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ABSTRACT

We use 473 weak motion surface records from a relatively soft soil site (CORSSA) and 81 from a relatively stiff soil site (DIM) in conjunction with downhole records obtained in rock in order to study linear seismic soil amplification in Aegion, Greece. We estimate peak 'soil-to-outcrop' amplification factors in the time domain for the two sites through linear regression of PGA values. We view the results derived from these very weak motion records as indicative of the entire linear elastic range based on the large dataset size. We compare the peak horizontal soil amplification factors we derive from records with those suggested by design codes based on site classification, and find that they define lower boundaries rather than predictions of the average. We also find that, although the vertical component is assumed unamplified, both datasets show a two-fold amplification in its peak value. The results are also compared with previous finite difference analyses. For CORSSA, the amplification values calculated from 2D analyses are quite similar to those based on records, while for DIM they are 35% lower. Finally, while the elastic response spectra are well within the design spectra due to the small PGA values, we normalize them as to PGA in the context of discussing site effects. Spectral shapes do not infer strong site effects at DIM, but they do so for CORSSA, indicating strong surface waves particularly around the site's fundamental period.

INTRODUCTION

It is well known that local site conditions can influence the characteristics of strong ground motion in various ways, collectively referred to as site effects. The local geology at a site can modify the amplitude, frequency content and duration of seismic motion as it travels from bedrock to the ground surface. Site effects are related to the thickness and impedance contrast between soil layers, the surface topography as exhibited by the relief, and the subsurface topography in terms of lateral discontinuities. Soil layer effects have been investigated more extensively than surface and subsurface topography effects, which are more case-specific and tied to two-dimensional phenomena. Thus, when it comes to estimating the seismic force applied to structures, design codes take soil amplification into account in a rather more exact, detailed and straightforward way.

In this study, we use two relatively large datasets to estimate peak soil amplification of weak motion in the time domain at two nearby yet different sites in Aegion, Greece, and compare it to some design code specifications. We also make comparisons between instrumental and numerical results. Finally, we make mention to more complex site effects taking place in the region.

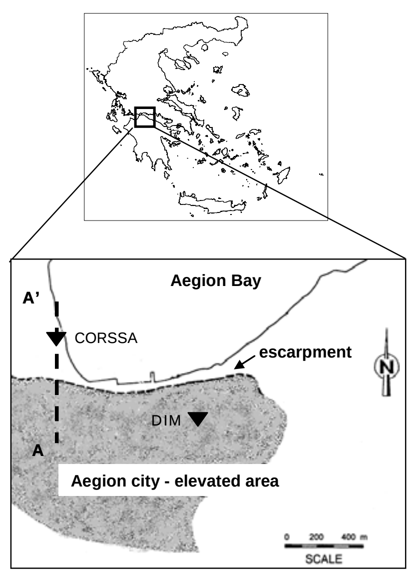
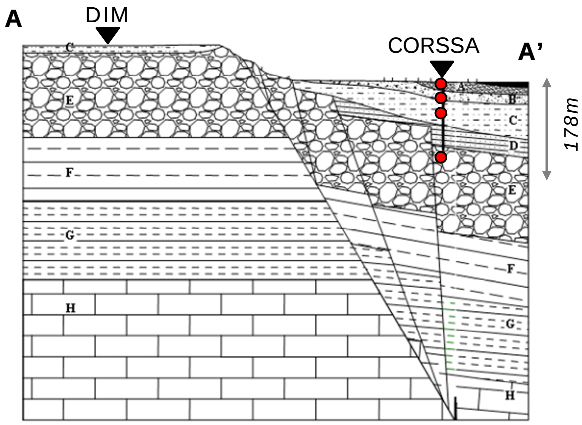


Fig. 1. Map of Greece showing the location of Aegion city and map of the city (adapted from Athanasopoulos et al. 1999). The fault trace, elevation differences, and location of instrumented sites CORSSA and DIM are marked on the map.



Formation	Description	Vs (m/sec)
A	Soft marine deposits consisting of sandy silt, silt, silt and clay (SM-ML-CL)	150-200
B	Soft sediments consisting of clayey silt, sandy clay, silty clay with few gravels (SC-ML-CL)	220-310
C	Hard deposits consisting of clayey silt, sandy clay, silty clay, with few gravels (SC-ML-CL)	370-490
D	Very hard deposits consisting of sandy gravels, sandy clay with few gravels (GW-GP-CL), NSPT	490-590
E	Stiff conglomerate with RQD 20% - 30%	800-1200
F	Marine clay	>800
G	Radiolarits and limestones	>1000
H	Limestone	>1200

Fig. 2. Geotechnical model of a roughly N-S section crossing the fault, as seen in section A-A’ of Fig. 1 and soil properties (adapted from Apostolidis et al. 2005). Downhole accelerometers are marked as red circles and surface accelerometers as black triangles.

THE AREA STUDIED

The area studied is the city of Aegion. It lies on the Southern part of the Gulf of Corinth, Greece (Fig. 1), one of the most active seismic areas in Europe, comprising many WNW-trending, north-dipping active normal faults. The city has been struck by significant earthquakes in the past, the strongest recent one being that of June 15, 1995 (Ms=6.2). The chosen region is a complex geological structure. It is traversed by the Aegion fault, whose escarpment of roughly 90 m divides the city into two levels: the lower Northern part lying on the hanging wall and the upper Southern part lying on the foot wall (Fig. 1). On the other hand, another characteristic feature of the site relates to the loose soft deposits present downhill, which form an open basin whose depth increases along with the sea depth.

