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SEISMIC HAZARD ASSESSMENT IN GREECE IN TERMS OF SPECTRAL VALUES

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ABSTRACT

Seismic hazard in Greece, to date, has been assessed in terms of macroseismic intensity, peak ground acceleration and velocity. Design spectra were then determined by scaling standard spectral shapes to the design values of the ground motion parameters. In order to overcome disadvantages incorporated in the "standard spectral shape" methodology, regression analyses directly on response spectral values have been performed utilizing both strong motion records from shallow earthquakes in Greece and suitable records from intermediate depth subduction earthquakes. The resulting attenuation relations are used directly in seismic hazard analysis for the assessment of uniform hazard response spectra. It is intended that seismic hazard parameters expressed directly in terms of spectral values, as well as careful consideration of both shallow and intermediate depth earthquake hazard contribution, will form the basis for developing more realistic design values in the seismic code of Greece.

INTRODUCTION

Seismic hazard in Greece has been assessed by many investigators in terms of macroseismic intensity (Papaioannou 1984,1988, Papaioannou et al. 1985, Papazachos et al. 1985,1993) or in terms of peak ground acceleration and velocity (Macropoulos 1978, Dracopoulos and Macropoulos 1983, Papaioannou 1984, Macropoulos and Burton 1985, Papazachos et al. 1993). From the suggested seismic hazard maps one could easily estimate the distribution of the seismic zone coefficient over the country and then compute seismic horizontal base shear from common seismic design formulas.

The new seismic code provisions in Greece (NEAK 1992) for the computation of the lateral-force coefficient, ε_h , follows the formula,

$$\varepsilon_h=\varepsilon_o\gamma_n\frac{\beta(T)}{q}\theta \qquad (1)$$

where ε_o is the expected "effective" acceleration during the design period considered, γ_n the importance factor, $\beta(T)$ the spectral coefficient dependent on building's natural period, q the quality factor of the building and θ the foundation factor. It is clear that the adoption of one or another spectral shape for a certain region in Greece can significantly change the final values

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of the lateral-force coefficient.

The conventional way for arriving at spectral coefficients is the adoption of standard spectral shapes, independent of earthquake magnitude and source distance, which are mainly based on strong motion data from western United States. Until recently efforts to predict response values, peak acceleration, or any strong motion parameter for that matter, were handicapped by the scarcity of strong motion data in Greece. The development and operation of a strong motion network throughout the country during the last decade, enabled us to acquire a significant number of strong motion records from shallow earthquakes in Greece (Anagnostopoulos et al. 1985, Anagnostopoulos et al. 1987) capable of producing attenuation relations (Theodulidis and Papazachos 1992,1994) as well as spectral acceleration amplification factors. Due to lack of strong motion data from intermediate depth subduction earthquakes in Greece, relevant data have been gathered from other regions of the world with similar seismotectonic characteristics and appropriate attenuation relations have been also defined (Theodulidis and Papazachos 1990).

In this paper, spectral acceleration amplification factors for two soil conditions, namely "rock" and "alluvium", based mainly on data from shallow earthquakes in Greece are defined. Furthermore, utilizing a recently proposed source model in Greece (Papazachos 1992) and the above mentioned attenuation relations, expected peak ground accelerations and uniform hazard acceleration response spectra are assessed for 11 sites almost uniformly distributed over Greece. Some important differences in spatial change of spectral shape are pinpointed. Expected spectral values are also assessed for these sites based on expected peak ground accelerations and spectral acceleration amplification factors. These spectral values are compared with those of uniform hazard spectra and the resulting differences are discussed.

METHOD APPLIED AND DATA USED

The method adopted for seismic hazard analysis was that of Cornell (1968). According to this method, using all the available seismological, seismotectonic and geological data, the region under study is divided into seismic sources. Within every individual source the occurrence of future events is considered to be equally probable at any location. For each source, the rate of occurrence of events above a chosen threshold, the seismic parameter b of the frequency-magnitude relation as well as the maximum earthquake magnitude that can occur, are estimated. Then, with the aid of attenuation relations between a dependent strong motion parameter (macroseismic intensity, peak ground acceleration etc.) and the independent magnitude-distance, the total probability, that a certain level of this strong motion parameter is to be exceeded at a site, is estimated. Calculations have been made by using an appropriate computer code, namely the EQRISK (McGuire 1976). Some minor modifications have been performed in this code allowing for the incorporation of individual attenuation relation for every seismic source. Thus, the problem of simultaneous contribution to seismic risk at a site from both shallow and intermediate depth subduction earthquakes is overcome.

