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Effects of site geology on the attenuation of macroseismic intensity in Central Greece

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The contribution of different categories of local geological conditions to the observed macroseismic intensities in Central Greece is investigated. The method is developed using two large earthquakes in the Halmyros Basin, Central Greece. The main parameters of the earthquakes chosen are : 1957 March 8, 6.8 M_S and 1980 July 9, 6.2 M_S , both near Volos-Halmyros. They were both shallow earthquakes, with maximum observed intensities of IX+ and VIII+ respectively , while the available macroseismic and surface geological information comes from about 230 and 570 sites respectively . There are five main surface geological categories, in which the data can be classified. Differences between, and recent revisions of, intensity scales are considered in order to eliminate possible over- or under-estimates of intensity and to obtain an homogeneous intensity data set.

Attenuation laws are derived using both earthquakes and they are compared to determine the attenuation factors appropriate for different rock types. They are also tested for different azimuths from the macroseismic epicentre in order to asses the influence of the radiation pattern of the earthquake in relation to the degree of attenuation in a specific direction. The comparison of the detailed intensity results with strong motion data from the same area and in different geological formations, indicates that there is some relation between them.

Utjecaj lokalnih geoloških svojstava na prigušenje makroseizmičkog intenziteta u središnjoj Grčkoj

Proučavan je utjecaj različith kategorija lokalnih geoloških svojstava na opažene makroseizmičke intenzitete u središnjoj Grčkoj. Postupak je razvijen koristeći podatke za dva velika potresa (8. ožujka 1957, M_S = 6.8 i 9. srpnja 1980, M_S = 6.2) koji su se dogodili u središnjoj Grčkoj u oblasti Volos-Halmyros. Oba su bili plitki potresi maksimalnih opaženih intenziteta IX+, odnosno VIII+. Raspolagali smo makroseizmičkim podacima i podacima o lokalnim uvjetima tla s 230 odnosno 570 lokacija. Podaci se prema površinskim geološkim uvjetima mogu podijeliti u pet glavnih kategorija. U obzir su uzete i razlike među ljestvicama intenziteta, kao i njihove nedavne preinake, kako bi se uklonile mogućnosti precjenjivanja ili potcjenjivanja intenziteta, a skup podataka učinio homogenim.

Izvedene zakonitosti prigušenja akceleracije su međusobno uspoređene kako bi se odredili faktori prigušenja različitih vrsta stijena. Testirana je i azimutalna ovisnost radi usporedbe utjecaja smjera pomaka u žarištu potresa sa stupnjem prigušenja u određenom smjeru. Usporedba detaljnih makroseizmičkih rezultata i podataka o akceleracijama iz istog područja pokazuje da među njima postoji određena zavisnost.

1. Introduction

For seismic hazard analysis, once a causative fault or a radiated tectonic province has been identified and a corresponding design earthquake has been associated with it, the problem is to determine the ground motion at several sites, resulting from the occurence of such an earthquake. The result of the related ground motion is damages to engineering structures, which are known to depend on the following four factors : the earthquake source parameters, the material properties of the earth media along the various paths through which the seismic waves travel, the local geological conditions of the site under consideration and the structure itself. The characteristics of ground shaking that are of major interest to engineers for design purposes are : its frequency composition, the level of strong ground motion (intensity, acceleration, etc.) and its total duration.

The complicated nature of the earthquake source mechanism, the highly irregular structure of the earth's mantle and crust, and the difficulty in making reliable measurments, make it hard to find the relative influences on the ground motion. For these reasons the different deeper geological layers, which correspond to different velocities of seismic waves, are considered to have a secondary importance in this study, whereas the surface local geological conditions, classified in five main categories, are considered to contribute to the different amplification of intensities.

The intensity of an earthquake, as a seismic parameter, has been widely used by the seismologists because of its ability to describe the degree of damage caused by an earthquake, rather than its accuracy. Furthermore, isoseismal maps have been frequently used for deriving intensity attenuation laws.

In the present study the attenuation of intensity is approached by using the actual observed intensities at specific sites, without taking into consideration any smoothing procedure of the isoseismal technique. In such a way we are able to take into account irregularities that could not be "seen" in a smoothed isoseismal map.