After a series of field and laboratory tests, as well as borehole logging, geophysical prospecting and microtremor measurements, Apostolidis *et al.* (2005) modeled the complex geology of the site in sufficient detail and estimated the geotechnical and dynamic soil properties to a satisfactory degree. The model proposed by them can be seen in Fig. 2.

Two locations near this site are instrumented with broadband 3D accelerometers, marked in Fig. 1 as CORSSA and DIM. In the upper part of the city, a surface accelerometer is installed at the City Hall, or ‘Dimarhio’ (DIM), often referred to as OTE, the name of its location prior to 1996. This station lies on a 20m-thick layer of deposits overlying a stiff conglomerate base. The Corinth Soft Soil Array (CORSSA) lies at the lower part of the city, near the coast. It is a vertical array consisting of four accelerometers at depths of 14m, 31m, 57m and 178m, as well as a surface accelerometer. The soil profile there consists of deep, soft, loose marine materials overlying the hard conglomerate, which is found at a depth of 160m on this side of the fault. So the deepest accelerometer of the array lies within the rock and can be used as a reference station with respect to surface motion taking place in soil.

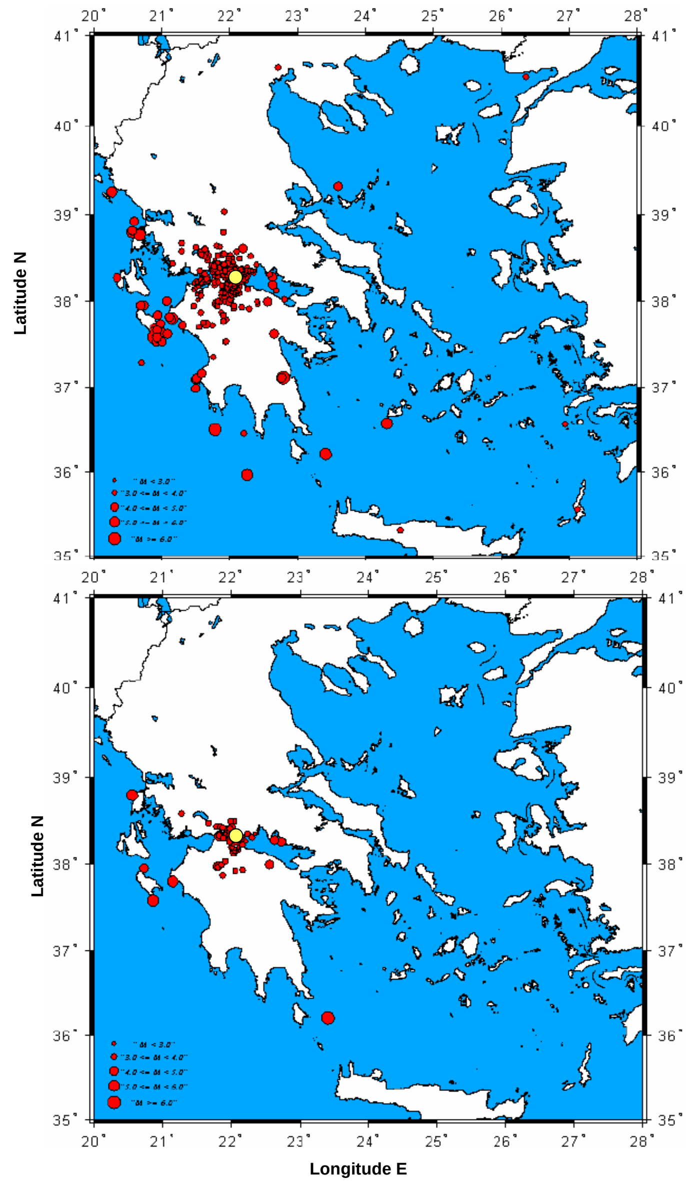


Fig. 3. Top: Epicenter distribution of the 473 events of Dataset1 (CORSSA). Bottom: Epicenter distribution of the 81 events of Dataset 2 (DIM). Epicenters are shown as red circles and the location of Aegion is shown as a yellow circle.

DATASETS

Two datasets are used in this study. Dataset 1 consists of 473 earthquakes recorded at all stations of CORSSA over a period of 6 years since the array began to operate in 2002 (Fig. 2a). From the five stations of the array, only records from the surface and deepest stations are used here. Dataset 2 consists of 81 earthquakes recorded simultaneously by the uphill surface station, DIM, and the reference station downhill during the same period (Fig. 2b). The events have local magnitudes between M2 and M6.5, epicentral distances up to 270 km, and focal depths down to 110 km. Event parameters were taken from the four major Greek earthquake catalogs (NOA, AUTH, NKUA, PSL). All records correspond to weak motion, since their peak ground acceleration is not higher than 0.02g.

The horizontal components of all records were rotated with respect to the orientation of the Aegion fault (roughly E-W), which is also the orientation the deposit-conglomerate interface defining the basin in the lower part of town. For the purposes of this study and in order to also account for site effects, the radial (fault-normal) and transverse (fault-parallel) components of motion will be studied.