Calculations in the EQRISK code can be represented in the most basic form by the "total probability theorem" (McGuire 1976):

$$P\{A\}=\iint P\{A/s \text{ and } r\} f_S(s) f_R(r)\, ds\, dr \qquad (2)$$

where P idicates probability, A is the event whose probability is sought and represents the event that a specific value of ground motion intensity is exceeded at the site of interest during an earthquake. S and R are continuous, independent random variables which influence A and represent earthquake size and distance from the site of interest.

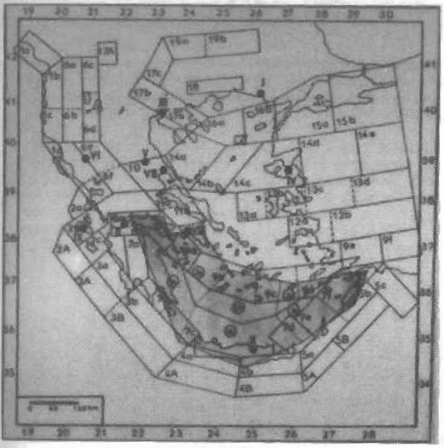

Fig. 1: Shallow (1a,...,19b) and intermediate depth (1a,b,c, 2a,b,c in open circles over the shadowed zones) seismic sources in Greece and surrounding area (Papazachos 1990,1991). Black circles (I,..., XI) denote the sites where seismic hazard has been assessed.

For the calculation of spectral acceleration amplification factors a subset of the strong motion data used in a previous paper (Theodulidis and Papazachos 1992) has been used. This data subset consists of 18 horizontal components recorded on "rock" and 38 horizontal components on "alluvium", obtained from earthquakes with surface wave magnitude Ms from 5.5 to 7.5 and epicentral distances between 9km and 236 Km.

As an intermediate depth subduction source model the one proposed by Papazachos(1990) consisting of 6 sources was used, while shallow source model the one proposed by the same investigator (Papazachos 1992) consisting of 68 sources was adopted (fig. 1). In tables 1,2 the parameters necessary in seismic hazard analysis are given for every individual source of shallow and intermediate depth earthquakes, respectively. The a,b are parameters of the frequency-magnitude (Gutenberg-Richter) relation, r is the annual rate of events with M>=5.0 and Mmax the maximum magnitude of the seismic source.

As an attenuation model for peak ground acceleration, a_g , the following relations for shallow and intermediate depth subduction earthquakes, respectively, were used (Theodulidis and Papazachos 1990,1992),

$$\ln a_g=3.88+1.12Ms-1.65\ln(R_{ep}+15)+0.41S \qquad (3)$$

$$\ln a_g=3.47+0.75Mw-0.85\ln R_{CER}+0.27S \qquad (4)$$

where Ms is surface wave magnitude and Mw moment magnitude, R_{ep} epicentral and R_{CER} from the center of energy release distances and S a binary variable which takes values 1 for "rock" and 0 for "alluvium".

For the attenuation of pseudovelocity, PSV(T), the appropriate scaling coefficients C1(T), C2(T), C3(T) and C4(T) of the formula,

$$\ln PSV(T)=C1(T) + C2(T)M + C3(T)\ln(R+R0) + C4(T)S \qquad (5)$$

were used, where R0 is equal to 15 for shallow and equals to 0 for intermediate depth subduction earthquakes. In tables 3 and 4 these scaling coefficients, at certain period values used in seismic hazard assessment and damping D=0.05, for shallow and intermediate depth earthquakes, respectively, are given (Theodulidis and Papazachos 1990,1994)

RESULTS

The resulting mean spectral acceleration amplification factors and the one standard deviation are given in table 5 and figure (2). The maximum

Table 1: Parameters of the 68 seismic sources of the shallow earthquakes (fig. 1) in Greece and surrounding area.