Thus, starting from intensity attenuation law of the general form (Chandra, 1979)

$$I - I_o = a + b\,R + c\,\log R$$

we study the behaviour of a group of sites, having similar surface characteristics, and various attenuation coefficients a_i are derived.

In addition to this, and in order to examine the influence ot the type of focal mechanism into the intensity attenuation law, the distribution of intensities across and perpendicularly to the probable earthquake faulting is taken into account for each geological category.

Finally, since for the first time there are strong motion records available from the area under study, we take the opportunity to compare the recorded acceleration to the expected intensity at three different geological formations.

2. Methodology

The empirical attenuation relations published in recent papers (Evernden 1975-1976, Gupta and Nuttli 1976, Chandra 1979) are of the form

$$I(R) - I_o = a_i + b_i R + c_i \log R \tag{1}$$

where $I(R)$ is the intensity at a distance R from the epicentre of an earthquake of epicentral intensity I_o, a_i the attenuation factor, and b_i and c_i constants.

The application of such a formula for different local geological conditions, produces various factors a_i, which show the rate of the decay of intensity in different ground conditions. For this procedure we applied a regression analysis computer program in order to estimate these coefficients.

The same technique, when applied across or perpendicularly to a fault, provides new attenuation factors, which prove that the attenuation of intensity is azimuthally independent in the area under study. Detailed studies of near-field attenuation laws have shown that the coefficients a_i, which correspond to the above two directions respectively, are identical.

3. Data

In the present study we considered two main earthquakes with epicentres located in the area of Volos-Halmyros, both caused by active faults, having an almost E-W orientation, few kilometers south of Volos town. The parameters of the studied earthquakes are presented in Table 1.

The macroseismic data of the first event were derived by using a local version of MM ; thus we should note that high intensities might be underestimated in com-

Table 1. Parameters of the studied earthquakes

Year	*Month*	*Day*	*Origin*	*Lat*	*Lon*	*Depth*	M_s	I_o
1957	MAR	08	12:21:18.7	39.34	22.66	6	6.8	9.5
1980	JUL	09	02:11:57.3	39.29	22.91	9	6.2	8.5

parison with MSK. This was especially studied by Shebalin(1969) using the method of relation of successive isoseismal surfaces. His results were reexamined for the Greek version of MM scale on the basis of the original description. The differences between the two scales do not exceed 0.5°. For computational reasons, intensities of a value VII-VIII or VII+, for example, have been taken as 7.5, in both cases. It must also be underlined that the manner of the buildings' structure has been dramatically changed through the period of occurrence of these two events.

Table 2. Classification of geological categories.

Type of Surface Formation	Geological Category	Velocity of *P* waves (km/sec)
Alluvial deposits, fans valley deposits	G_1	1.0-2.0
Flysch	G_2	2.0-3.0
Neogene of undivided formation	G_3	1.8-3.6
Limestones	G_4	3.2-5.5
Metamorphic rocks	G_5	4.8-5.0

Each site of observation was treated as a point on a map, by measuring its acurate latitude and longitude from the topographical maps of Greece (scale 1:50000), and its distance from the epicentre was computed. Then the specific local surface geological conditions for all sites were taken from the geological maps of Greece (scale 1:50000). For sites with more than one geological condition, such as big cities, we considered the softer ground, as the ground corresponding to the reported intensity. The different geological categories that are common at the study area and for which there are many macroseismic data, are classified in Table 2, according to their hardness and in increasing order of their P-wave velocities. From now on, we are going to use the abreviated geological form G1, G2, ..., G5, as defined in Table 2.

On April 30, 1985, a strong earthquake of magnitude M_S 5.5 occurred in the same area, and the accelerations at the near-field sites were recorded. The epicentre of this earthquake as well as the sites of the SMA1 strong motion instruments are indicated in the map of Figure 1. These instruments have been installed at different soil conditions in order to study the amplification factor, i. e. the influence of the local soil to the level of acceleration. Details for the soil conditions at the SMA1 sites are described in Table 3.

Table 3. Description of the soil conditions at the SMA-1 sites.

