of shear waves was determined for the first 50 m from inversion of recorded explosions. We computed synthetic accelerograms using a

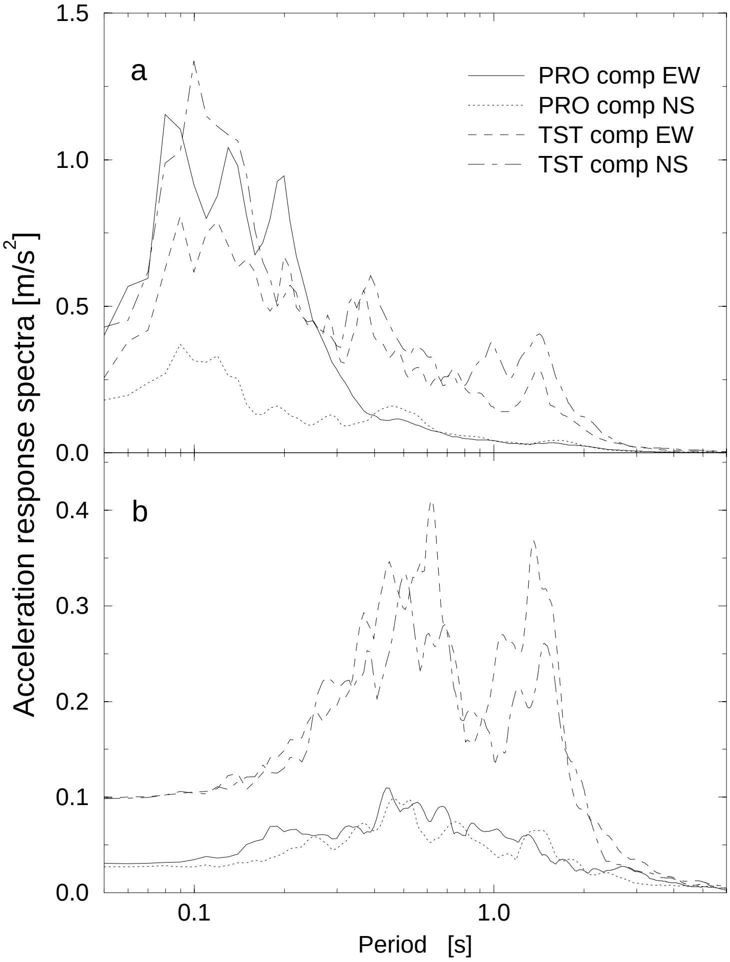


Figure 16. Acceleration response spectra of two events recorded at stations TST (on soft soil) and PRO (on rock) at Euroseistest. (a) Event # 1. (b) Event # 2.

1D model of the soil column under TST and the two horizontal recorded accelerograms at PRO, on rock, as input. Again, we computed response spectra for the synthetic accelerograms, and evaluated amplification using ratios of response spectra. The results are given in Figure 17. Diagrams (a) and (b) show results for NS and EW component for the first event. Diagrams (c) and (d) show the results for the same components and data from the second event. In Figure 17, solid lines show the ratio of observed response spectra at TST relative to that at PRO. Dotted lines show the ratio of response spectra computed at the surface of the 1D model of the soil column under TST using PRO record as input, relative to observed response spectra at PRO. In Figures 17a, b, and d, the ratios between observed response spectra at TST and that observed at PRO (solid lines) show a large peak between 1 and 2 s period. The amplitude of this peak significantly exceeds the amplification values predicted by the 1D model (dotted lines), although the difference depends very much on the component of motion and for which event. Figure 17c shows that, for the NS component of the second event, amplification at TST is very similar to that computed using the 1D model. In the four diagrams of Figure 17, results for 1D computations fall above observations at short periods. This suggests that attenuation factors used in the 1D model are underestimated. However, larger attenuation in the model would increase the difference between the solid and dotted lines in Figures 17a, b, and c. We observe a large variation of amplification factors in the observed records (solid lines), with little consistency between the two events. Neither is there consistency in the difference between observed and predicted (by the 1D