DATA PROCESSING

Reference station

We intend to use the downhole station that lies at 178m w
the conglomerate as ‘bedrock’ reference, since no
outcrop station is available in the vicinity. For this reaso
need to assess whether the motion there can be considere
reference motion, i.e. we need to show that there is no st
destructive wave interference between the upgoing
downgoing wave fields at that depth (Steidl *et al.*, 1996).
way to investigate whether this condition applies i
calculate the horizontal-to-vertical spectral ratio (HVSR
the records of that station, as was done for example by Le
and Chávez-García (1993). If this ratio is relatively flat an
near-unit amplitude for the frequency range of interest,
the station is adequate for estimating site effects at c
stations based on its own motion. The average HVSR fo
473 events recorded at depth is shown in Fig. 4 for
horizontal components, radial and transverse. The ave
amplification over the frequencies of interest is betweer
and 1.6, which –given the uncertainty of average spe
ratios– can be considered as roughly equal to 1.0.

This justifies the use of downhole records at CORSSA as reference for the surface records of the same array. However, we will also use them as reference for the surface records at DIM. This we will do rather more tentatively, because DIM is located at some 400-500 m from CORSSA and within a complex geological context. However, this is not unheard of, since Steidl *et al.* (1996) mention that good downhole records can be used as reference even at distances as far as 20 km from the site they are taken from.

Peak ground motion at CORSSA

One way to study soil amplification is in the time domain, focusing on peak values, i.e. the zero-period value of the spectrum. This is the approach we use here, focusing on PGA and calculating certain peak response characteristics that are prescribed in design codes, in order to compare them later on. We compare the peak acceleration at each of the two surface stations with the peak acceleration at the downhole reference station (multiplied by 2 in order to account for the surface doubling effect that would take place if it were indeed an outcrop reference station) and estimate peak to peak ‘soil-to-outcrop’ amplification. The peak values at the surface of CORSSA station are shown in Fig. 5 for the two horizontals and for the vertical component. In all cases, surface versus bedrock values seem to follow a roughly linear trend. This was expected due to the very small amplitudes, indicating very small strain and purely linear behavior.

The peak amplification factors derived from each event in Dataset 1 are shown in Fig. 6, along with the average peak amplification factors per component, which were calculated through linear regression of the pairs plotted in Fig. 5. The average peak amplification is 2.6 for the transverse component and 2.25 for the radial one. We also note that the peak value of vertical component is amplified by an average factor of 1.9 in

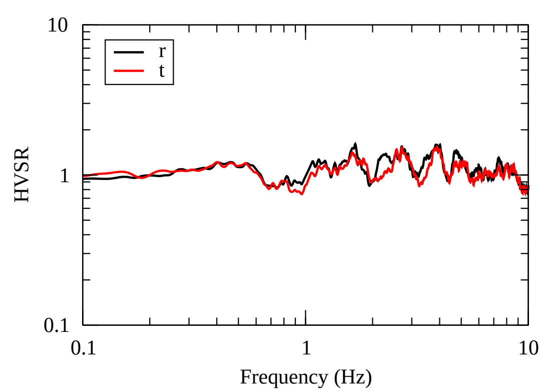


Fig. 4. Horizontal-to-vertical spectral ratio for the reference station of CORSSA array, at 178m depth from the surface, within the stiff conglomerate. Amplification is roughly unit.

Peak ground motion at DIM

The peak values at DIM station for the three components are shown in Fig. 8. Again, we have very small PGA values, indicating completely linear behavior. The peak amplification factors derived from each event of Dataset 2 along with the average amplification factor calculated for each component through linear regression are shown in Fig. 9. The average peak amplification is 2.55 for the transverse component and

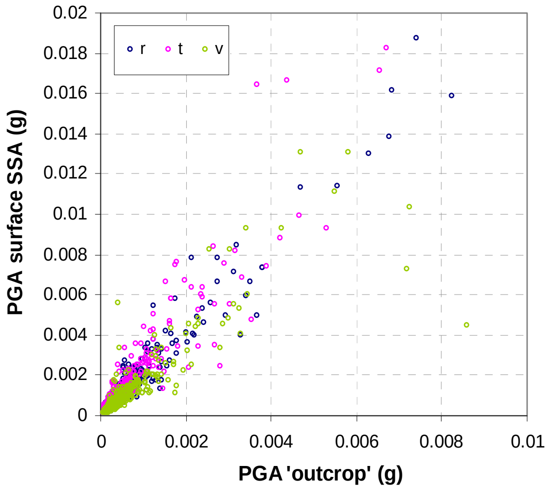


*Fig. 5. Peak ground acceleration at the surface of CORSSA with respect to peak "outcrop" (=2*downhole) acceleration for the two horizontal components, radial and transverse, and for the vertical component.*

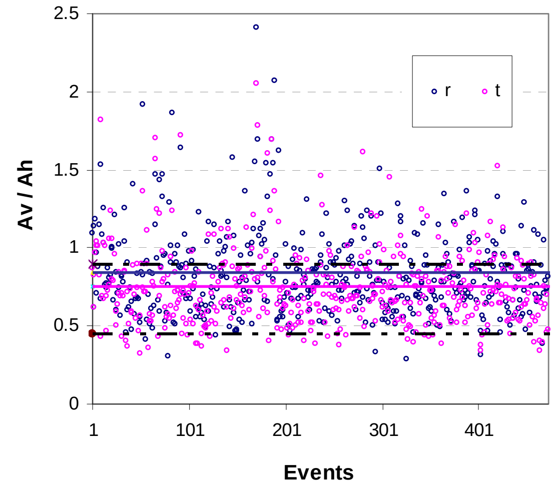


Fig. 7. Ratios of peak vertical to peak horizontal acceleration at the surface of CORSSA for the radial and transverse components. The average values are also drawn (solid lines), as well as the values prescribed by EC8 for spectrum types 1 and 2 (dot-dashed and dot-dot-dashed line).