Name of SMA-1 site and soil category	Description of soils
G_A Almyros	Quaternary deposits of small thickness pleio-pleistocene dilluvimum (not more than 140 m thickness), neogene deposits, bedrock (limestone-schists) at about 700 m.
G_B Nea-Anchialos	Pleio-pleiostocene dilluvium (red formations, 150-160 m thickness), neogene formations with some coal elements (150-200 m thickness), bedrock (limestones-schists).
G_C Nea-Anchialos Air-base	Thick alluvium (100 m thickness). Possibly some old dilluvium formations with marl elements, bedrock (ophiolites).

4. Application of the method

The procedure of regression analysis for each geological category was based on formula (1), which has been widely used worldwide (Chandra, 1979) and in Greece especially (Drakopoulos 1983, Stamelou 1985). The results for the coefficients a_i, b_i, c_i as well as the correlation coefficient cc, and standard error of estimate, SE, are shown in Table 4. It must be emphasised that the method was applied first for each event independently, and then we combine both events. In Figures 2-4 the attenuation laws for all the geological conditions are presented for each event individually and for the combination of the two events, while in Figures 5-6 the existing isoseismal maps are presented.

Focal mechanism studies in the area under consideration have shown that the stress field is tensional with normal faulting. The azimuths of the tensional stress is in a N-S orientation and the faults are systematically oriented in an E-W direction (Drakopoulos, Delibasis 1982).

Errata corrige !

In the course of composing the paper : Kouskouna V., Makropoulos K., Drakopoulos J. and Burton P.: Effects of site geology on the attenuation of macroseismic intensity in Central Greece, Table 4 has been dropped out. Please insert it after page 53 of this Volume of "Geofizika".

Table 4. Results of the application of the multiple regression analysis method. a_i, b_i, c_i are the regression coefficients, cc the correlation coefficient, SE the standard error of estimate of $I-I_o$, and No. of obs. the number of observations.

Event	Geology	a_i	b_i	c_i	cc	S.E.	No. of obs.
1	G1	+2.86	-0.01	-3.29	0.9	0.94	121
1	G2	+3.21	0.00	-3.55	0.9	0.88	15
1	G3	+8.09	+0.02	-7.58	0.9	0.86	15
1	G4	+6.30	+0.01	-6.10	0.9	0.76	13
1	G5	+1.27	-0.02	-1.90	0.8	0.77	63
2	G1	-0.82	-0.01	-1.90	0.8	0.81	338
2	G2	11.34	+0.01	-8.01	0.8	0.51	58
2	G3	+8.33	+0.01	-6.99	0.8	0.72	47
2	G4	+5.95	0.00	-5.25	0.8	0.67	51
2	G5	/	/	/	/	/	10
1,2	G1	+1.28	-0.01	-2.21	0.8	1.21	459
1,2	G2	+2.19	-0.01	-2.38	0.8	0.76	73
1,2	G3	+7.02	+0.01	-6.31	0.8	0.81	62
1,2	G4	+5.02	0.00	-4.85	0.8	0.87	64
1,2	G5	-0.98	-0.02	-0.63	0.7	0.80	73

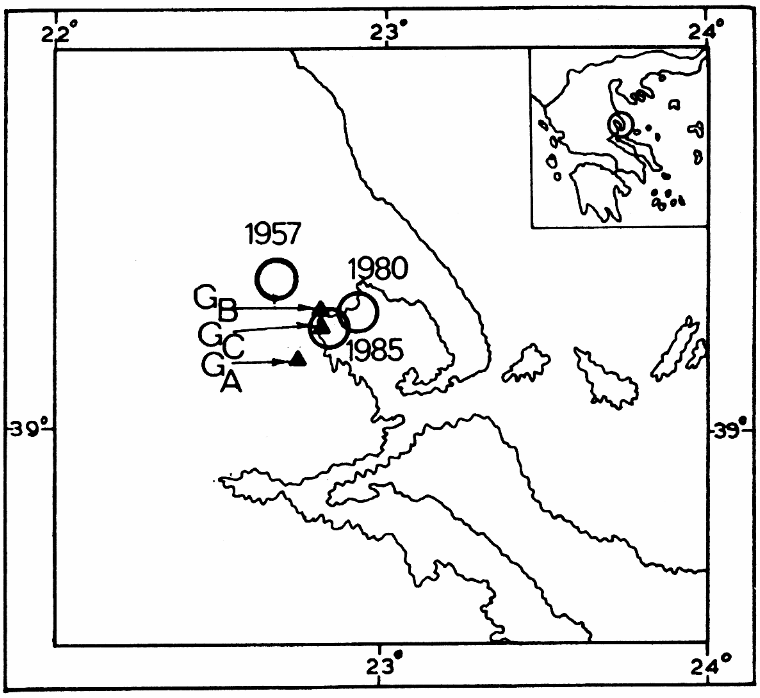

Figure 1. Epicentres of the earthquakes and SMA-1 strong motion instruments sites in the area of Volos-Halmyros.