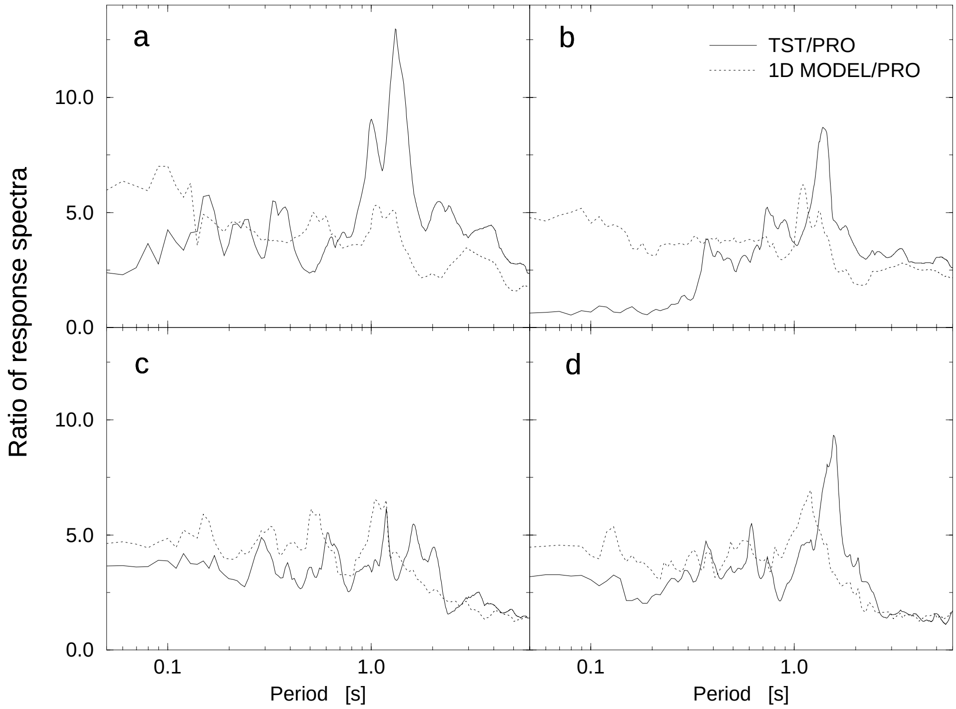


Figure 17. Ratios of response spectra for Euroseistest array data. Solid lines show ratios between observed response spectra at TST (at the centre of the valley) and PRO (on rock). Dotted lines show ratios between response spectra of the synthetic record at the surface of the 1D soil profile at station TST relative to input motion (PRO record). (a) NS component, event # 1. (b) EW component, event #1. (c) NS component, event # 2. (d) EW component, event # 2.

model) maximum amplification. This difference varies between a factor 1.3 to 2.5 for Figures 17a, b, and c.

However, we have shown before that we may expect different behaviour between motion parallel to the axis of the valley (SH) and that perpendicular to the same (SV). For this reason we have rotated the observed accelerograms, and repeated the calculation using horizontal components rotated according to the orientation of the axis of the valley (some 60° to the East at the instrumented section). The results are shown in Figure 18, again in four diagrams corresponding to the two horizontal components and the two analysed events. As previously, solid lines show the ratio of observed response spectra at TST relative to that at PRO. Dotted lines show the ratio of response spectra computed at the surface of the 1D model of the soil column under TST using PRO record as input, relative to observed response spectra at PRO. In this figure, we observe a more coherent picture of site effects. The difference between observed amplification (solid lines) and that computed using the 1D model (dotted lines) is more consistent between the two events for three of the diagrams. The horizontal component perpendicular to the axis of the valley (SV motion, Figure 18c) still shows amplification similar to that computed using the 1D model for the second event, in large contrast with the other components. However, the other three diagrams show again that amplifications computed using the 1D model of TST (dotted lines) are significantly smaller than observed amplification (solid lines). Again, results for 1D computations fall above observations at short periods, suggesting that attenuation factors used in the 1D model are underestimated. The difference between observed amplification and computed maximum amplification from the 1D profile is now more homogeneous, and varies between 1.8 and 2.6 in Figures 18a, b, and d. These numbers, expressing the difference between computed amplification for a 1D profile of TST and observed amplification at this site, are in very good agreement with the basin amplification factors we determined above. However, we do not see smaller amplification in diagram (a), corresponding to SV motion, relative to diagram (b), corresponding to SH motion. Additionally, the large difference in observed amplification between the two events for the component perpendicular to the axis of the valley (Figures 18a and c) is puzzling.