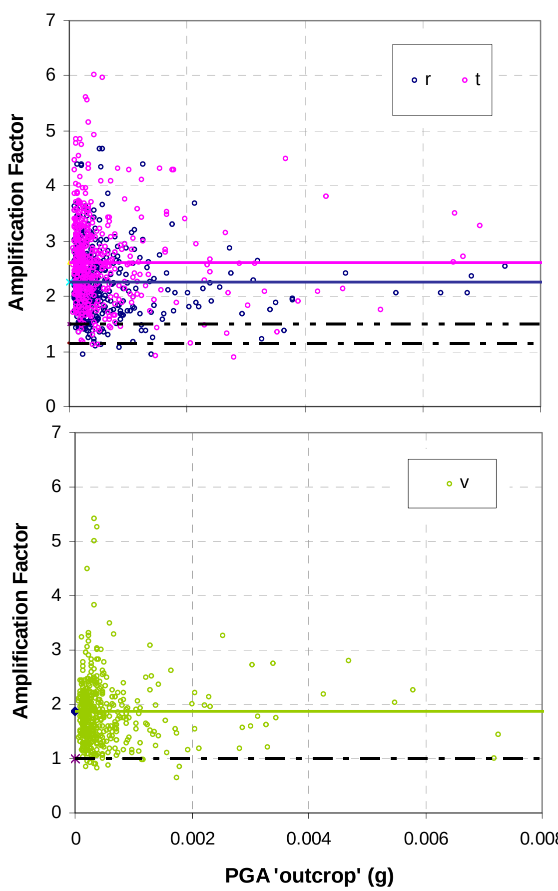


Fig. 6. Peak to peak amplification factor at the surface of CORSSA with respect to peak "outcrop" acceleration: a. for the two horizontal components, radial and transverse b. for the vertical component. The average values are also drawn (solid lines), as well as the value prescribed by EC8 for spectrum types 1 and 2 (dot-dashed and dot-dot-dashed line).

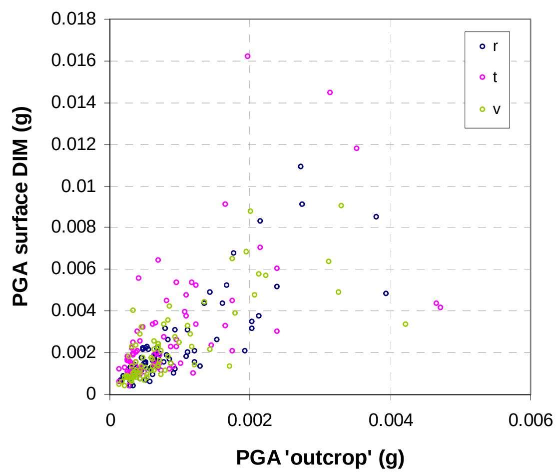


Fig. 8. Peak ground acceleration at DIM with respect to peak "outcrop" acceleration for the radial, transverse, and vertical component.

2.35 for the radial. We also note that the vertical component is amplified by 2.2 on average in the time domain.

We calculate the ratio between the peak vertical and the peak horizontal acceleration, which is on average 1.11 and 0.89 for the radial and transverse component respectively (Fig. 10).

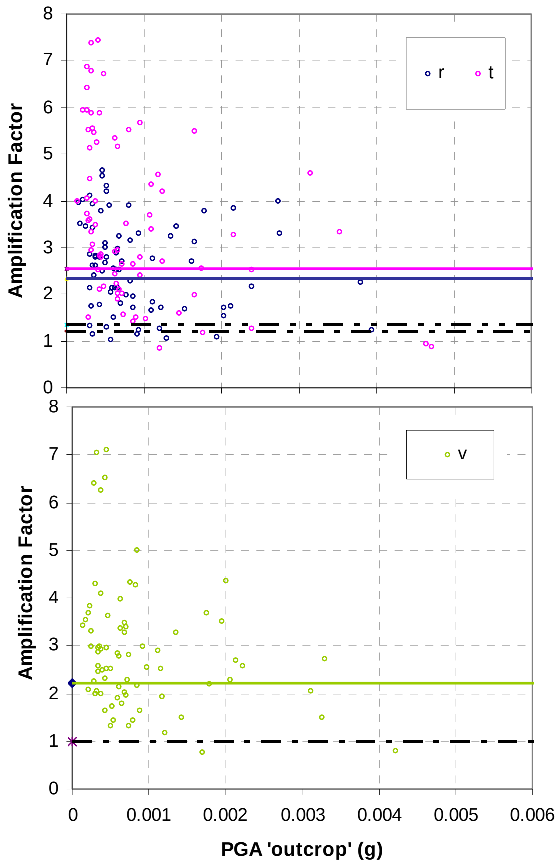


Fig. 9. Peak to peak amplification factor at DIM with respect to peak "outcrop" acceleration: a. for the two horizontal components, radial and transverse b. for the vertical component. The average values are drawn (solid lines), as well as the value prescribed by EC8 for spectrum types 1 and 2 (dot-dashed and dot-dot-dashed line).