The above procedure was applied in the two main E-W and N-S directions, i. e. across and perpendicularly to the causative faulting. The results, however, have shown that there was not any difference from our previous results.

As mentioned previously, the earthquake of 30 April 1985 was recorded at three sites (Figure 1). The measured accelerations, the corresponding periods, the abbreviated forms of the soil conditions and the epicentral distances have been tabulated in Table 5.

The next step is to compare the reported intensities of this earthquake at the above three sites with calculated ones from the regression analysis procedure, and the recorded accelerations to the ones obtained from the general formula applied in Greece,

$$a = 2164\, e^{0.7m}(R+20)^{-1.8} \qquad (\mathrm{cm/sec^2}) \qquad (2)$$

where R is hypocentral distance in km. These comparisons are also illustrated in Table 5.

Table 5. Comparison of the reported intensities to the calculated ones by the two methods.

Site	Geology	Orientation	Comp	Dist. (km)	Acc. obs. (g)	Acc. cal. (g)	I_{obs}	$I_{cal.}$
Almyros	G_A	E45S	L	7.4	0.177	0.262	V+	5.3
			T		0.116			
Nea Anchialos	G_B	N60W	L	4.8	0.137	0.314	VI	5.7
			T		0.093			
Air Base	G_C	N50E	L	4.7	0.228	0.316	VI	5.7
			T		0.263			

It must be mentioned here that the existing empirical relations for transformation of acceleration to intensity, are based mainly on higher levels of intensities. Thus, in our case it was difficult to adopt such an empirical formula valid for small excitation levels.

5. Discussion and conclusions

It is evident from Table 3 that larger values of the attenuation coefficient a_i are systemically observed in cases of hard rocks, while smaller values are related to the softer ones. The values of b_i are, as expected, small and of the same order, independently of the excitation level (magnitude of the earthquake) and of the surface soil conditions. There is a clear tendency that the absolute values of c_i are larger in cases of hardsoils, in comparison with the softer ones. Thus we can conclude that in hard soils, the attenuation in near-field distances is more abrupt. Although there is a clear scattering in our data, as it is indicated in Figures 2-4, the large correlation coefficients presented in Table 3, confirm that our results are noteworthy. However, we beleive that if we had at our disposal ground water tables for all sites, the scattering in the intensity data would be smaller and the study of attenuation of intensities for a certain geological category, would be more representative. From the above figures it can be concluded that there is an entirely different attenuation law for various geological categories.

A limitation to our work is that we have detailed set of sites of observations only from two events, and the period between these two earthquakes is rather long. More reliable results can be obtained by using a large number of macroseismic data from earthquakes of the same area during this period of time. Since there are other factors governing the macroseismic distribution, it is difficult to study the influence of the surface soil separately, so we suggest that further work is needed in this direction.