Source	S(*)	a	b	r	Mmax	Source	S(*)	a	b	r	Mmax
1a	0.65	4.77	1.0	0.59	7.1	1b	0.50	4.58	1.0	0.38	6.4
1c	0.40	4.50	1.0	0.32	6.5	1d	0.69	4.70	1.0	0.50	6.4
1e	0.35	4.48	1.0	0.30	6.4	2a	0.25	4.68	1.0	0.48	7.0
2b	0.55	5.15	1.0	1.41	7.2	2c	0.37	4.77	1.0	0.59	7.0
2A	0.55	4.99	1.0	0.98	6.5	3a	0.58	4.73	1.0	0.54	7.5
3b	0.98	4.43	1.0	0.27	7.1	3A	0.65	4.41	1.0	0.25	6.5
3B	1.16	4.69	1.0	0.49	6.5	4a	0.66	4.77	1.0	0.59	7.2
4b	0.71	4.50	1.0	0.32	7.2	4A	0.96	4.78	1.0	0.60	7.0
4B	0.80	4.58	1.0	0.38	6.5	5a	0.58	4.65	1.0	0.45	7.1
5b	0.42	3.94	1.0	0.09	7.2	5c	0.76	4.63	1.0	0.43	7.2
5A	0.47	4.46	1.0	0.29	6.5	5B	0.58	4.60	1.0	0.40	6.5
6a	0.62	4.53	1.0	0.34	6.5	6b	0.41	4.29	1.0	0.19	6.5
6c	0.36	3.09	0.8	0.12	6.5	6d	0.50	3.46	0.8	0.29	6.7
6e	0.51	3.19	0.8	0.15	6.5	6f	0.46	3.21	0.8	0.16	6.5
7a	0.56	3.89	0.9	0.25	6.4	7b	0.36	3.48	0.9	0.10	6.4
7c	0.41	3.68	0.9	0.15	6.4	7d	0.58	3.57	0.8	0.37	6.5
7e	0.52	3.18	0.8	0.15	6.5	7f	0.83	3.32	0.8	0.21	6.8
8a	0.30	4.38	1.0	0.24	6.6	8b	0.30	4.56	1.0	0.36	7.0
8c	0.43	4.63	1.0	0.43	6.7	9a	0.43	4.03	1.0	0.11	6.7
9b	1.18	3.93	1.0	0.09	6.5	9c	0.80	3.43	0.8	0.27	7.5
9d	0.71	3.98	0.9	0.30	7.0	9e	0.65	3.93	0.9	0.27	6.8
9f	0.63	3.78	0.9	0.19	6.8	10	0.82	3.87	0.8	0.74	7.0
11a	0.42	3.58	0.9	0.12	7.0	11b	0.39	3.93	0.9	0.27	6.8
12a	0.84	4.07	0.9	0.37	6.9	12b	1.68	4.18	0.9	0.48	7.0
13a	0.52	3.77	0.9	0.19	6.4	13b	0.72	4.00	0.9	0.32	6.8
13c	0.88	3.88	0.9	0.24	6.8	13d	0.11	3.74	0.9	0.17	6.7
14a	1.11	3.64	0.8	0.44	7.0	14b	0.94	3.59	0.8	0.39	7.1
14c	1.73	3.74	0.8	0.55	7.2	14d	1.71	3.50	0.8	0.32	6.4
14e	1.41	3.78	0.8	0.60	7.1	15a	1.81	3.07	0.7	0.37	7.7
15b	2.41	3.01	0.7	0.32	7.6	16a	0.76	2.92	0.7	0.26	7.5
16b	0.76	2.84	0.7	0.22	6.7	17a	0.64	3.01	0.7	0.32	7.0
17b	0.45	2.51	0.7	0.10	6.8	17c	0.43	2.86	0.7	0.23	7.7
17A	0.28	2.34	0.7	0.07	6.4	18	0.44	2.42	0.7	0.08	7.3
19a	0.51	2.34	0.7	0.07	7.0	19b	0.71	2.47	0.7	0.09	7.0
BS(**)	20.9	2.46	0.8	0.03	6.0						

(*)Surface X10.000 km^2 (**)Background seismicity

Table 2: Parameters of the 6 seismic sources of intermediate depth aerthquakes (fig. 1) in southern Aegean.