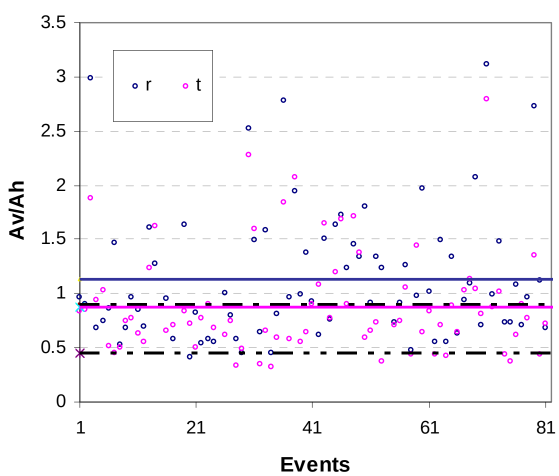


Fig. 10. Ratios of peak vertical to peak horizontal acceleration at DIM for the two horizontal components, radial and transverse. The average values are also drawn (solid lines), as well as the values prescribed by EC8 for spectrum types 1 and 2 (dot-dashed and dot-dot-dashed line).

COMPARISON WITH CODE PRESCRIPTIONS

Soil effects in codes

We searched for design codes that include a separate factor to account for soil effects on peak ground motion, i.e. for zero period. In many codes, soil effects are only accounted for at longer periods (T>0), while peak amplification (T=0) depends merely on the zonation and not the soil class; we found this to be the case with the Mexican code, the Turkish code, and the Greek code. We worked with the two codes which we found to include such a factor: the Eurocode and the USA code.

Eurocode: EC8

Brief outline of EC8 provisions. In Greece, EC8 (CEN, 2003) came into force on December 31, 2008 in the form of a temporary recommendation by law. In Part 1, for the purpose of calculating seismic actions on structures, soil effects are taken into account based on soil types. Five types (A through E, A being rock) are defined according to V_{s30} (average Vs in the first 30 m), N_{SPT} blow count, and undrained strength Cu, and two extra specific types are defined. Seismic zones and the respective ground accelerations are defined by each country's national code. The elastic response spectrum for design depends on the ground type and the ground acceleration for the specific zone.

If deep geology is not accounted for, then there is a third factor, the type of spectrum. Two types of spectra are defined. According to EC8, "if the earthquakes that contribute most to the seismic hazard defined for the site for the purpose of probabilistic hazard assessment have a surface-wave magnitude, Ms, not greater than 5.5, then it is recommended that the Type 2 spectrum is adopted". Type 1, which extends to longer periods, is used if the hazard is judged to be due mostly to events with Ms>5.5.

For the horizontal components of motion, soil effects at zero period are described in EC8 by the soil factor, S. S depends on ground type and spectrum type. For the vertical component, the zero-period spectral value is a fraction of the horizontal one: $S_v=a_{vg}.S$, where a_{vg}=90% for spectrum Type 1 and a_{vg}=45% for spectrum Type 2.

Application to Aegion. Spectrum type 1 is recommended by Greek legislation. However, only 7 out of 473 events in Dataset 1 have Ms>5.5, and only 4 out of 81 events of Dataset 2. Furthermore, these few events do not cause high PGA values at the sites (less than 0.01g, and these are not even the highest PGAs from within the datasets). For this reason, we also use the Type 2 spectrum in this study to account for the rest of the events, whose magnitude is smaller.

In Aegion, the ground profile at CORSSA is characterized by an average shear wave velocity of V_{s30}=200 m/s, which is between 180-360 m/s, which corresponds to soil type C according to EC8. Also, the average SPT blow count is N_{SPT30}=22, which is between 15-50, which again yields type C. Finally, the undrained strength measured at a depth of 40 m is Cu=80 kPa, which is between 70-250 kPa, the range of values defined for type C. So CORSSA can be considered as a type C site (deep deposits with a thickness of of tens or hundreds of meters). The soil factor for this site classification is S=1.15 for spectrum Type 1 and S=1.50 for Type 2.

The ground profile at DIM has an average V_{s30}=550 m/s. This is between 360-800 m/s, corresponding to soil type B. Also, the average SPT blow count for the first 20 m of soil above the conglomerate is N_{SPT20}=45, so this would most probably lead to N_{SPT30}>50, which applies to type B sites. We should note here that DIM cannot be considered as type E (i.e., 5-20 m of C- or D-type alluvium overlying stiff A-type material), because the 20 m of topsoil present actually belong to type B. So the profile here belongs to type B. The soil factor for this site classification is S=1.20 for spectrum Type 1 and S=1.35 for Type 2.

Comparison with records. For the case of CORSSA, Fig. 6 shows that the amplification factor calculated for most of the events in Dataset 1 is higher than the value prescribed by EC8, irrespective of the spectral type used, for horizontal and vertical components. Actually, looking at the distribution of the results, the values given by EC8 (especially for Type 1 spectrum) seem to define a lower boundary for our results. Regarding the relation between horizontal and vertical peak amplification, Fig. 7 shows that use of the Type 1 spectrum roughly predicts the average value calculated for the A_v/A_h ratio, while use of the Type 2 spectrum again yields a lower boundary. The same observations can be made for the uphill station, DIM, when looking at Dataset 2 in Fig. 9. Tables 1, 2, and 3 show comparisons between the results derived from Datasets 1 and 2 and the prescriptions of EC8 for soil classes C and B respectively.