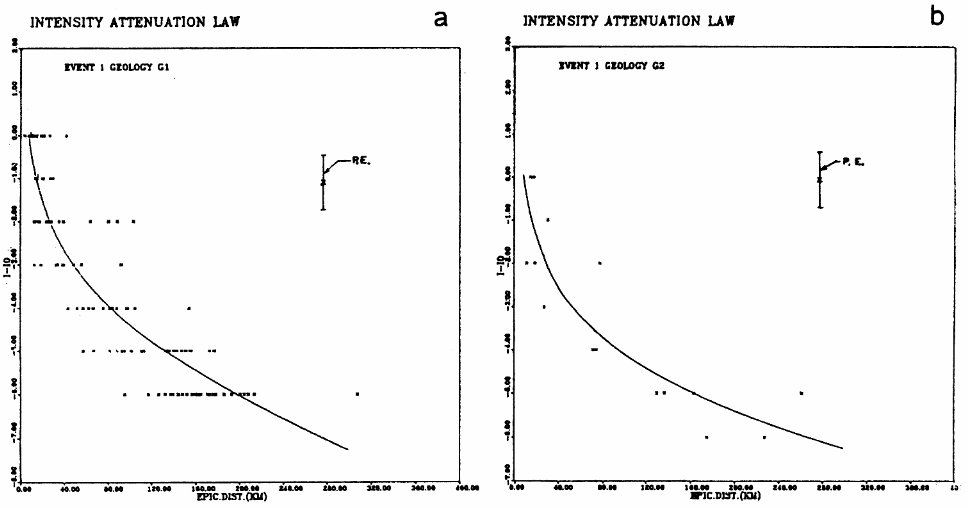

Figure 2a. Attenuation curve I-I_0 versus epicentral distance (D in km) for the earthquake of March 1957 and for geology G1 (see Table 2). The probable error, PE, is $2/3\sigma_{I-I_0}$.
b) Attenuation curve for geology G2

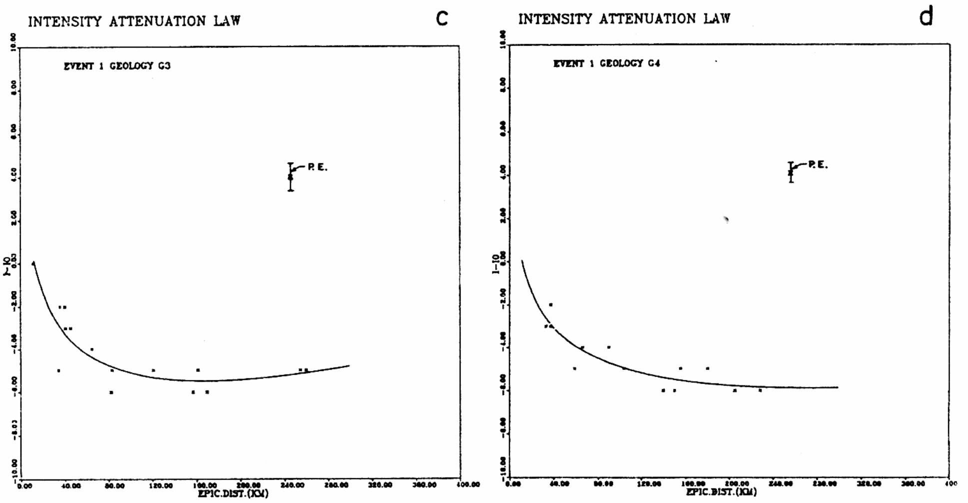

Figure 2c,d. Attenuation curve for geologies G3 and G4 (see also Figure 2a,b)

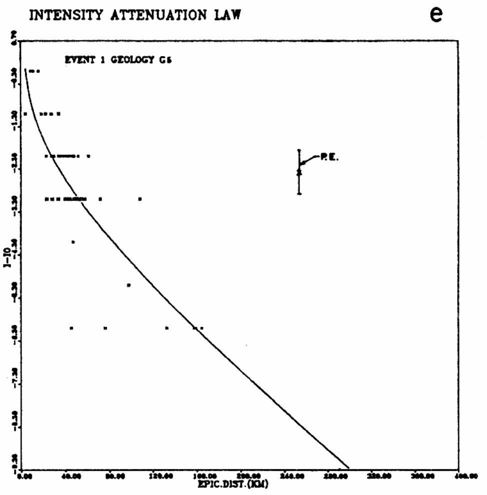

Figure 2e. Attenuation curve for geology G5 (see also Figure 2a,b)