Source	S(*)	a	b	r	Mmax	Source	S(*)	a	b	r	Mmax
1a	3.46	2.33	0.56	0.34	7.9	1b	3.15	2.43	0.56	0.43	8.2
1c	1.33	2.26	0.56	0.29	8.0	2a	1.15	2.85	0.75	0.13	7.1
2b	1.89	3.00	0.75	0.18	7.1	2c	0.51	2.53	0.75	0.06	7.1

(*)Surface X10.000 km^2

value of the mean factor on "rock" is equal to 3.45 at T=0.15 sec, while on "alluvium" is equal to 2.46 at T=0.30 sec. In figure (3) the distribution of the data used to derive the attenuation relation (3), in a magnitude-

Table 3: Scaling coefficient of the attenuation relation(4), for damping D=0.05, for shallow events.

T(sec)	C1(T)	C2(T)	C3(T)	C4(T)
0.05	-0.706	1.149	-1.732	0.551
0.10	0.464	1.129	-1.751	0.668
0.15	0.881	1.182	-1.776	0.760
0.20	1.217	1.090	-1.591	0.432
0.30	1.460	1.148	-1.636	-0.086
0.50	0.466	1.368	-1.674	-0.458
0.75	0.021	1.534	-1.830	-0.683
1.00	-0.696	1.684	-1.910	-0.843
2.00	-3.137	2.114	-2.121	-0.989
3.00	-3.693	2.173	-2.151	-0.971

Table 4: Scaling coefficient of the attenuation relation(4), for damping D=0.05, for intermediate depth subduction events.

T(sec)	C1(T)	C2(T)	C3(T)	C4(T)
0.05	-1.032	0.694	-0.778	0.309
0.10	0.315	0.657	-0.822	0.263
0.15	0.814	0.652	-0.805	0.228
0.20	0.826	0.644	-0.697	0.110
0.30	0.661	0.681	-0.634	-0.052
0.50	0.280	1.014	-0.991	-0.187
0.75	-1.250	1.267	-0.997	-0.334
1.00	-1.961	1.309	-0.885	-0.442
2.00	-4.223	1.077	-0.209	-0.577
3.00	-4.906	1.204	-0.350	-0.495

distance space is shown. For the calculation of the spectral acceleration amplification factors of figure (2) only the recordings with magnitude greater or equal to 5.5 were used.

Estimates of 5%-damped uniform hazard horizontal acceleration response spectra for 11 Greek cities (numbered in fig. 1), using the previously mentioned seismic sources and attenuation models as input into the probabilistic analysis, are given in figure (4). These spectra are referred to "rock" and "alluvium" soil conditions and to mean return period, Tm =475 years.

In table 6, the expected horizontal peak ground accelerations for the 11 Greek cities , for various mean return periods, Tm , on "rock" and on "alluvium", are given. By using the expected peak ground acceleration for Tm =475 years and the mean spectral acceleration amplification factors of table 5, the "standard spectral shape" response spectra for the 11 cities were estimated.

DISCUSSION AND CONCLUSIONS

Spectral acceleration amplification factors proposed in this study (fig. 2) are based on two categories of soil classification. Certainly, this classification requires more refinement after the enrichement of the relevant data bank. On the other hand,

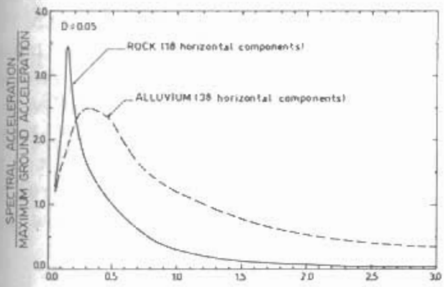

Fig. 2: Spectral acceleration amplification factors proposed for the area of Greece.

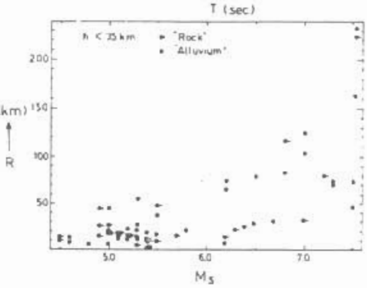

Fig. 3: Distribution of strong motion data used for the estimation of the relations (2),(3),(4) (Theodulidis and Papazachos 1992).