Table 1. EC8 soil factor S_h vs. peak horizontal amplification from records

S_h	EC8		Regression	
	Type 1	Type 2	r	t
CORSSA	1.15	1.50	2.25	2.60
DIM	1.20	1.35	2.3 5	2.55

Table 2. EC8 soil factor S_v vs. peak vertical amplification from records

S_v	EC8	Regression
CORSSA	1.00	1.90
DIM	1.00	2.20

Table 3. EC8 ratio of soil factors S_v/S_h vs. ratio of peak amplifications from records

$a_{vg}=S_v/S_h$	EC8		Regression	
	Type 1	Type 2	r	t
CORSSA	0.90	0.45	0.84	0.76
DIM	0.90	0.45	1.11	0.89

USA code: FEMA450

Brief outline of FEMA450 provisions. Similarly to EC8, FEMA 450 (BSSC, 2003) defines five ground types (A through E) according to V_{s30}, N_{SPT}, and Cu, along with a sixth special site category. Seismic zones and the respective ground accelerations are also defined. The elastic response spectrum for design depends on site classification and on the ground acceleration for the specific zone at 0.2 s and 1 s periods.

For the horizontal components of motion, soil effects at short periods (between zero and T_o) are described by the site coefficient for short periods, F_a. F_a depends on ground type and on S_s, i.e. the spectral acceleration corresponding to 0.2 s based on the mapped maximum considered earthquake.

Application to Aegion. In order to compare the site coefficient F_a of FEMA450 with the soil factor S of EC8, we need to assume the value of S_s. The Greek Seismic Code (OASP, 2001) defines the ground acceleration in the region of Aegion (zone 2) as 0.24g. For comparison at zero period we may consider this as equivalent to S_s=0.25.

The ground profile at CORSSA has V_{s30} between 180-360 m/s, N_{SPT30} between 15-50 and Cu between 50-100 kPa, so the site is classified by FEMA450 as type D. Assuming S_s=0.25, this yields F_a =1.6.

The ground profile at DIM has an average V_{s30} between 360-760 m/s and N_{SPT30}>50, so it is considered type C. This yields F_a =1.20.

Comparison with EC8 and records. For the case of CORSSA, the FEMA F_a coefficient is higher than the S factors of EC8, but looking at the distribution in Fig. 6 it still seems closer to being a lower boundary than an average. Regarding DIM station, F_a coincides with the lower of the two S values (spectrum type 1), and hence gives a lower limit for the amplification as depicted in Fig. 9. If we had made any other assumption as to the value of S_s (i.e., if we had chosen a higher ground acceleration), the F_a coefficients would have been still lower.

Table 4. EC8 soil factor S vs. FEMA450 site coefficient F_a

	EC8		FEMA450
	Type 1	Type 2	
CORSSA	1.15	1.50	1.60
DIM	1.20	1.35	1.20

COMPARISON WITH THEORETICAL RESULTS

Numerical modeling

In some previous work (Ktenidou *et al.*, 2009), the site was modelled numerically based on the cross-section of Fig. 2. Dynamic 2D analyses were performed using two different finite difference schemes. The first one was the P-SV code FLAC 2D (Itasca, 2002) and the second one was the SH code elaborated by Moczo (1989) and Moczo and Bard (1993). Synthetic time histories at locations in the model corresponding to the locations of the accelerometers were among the results obtained from these analyses. The peak values of these traces are used here.

Based on the cross-section, the direction that is perpendicular to the fault and to the basin edge (approximately N-S) corresponds to the radial component of the instrumental data and to the SV direction of wave propagation in the first numerical model. Similarly, the direction parallel to the fault corresponds to the transverse component of the records and the SH direction of wave propagation in the second model. So this is the way we will compare the instrumental results to the numerical ones in the horizontal sense (codes, of course, do not distinguish between the two horizontal components).

We cannot draw any conclusions as to the vertical component of motion from the numerical analysis because the incident motion for both schemes was a vertically propagating horizontal pulse (SV or SH) and no vertical motion was inserted into the models. Only in the first numerical scheme was vertical 'parasitic' motion generated, as a result of P-SV interaction.

Comparison of theoretical results with records

The peak amplification calculated for the two sites using the two codes is shown in Table 5, in comparison with the results from the regression of Datasets 1 and 2. The amplification of the transverse component is larger than that of the radial one, particularly at CORSSA. This instrumental result is reproduced by the numerical analysis results. Some comments on this observation are given in Ktenidou *et al.* (2009).

For CORSSA, the amplification values calculated from the 2D analysis are quite similar to those based on Dataset 1. So if no records were available at this site, numerical analysis could have roughly predicted the peak amplification and it would have been quite higher than what is prescribed by the two codes (up to 60-80% higher than the S factor for EC8 Type 2 spectra). On the other hand, amplification calculated numerically for DIM is around 65% of what was calculated based on the records. Even so, numerical predictions are still higher than code prescriptions (10-20% higher than the S factor for EC2 Type 2 spectra).

Table 5. Numerical vs. instrumental peak horizontal amplification

	Regression		2D analysis	
	r	t	SV	SH
CORSSA	2.25	2.60	2.21	2.80
DIM	2.35	2.55	1.50	1.67

SOIL LINEARITY AND APPLICABILITY OF RESULTS

Up to now we have worked with peak values in the time domain, which correspond to a spectral period of zero. Although the PGA values of our datasets are very small (lower than 0.02g for both sites, which would not infer any actual hazard), we believe it is theoretically justified to use our amplification factors as representative of the amplification in the entire small-strain region, based on the assumption of linear elasticity and on the sheer volume of the datasets (particularly at CORSSA). Due to the very small amplitude of the records, it is certain that soil behavior is purely linear and free of any damping increase or stiffness degradation. Although there is no consensus as to exactly when non-linear effects begin to take place (e.g. Dickenson and Seed 1996 found that for soils similar to the ones we study here, non-linearity might occur for rock PGA values of around 0.2 to 0.3g), it is certain that the linear range spans much more than the small range studied here.