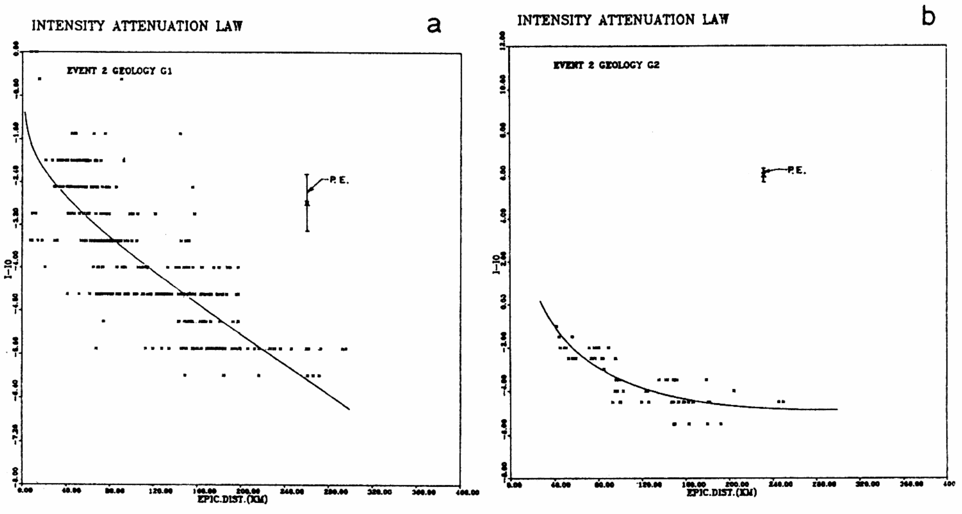

Figure 3a. Attenuation curve I-I_o versus epicentral distance (D in km) for the earthquake of July 1980 and for geology G1 (see Table 2). The probable error, PE, is $2/3\sigma_{I\text{-}I_o}$.

b) Attenuation curve for geology G2

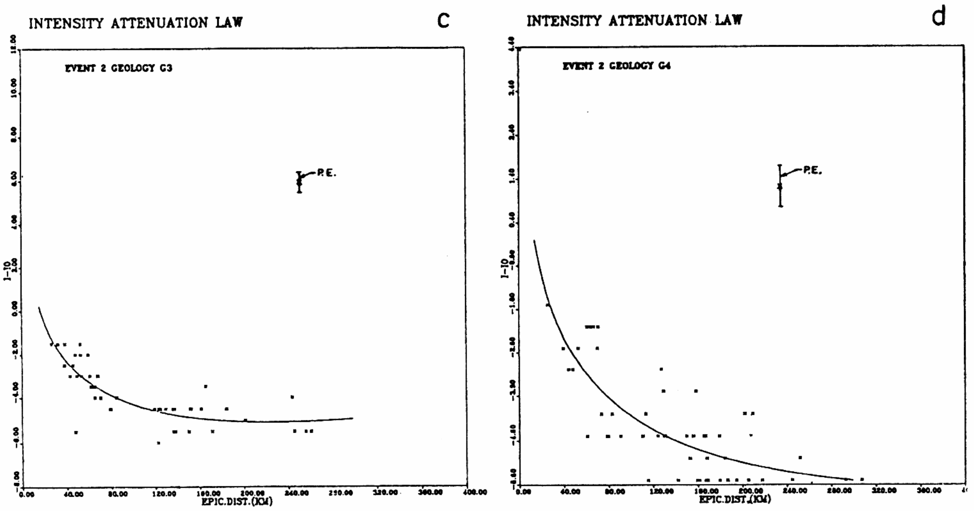

Figure 3c, d.Attenuation curve for geologies G3 and G4 (see Figure 3a, b)