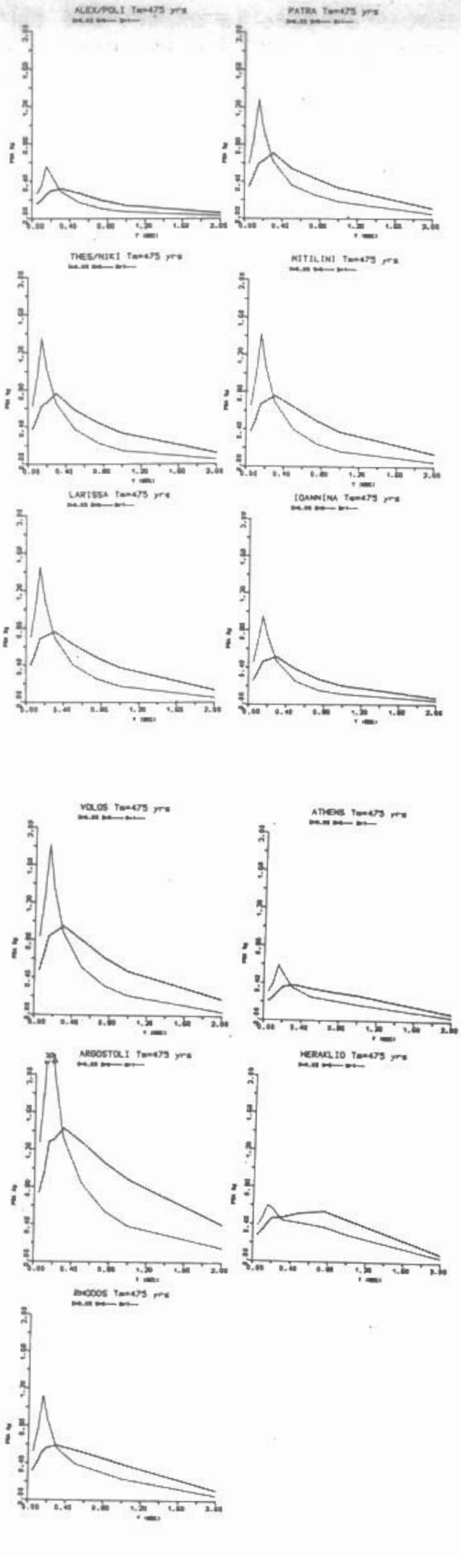

Table 5: Mean and mean +1 standard deviation spectral acceleration amplification factors (PSA/a_g) in Greece, for critical damping D=0.05.

	"Rock"		"Alluvium"	
T(sec)	Mean	1 SD	Mean	1 SD
0.05	1.29	0.18	1.13	0.20
0.10	2.00	0.51	1.60	0.54
0.15	3.45	0.86	1.84	0.48
0.20	2.64	0.81	2.23	0.65
0.30	1.61	0.76	2.46	0.66
0.50	1.03	0.60	2.28	0.95
0.75	0.52	0.35	1.55	0.77
1.00	0.28	0.19	1.21	0.73
2.00	0.07	0.05	0.54	0.58
3.00	0.03	0.02	0.34	0.53

classifying accelerograms into the two corresponding groups has enabled us to carry out a crude, but simple, test of the possible effects of local site conditions on the amplitudes of the recorded strong ground motion (Theodulidis and Papazachos 1992). The relatively higher spectral acceleration amplification factors proposed in this study, 3.5 on "rock" at periods around 0.15 sec in comparison with those of Seed et al.(1976),2.5, may be due to various characteristics (source spectrum, attenuation path, site effects) of strong motion in Greece. In order to quantify the influence of each individual factor, further research based on better documented data is needed. It is also remarkable that at long period values, T>1.0 sec, the Seed et al.'s (1976) spectral acceleration amplification factors become more than double from those proposed in this study. Given that the mean earthquake magnitude of our data set used, Ms=6.6 ± 0.67, is comparable with that of Seed et al. (1976), an additional reason of this difference could be attributed to the different data processing procedures especially in the selection of low fre-

Fig. 4: Uniform hazard acceleration response spectra for 11 sites in Greece. Thick line reffers to "alluvium" and thin to "rock" soil conditions.

Table 6: Expected horizontal peak ground accelerations (in cm/sec^2) for 11 cities of Greece.