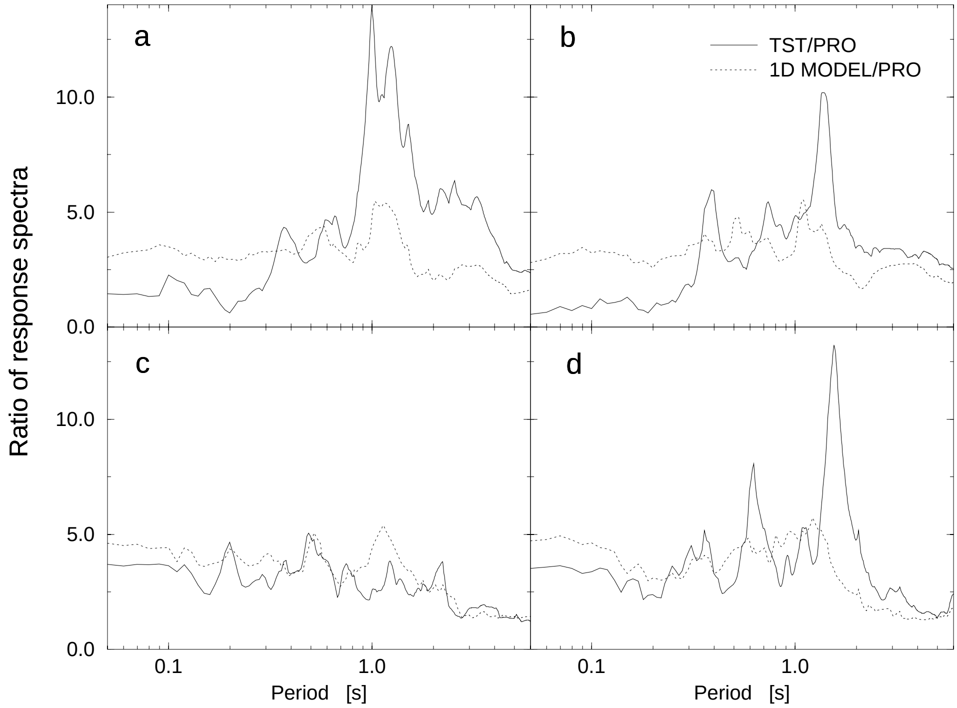


Figure 18. Ratio of response spectra for Euroseistest array data. Solid lines show ratios between observed response spectra at TST (at the centre of the valley) and PRO (on rock). Dotted lines show ratios between response spectra of the synthetic record at the surface of the 1D soil profile at station TST relative to input motion (PRO record). (a) Horizontal component, perpendicular to the axis of the valley (SV motion), event # 1. (b) Horizontal component, parallel to the axis of the valley (SH motion), event # 1. (c) Horizontal component, perpendicular to the axis of the valley (SV motion), event # 2. (d) Horizontal component, parallel to the axis of the valley (SH motion), event # 2.

The soft soil sediments filling the valley of Euroseistest amplify response spectra by a factor larger than 10 between 1 and 2 s relative to motion on rock. Amplification computed for a 1D model using a very reliable geotechnical model accounts for an amplification factor of about 5. Thus, 2D site effects amplify ground motion by a factor of about 2 in addition of 1D site effects. However, the amplitude of the large peak of amplification differs very much between the two events for the component perpendicular to the axis of the alluvial valley. This peak attained a value of 14 (relative to rock motion) for one event, and was about 5 for the second one. This variability confirms previous results of site response studies of alluvial valleys: site response may vary significantly depending on factors like angle of incidence, direction of incoming waves, and polarization of shear waves relative to the axis of the valley. Indeed, consideration of the latter factor leads to more coherent 2D amplification factors at station TST. The large variability of observed amplification for this two events underscores the usual recommendation in observational site response studies; a large number of significant events should be analyzed to obtain a meaningful average.

Conclusions

We have explored the possibility of quantifying the additional amplification that may stem from the two-dimensional configuration of soil deposits. Our purpose has been to investigate the possibility of including some kind of provision for such complex site effects in terms of a modern seismic building code, such as Eurocode 8. For this reason, we presented our results in terms of ratios of response spectra.

We recall the main restrictions of our study. We did not consider topographic site effects, but only sedimentary valleys. The reason is that topographic amplification of seismic ground motion is usually smaller than that occurring on sedimentary basins. Thus, in terms of a building code, topographic site effects are less relevant. We only explored the effect of a particular shape of two-dimensional alluvial valleys. Our justification is that site effects in three-dimensional sedimentary structures are only quantitatively different from those in two-dimensional valleys (e.g., Jiang and Kuribayashi, 1988). However, two-dimensional site effects introduce phenomena that are physically different from what occurs in a one-dimensional case.

In addition to this, theoretical studies on site effects clearly show that the detailed shape of the sediment-bedrock interface does not affect significantly the response in the low frequency range, where the deterministic approach we have used is useful. Another restriction of our study is that we have computed results only for the case of homogeneous sediments. However, as pointed out by Bard and Gariel (1986), heterogeneity of the sediments does not change the nature of the seismic response of alluvial valleys but dramatically increases the number of parameters of the problem. Additionally, using homogeneous sediments leads us to err on the conservative side, which is reasonable in terms of our objective. Finally, we have considered only linear elasticity, both in wave propagation calculations and in computation of response spectra. The latter restriction is being removed in our current work. The restriction to linear elasticity is more difficult to remove. Nonlinear models of soil behaviour would increase the number of parameters in a way to make eventual application of our results meaningless. However, Borcherdt (1994) suggests that nonlinear elasticity results in smaller response spectra, and we would again be on the conservative side.