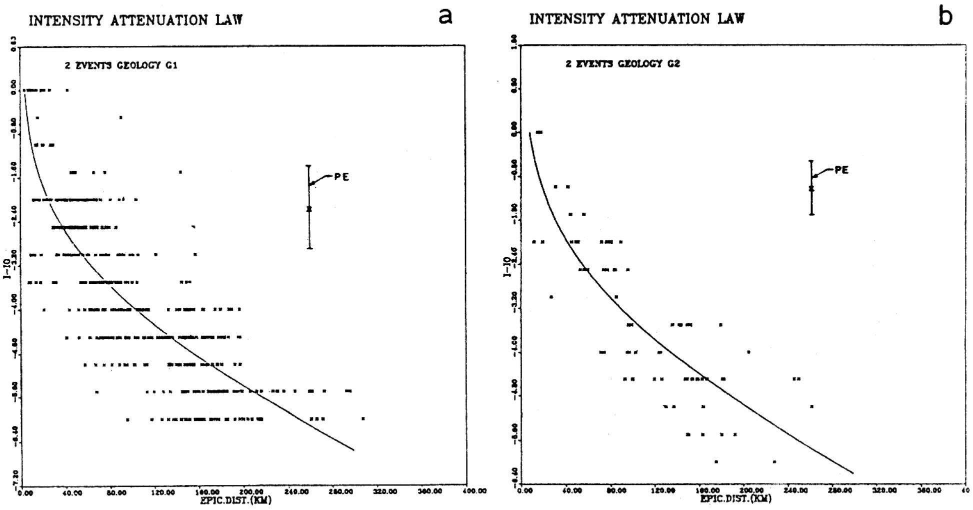

Figure 4a. Attenuation curve I-I_o versus epicentral distance (D in km) for the combination of two earthquakes and for geology G1 (see Table 2). The probable error , PE, is $2/3\sigma_{I-I_o}$.
b) Attenuation curve for geology G2

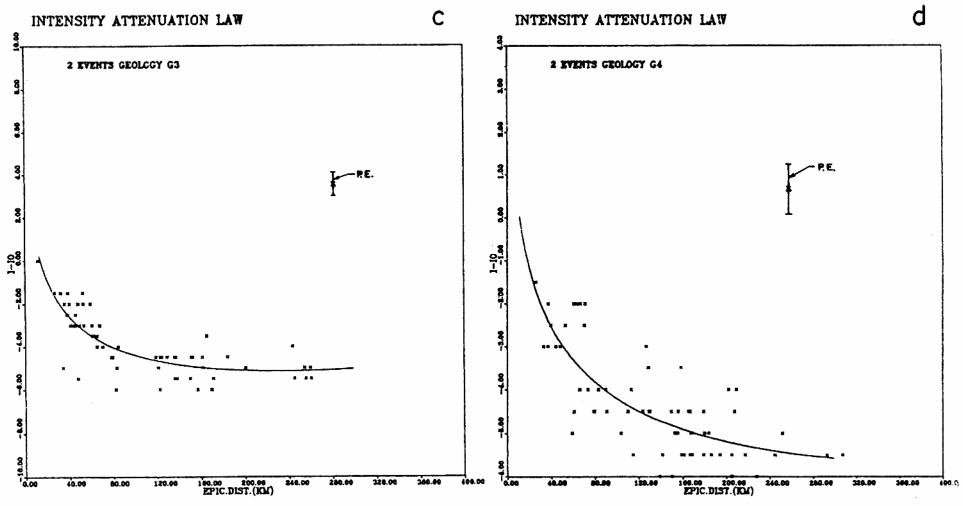

Figure 4c,d. Attenuation curve for geologies G3 and G4 (see Figure 4a).

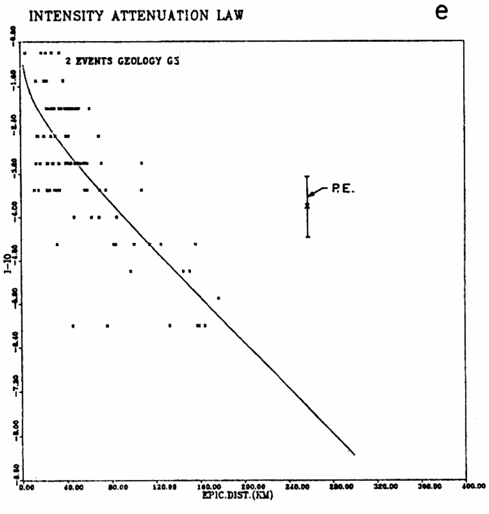

Figure 4e. Attenuation curve for geology G5 (see Figure 4a)