Site	Tm(yrs)->	50	100	200	475	950	1900
I Alex/poli	R*	97	125	153	198	240	274
	All**	65	82	104	132	154	179
II Patra	R	225	279	341	440	507	582
	All	150	189	229	284	338	388
III Thes/nikiR	170	237	318	457	576	723	
	All	114	156	213	295	377	459
IV Mitilini	R	182	252	337	476	600	754
	All	122	167	225	315	401	496
V Larissa	R	207	275	361	494	615	764
	All	139	183	237	319	398	486
VI Ioannina	R	158	202	254	323	392	464
	All	106	135	169	219	256	299
VII Volos	R	268	352	457	588	.719	859
	All	179	234	300	394	474	569
VIII Athens	R	136	161	190	234	261	289
	All	100	121	137	160	181	205
IX Argostoli	R	393	515	660	883	1062	1273
	All	263	351	448	607	731	870
X Heraklio	R	169	216	249	275	298	322
	All	127	158	195	215	224	233
XI Rhodos	R	186	242	297	385	468	553
	All	133	168	211	264	315	373

(*):"Rock", (**):"Alluvium"

quency filters. It is generally observed a dependence of the spectral acceleration amplification factor on distance, for a given type of soil, since closer sources are enriched in higher frequencies. But the limited number of strong motion data used in this paper did not enable us to carry out such a sensitivity study.

In figures (5a) through (5d) some comparisons between uniform hazard and "standard spectral shape" response spectra are attempted. Spectra of figure (5a) reffer to a site of the background seismicity with very low annual rate, $r_{m>=5.0}$ =0.03, spectra of figure (5b) to a site of relatively low shallow earthquake seismicity, $r_{m>=5.0}$ =0.32, and spectra of figure (5c) to a site of relatively high shallow earthquake seismicity, $r_{m>=5.0}$ =1.41. The site of figure (5d) is mainly affected by interme-

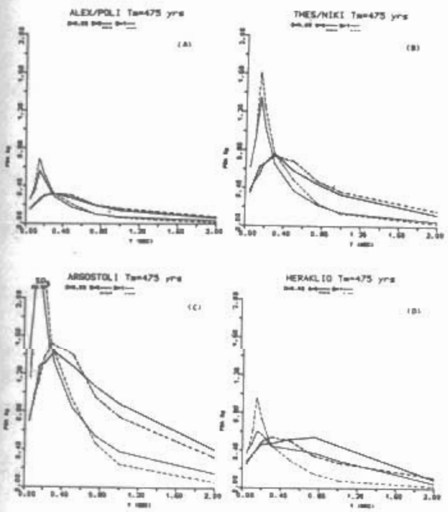

Fig. 5: Comparison between uniform hazard (solid lines) and "standard spectral shape" methodology (dashed lines) acceleration response spectra for 4 sites in Greece.

diate depth sources. From these figures it can be deduced that for background and low rate shallow earthquake seismicity both methodologies give comparable expected response spectra but for the sites of high seismicity there are differences at long periods, T>0.8 sec, with the uniform hazard spectra giving systematically higher spectral accelerations and retaining comparable spectral shapes. Regarding the response spectra of figure (5d), a change of spectral shape becomes apparent with the uniform hazard spectra shifted at longer periods.

Comparison of the normalized to the maximum pseudoacceleration uniform hazard spectra for the 11 Greek cities is shown in figure (6). Change of spectral shape is mainly observed at the site of Heraklio, Rhodos, Athens, which are essentially affected by the intermediate depth sources. The site of Argostoli although presents enriched spectral values at long periods, is still characterized by similar spectral shape with the rest of examined sites.

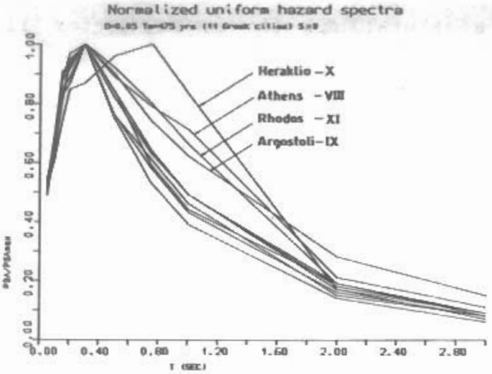

Fig. 6: Normalized, to the maximum pseudoacceleration, uniform hazard response spectra for 11 sites in Greece. Spectra which decline from the general shape are pinpointed.

Concluding, we can say that the use of different but appropriate attenuation relations for shallow and intermediate depth subduction earthquakes is a realistic step and it seems to be vital in seismic hazard assessment in Greece in terms of spectral values. Observed changes of spectral shape due to the contribution of intermediate depth subduction earthquakes may essentially affect the development of rational design values in the seismic code of Greece.

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