So the amplification results derived here could be extrapolated to higher PGA values (say 0.15g, though this could be subject to debate) as long as linear elasticity holds. Such PGA values, although low enough not to cause soil non-linearity, could however be high enough to represent the entire hazard in terms of expected ground acceleration at several sites. For example, while Aegion lies in zone 2 according to the Greek Seismic Code, with a suggested PGA of 0.24g which might imply a chance of non-linearity, on the other hand, many locations in Greece (including Athens and many important cities) lie in zone 1, whose suggested PGA is 0.16g and could fall within our linear range of study. Irrespective of seismic zoning, the soil amplification factor (S) in EC8 only depends on site classification. So the findings of this study could be relevant for other sites and zones as well, as long as the site type is comparable (B and C for DIM and CORSSA respectively). For sites in zone 1, we can assume that linear amplification is all that they will probably ever know; so it is of some interest that for site types B and C this amplification may be greatly underestimated by EC8 at zero period. For sites in zones 2 and 3, which are seismically more active, our results would only pertain to relatively low PGA values for which soil response would remain linear.

Results from numerical analysis

Due to the complex geological features present in the site we studied, we also look at the extent to which the stations used are influenced by site effects. We use results from the numerical analysis previously performed by Ktenidou et al. (2009). Figure 11 shows the peak ground motion estimated across the profile using the two numerical schemes: SH (transverse) and SV (radial).

Uphill, the soil profile is roughly constant over some hundreds of meters from the crest and the only possible source of additional site effects is the surface topography. It is known that sites in the vicinity of slope or hill crests are affected by the relief (see Geli *et al.* 1988 for a review). In this case however, the topographic amplification for horizontal components in terms of peak values is observed at distances smaller than 100 m from the crest of the Aegion fault (Fig. 11, top). So we can consider the motion at DIM, which is at 250 m from the crest, as relatively unaffected. Thus, the horizontal amplification factors we estimated at DIM can be attributed to a great extent to 1D soil layer effects (even if we were to take topography effects into account, based on EC8 the amplification factor -additional to soil layering- would be no more than 1.1 for the geometry at hand).

CORSSA, on the other hand, lies at about 250 m from the slope toe. The soil layering is not horizontal and the thickness of the layers varies with the distance from the toe. The motion there cannot be considered free from site effects, as there is a complex wave field with locally generated, laterally propagating surface waves due to the basin edge and all the lateral discontinuities. The numerical analyses showed that peak ground motion varies up to 500 m from the toe, and there is differential motion and amplification due to 2D phenomena (Fig. 11, bottom). However, it was also shown that the peak horizontal ground motion amplitude in the time domain corresponds to the direct S arrival and not to the later phases that contain mostly surface waves. So it is not so much the peak horizontal amplification that is affected by complex site effects, but rather the spectral amplification at longer periods, as will be seen in the next section. This does not apply to the vertical component, whose amplification is most probably related to complex 2D effects and namely diffracted Rayleigh waves.

Results from spectral ratio calculation

It has been mentioned that single values such as PGA are not adequate for describing ground motion in the presence of site effects (Chávez-García and Faccioli 2000, Raptakis et al. 2004). For this reason, after having focused on zero-period spectral values, we also look at the response spectra over the entire range of periods.

We calculated the five-percentile damped elastic response spectra for the two horizontal components of all surface records in Datasets 1 and 2. In terms of absolute values, all response spectra we computed are well within the design spectra defined by any code, due to the very small amplitude of motion. However, we normalized these results with respect to each component's PGA value and compared them to the normalized design spectra (Figs. 12 and 13) in order to discuss site effects taking place at Aegion, rather than code adequacy. We discussed codes at zero period, using soil linearity to extrapolate amplification results to larger PGA values.

The spectral shapes seen in Fig. 12 are quite typical of what is expected when site effects take place. The spectral ordinates for periods longer than the corner period Tc (roughly 0.6 s) are quite high. This cannot be interpretation based on near-field or directivity effects because, as seen in Fig. 3, the epicentral distances are on the whole not small enough. So we consider this as an indication of the existence of strong surface waves, particularly noticeable around the site's fundamental period (roughly 1.1 s). This corroborates the numerical results pointing to site effects at CORSSA. We can further observe that spectral values for the transverse component are higher than for the radial, especially near the fundamental period. This was also observed in the SSR ratios and numerical transfer functions calculated by Ktenidou *et al.* 2009, while there was no sign of it in the HVSR at 178 m (Fig. 4). Thus we can say that the response spectra, which generally include source, path, and site effects, in this case give strong indications of site effects, since they agree with techniques that isolate them.