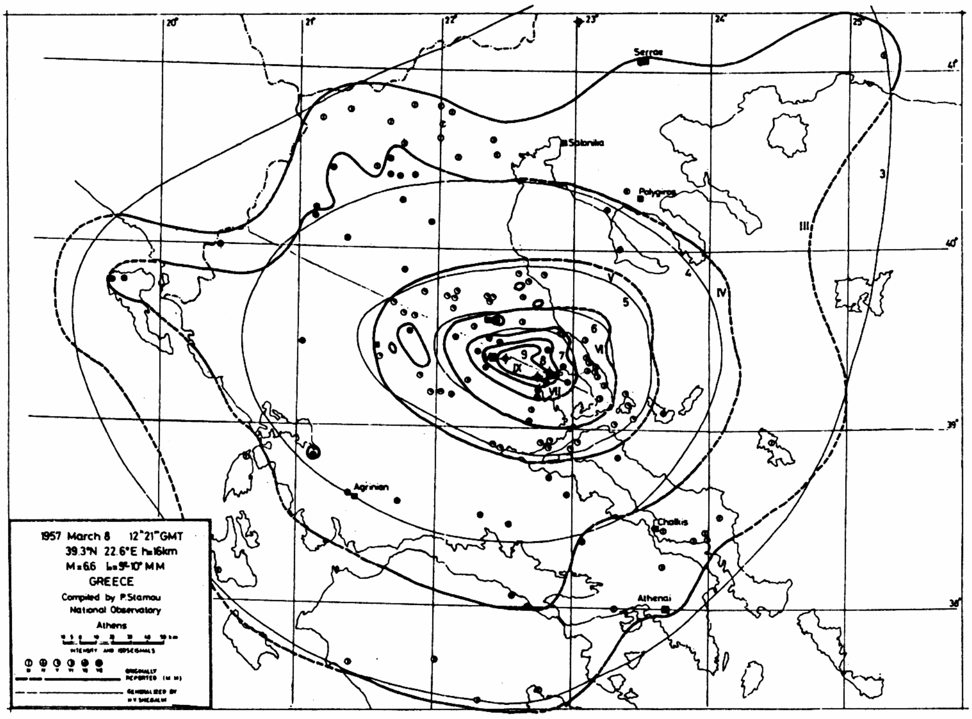

Figure 5. Isoseismal map of the 1957 March 8, main shock

From the attenuation laws in two main directions (E-W and N-S), i. e. across and perpendicularly to the supposed faulting and for the same geological categories, it can be concluded that the focal mechanism in those cases was not a governing factor for the distribution of the macroseismic intensities. This is also supported by the fact that the shape of isoseismal maps of earthquakes from the area under study, is not systematically elongated to one direction, but of a rather cyclic type.

It is clear from Table 5 that the estimated intensities at the sites of the strong motion instrument SMA-1, using the regression analysis results derived in this study, are in good agreement with the reported intensities at the same sites.

Using different empirical formulas for the relation between acceleration and intensity, which are based on a limited number of strong motion data in Greece, it was found that for our level of intensities, the agreement is not satisfactory. But we

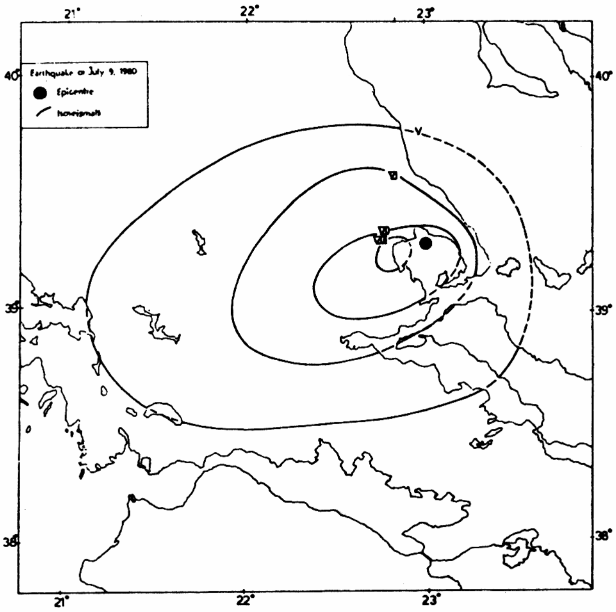

Figure 6. Isoseismal map of the 1980 July 9, main shock

can support the idea that the frequency components of these accelerations at different sites and the form of the response spectra are influenced by the nature of the soil conditions of the sites, which means that they change in a consistent fashion, depending on the rigidity of the soil formation. However, it must be emphasized that the level of acceleration will be clearly related to the soil conditions of the recording site when the characteristics of the various spectra are assessed. This has also been noted in many recent related studies.

Summarizing, it is suggested by this study that higher intensities apparently are correlated with areas of deeper alluvial fill, in comparison with harder rocks.

Such studies, in which a large variations of informations must be combined, are helpfull in bringing the problems involved in earthquake damages into a better focus.

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