Our results confirm what is well known to seismologists, but seems to be less accepted by the engineering community: two-dimensional site effects increase very significantly the ground motion amplitude in a wide period band. The amplification in the response spectra caused by the 2D configuration of a sedimentary valley attains a factor larger than 2, in addition to the 1D amplification.

From the point of view of this study, no relevant difference was found between 2D resonance (deep valleys) and 1D resonance plus lateral propagation (shallow valleys). This is surely related to the fact that the difference in behaviour between deep and shallow alluvial valleys (Bard and Bouchon, 1985) concerns the low frequency amplification peaks. However, after convolution with a wide band input signal, and representing ground motion through response spectra, this distinction tends to disappear.

We confirm the finding of previous studies, that 2D amplification becomes significant for lower periods than 1D amplification, owing to the additional lateral restriction to motion of the sediments. Thus, for our purposes we should consider a 2D basin amplification factor only at periods shorter than the 1D resonance period at the centre of the sedimentary deposit.

We have found that 2D site effects do not tend to 1D amplification values at shorter periods, but remain substantially larger. We have also shown that anelastic attenuation affects in a larger measure 2D response than 1D site response, because the former is produced by waves travelling along longer paths than the latter.

Our results indicate that the variations of amplification across the sedimentary valley, although not negligible, do not justify the complexity that would be required to specify a 2D basin amplification factor as a function of position across the sedimentary structure. Hence, the 2D basin amplification factor can in first approximation be assumed constant throughout the surface of the valley. This result applies only in terms of absolute amplification. Close to the edges of the valley, differential motion rather than absolute amplification may be the most important effect of lateral heterogeneity on strong ground motion.

Finally, let us summarize the results of our comparison with two sets of available data. In the case of the Kefalonia accelerograph array site, the data available were not helpful for our purpose because site effects were small, and only significant for frequencies higher than 5 Hz, a range where clearly our deterministic modelling is not useful. Observed site effects for this site are related to the amplification of the topmost surface layers, as dominant wavelengths are of the order of tens of m only. Thus, for the records analysed, 2D site effects can be safely ruled out. The network is still in operation, and maybe a larger earthquake, with more energy at longer periods may effectively elicit a 2D response of this sedimentary basin.

Observed site effects at Euroseistest site were much larger than those at Kefalonia, in the period range 0.3 to 3 s. Moreover, between 1 and 2 s period, site effects have amplified response spectra by a factor larger than 10 relative to rock motion. Amplification computed for a 1D model using a very reliable soil profile under the considered soil station accounted for an amplification factor of 5. Thus, 2D site effects amplified ground motion by a factor of about 2 in addition to 1D site effects. The estimate is in very good agreement with the 2D basin amplification factor obtained from our numerical models. This result was consistent for both events for the component parallel to the axis of the valley (SH motion), but appeared only for one event for motion perpendicular to the axis of the valley (SV motion). Clearly, additional events should be analyzed to obtain a more reliable amplification function for this component. An alternative would be to obtain strong motion data from other alluvial valleys, where detailed geotechnical investigations have been carried out.

In conclusion, we have shown that the most significant parameter controlling the proposed 2D basin amplification factor is the velocity contrast between sediments and bedrock. Thus, unlike the 1D site effects currently accounted for in seismic norms, the additional amplification caused by 2D effects may not be safely evaluated with the properties of the soil profile of the topmost layers (as suggested in Borcherdt, 1994); some information is also required on the properties of the bedrock underlying the soft sediments. Bearing in mind the limitations of this study, our numerical results suggest that in the case of subsoil class C (according to Eurocode 8 definitions) the additional amplification factor due to the lateral heterogeneity of a sedimentary deposit lying over competent bedrock is a factor between 2 and 3.

Acknowledgements

This research was carried out while the senior author was a visiting researcher at the Dipartimento di Ingegneria Strutturale of Politecnico di Milano, with financial support provided by the European Commission Project TRISEE, Environment and Climate 1994-98 Programme, Contract ENV4-CT960254. He would like to thank the persons that made this visit both possible and an enjoyable experience. Part of this visit was funded through a grant of DGAPA, UNAM. G. Gazetas provided data from the Kefalonia array, and K. Pitilakis from Euroseistest.

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