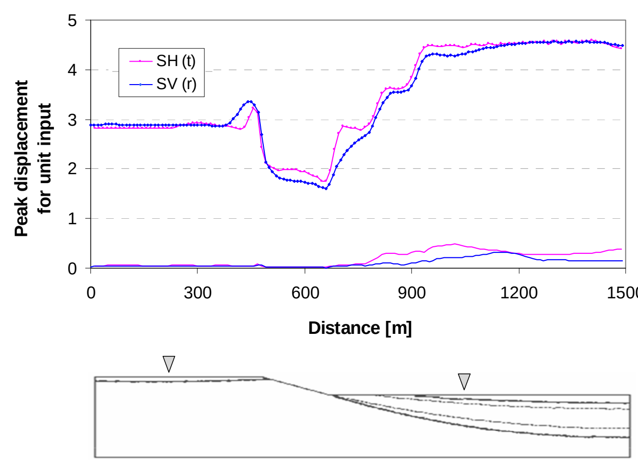


Fig. 11. Peak values of displacement corresponding to unit input amplitude along the cross section, as calculated by the two numerical schemes, SH (transverse) and SV (radial).Top: translational. Bottom: differential.

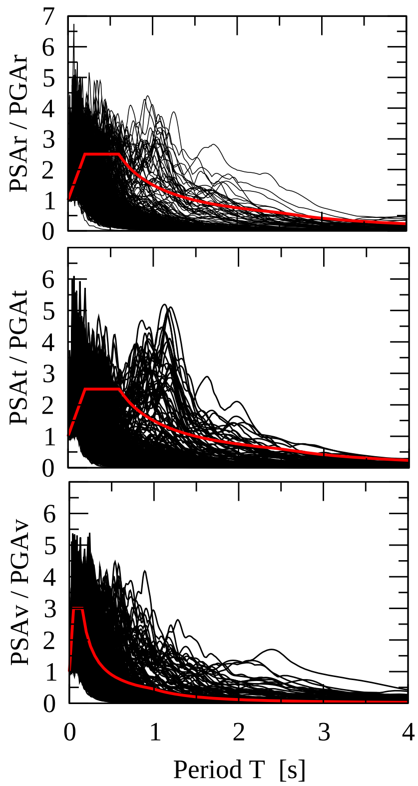


Fig. 12. Response spectra for the radial and transverse component, normalized by PGA and calculated with 5% damping a. for Dataset 1(CORSSA).The respective normalized design spectra according to EC8 are shown in red.

On the other hand, the spectral shapes seen in Fig. 13 do not indicate strong site effects at DIM. Only a few spectra do not reduce to very low values for periods longer than 0.5 s. In fact, these spectra correspond to events that have epicentral distances larger than 100 km and magnitudes larger than 5.0, which would be expected to carry energy at low frequencies, namely surface waves from the source.

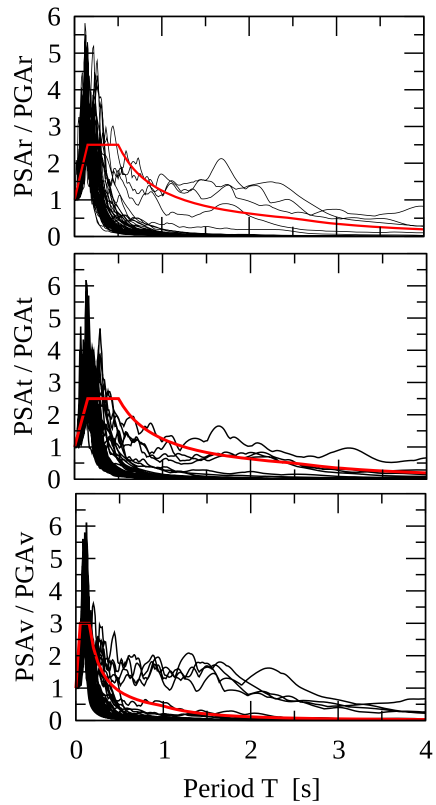


Fig. 13. Response spectra for the radial and transverse component, normalized by PGA and calculated with 5% damping for Dataset 2 (DIM). The respective normalized design spectra according to EC8 are shown in red.

CONCLUSIONS

Two relatively large datasets are used to estimate peak soil-to-outcrop amplification in the time domain through linear regression of their PGA values for the two sites under study; CORSSA, a relatively soft soil site, and DIM, a relatively stiff soil site. Although the PGA values of our records are much lower than any typical hazard assessment values, we view our results as indicative of the entire small-strain range and -due to the very small amplitudes- as free of any stiffness degradation or damping increase. Thus we proceed to compare the soil amplification factor derived with that suggested (at zero period) by design codes, namely EC8 and FEMA450, based on site classification. Compared with the peak horizontal values calculated for the datasets, code provisions seem more like lower boundaries than predictions of the average. Regarding the vertical component, it is implicit in both codes that it is not amplified, while both datasets show a two-fold amplification in its peak value. This means that there is some room for discussion concerning the soil factor as defined by codes for these soil classes.

Given the complex geology of Aegion, we also investigate whether the results are influenced by the surface or subsurface topographic features present. At zero period we use results from some previous finite difference analyses. According to the numerical analyses, complex 2D phenomena are present in the region. However, the peak horizontal amplitude at DIM and CORSSA is not affected by them to a great extent, so our results for the horizontal component may indeed be attributed, at least for the most part, to 1D amplification due to soil layering. Peak amplification of the vertical component, however, cannot be assumed independent of site effects. Since peak values are not always adequate to describe site effects, we also look at the response over the entire period range. While the elastic response spectra for the two horizontal components of all events used are well within the limits imposed by the code design spectra, we normalized them as to PGA and compared them to the normalized design spectra in the context of discussing site effects. Spectral shapes do not infer strong site effects at DIM, but they do so for CORSSA, where they indicate strong surface waves due to 2D phenomena that are particularly noticeable around the site's fundamental period, in agreement with previous numerical results.

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