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# SEISMIC HAZARD ASSESSMENT AND DESIGN SPECTRA FOR THE KOZANI–GREVENA REGION (GREECE) AFTER THE EARTHQUAKE OF MAY 13, 1995

N. THEODULIDIS,* V. LEKIDIS, B. MARGARIS, C. PAPAZACHOS, Ch. PAPAIOANNOU and P. DIMITRIU

Institute of Engineering Seismology and Earthquake Engineering (ITSAK), P.O. Box 53, Finikas, GR-55102 Thessaloniki, Greece

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**Abstract**—The Kozani–Grevena (Greece) destructive earthquake occurred in a region of low seismicity. A considerable amount of strong-motion data was acquired from the permanent strong motion network of the Institute of Engineering Seismology and Earthquake Engineering (ITSAK) as well as from a temporary one installed after the earthquake. On the basis of this data set as well as on the observed macroseismic intensities, local attenuation relations for peak ground acceleration and velocity are proposed. A posteriori seismic hazard analysis is attempted for the affected and surrounding areas in terms of peak ground acceleration, velocity, bracketed duration and spectral acceleration. The analysis shows that the event of May 13, 1995 can be characterized as one with a mean return period of 500 to 1000 years. Relying on the observed spectral-acceleration amplification factors and the expected peak ground acceleration for mean return period of 500 years, region-specific elastic design spectra for the buildings of the Kozani and Grevena prefectures are proposed. © 1998 Published by Elsevier Science Ltd. All rights reserved

## INTRODUCTION

The earthquake of May 13, 1995, occurred in the province of Western Macedonia (North-Western Greece), near the towns of Kozani and Grevena, at 11:47 local time (8:47 GMT). The area was previously considered as a low-seismicity area and is characterized as zone I in the new Greek seismic code (NEAK). According to Papazachos *et al.* (1997) the earthquake epicenter was located at 40.16 N, 21.67 E, with a focal depth of 14 km and a moment magnitude of $M = 6.6$. This earthquake was generated by a normal fault with a small dextral strike slip component (strike = 240°, dip = 31°, rake = −98°) which strikes in an ENE–WSW direction, dips to NNW and has length, $L = 30$ km and width $w = 15$ km (Papazachos *et al.*, 1996). The earthquake and its aftershocks caused extensive damage—

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*Author to whom all correspondence should be addressed.

with partial and total collapses—mainly in villages situated to the S–SW of the town of Kozani and all the way to the town of Grevena (Fig. 1). The urban areas themselves were only slightly affected.

At the moment when the earthquake occurred there was only one strong-motion instrument, an SMA-1 analog accelerograph, close to the epicentral area in the basement of the Kozani prefecture building. This and seven more instruments in North-Western and Central

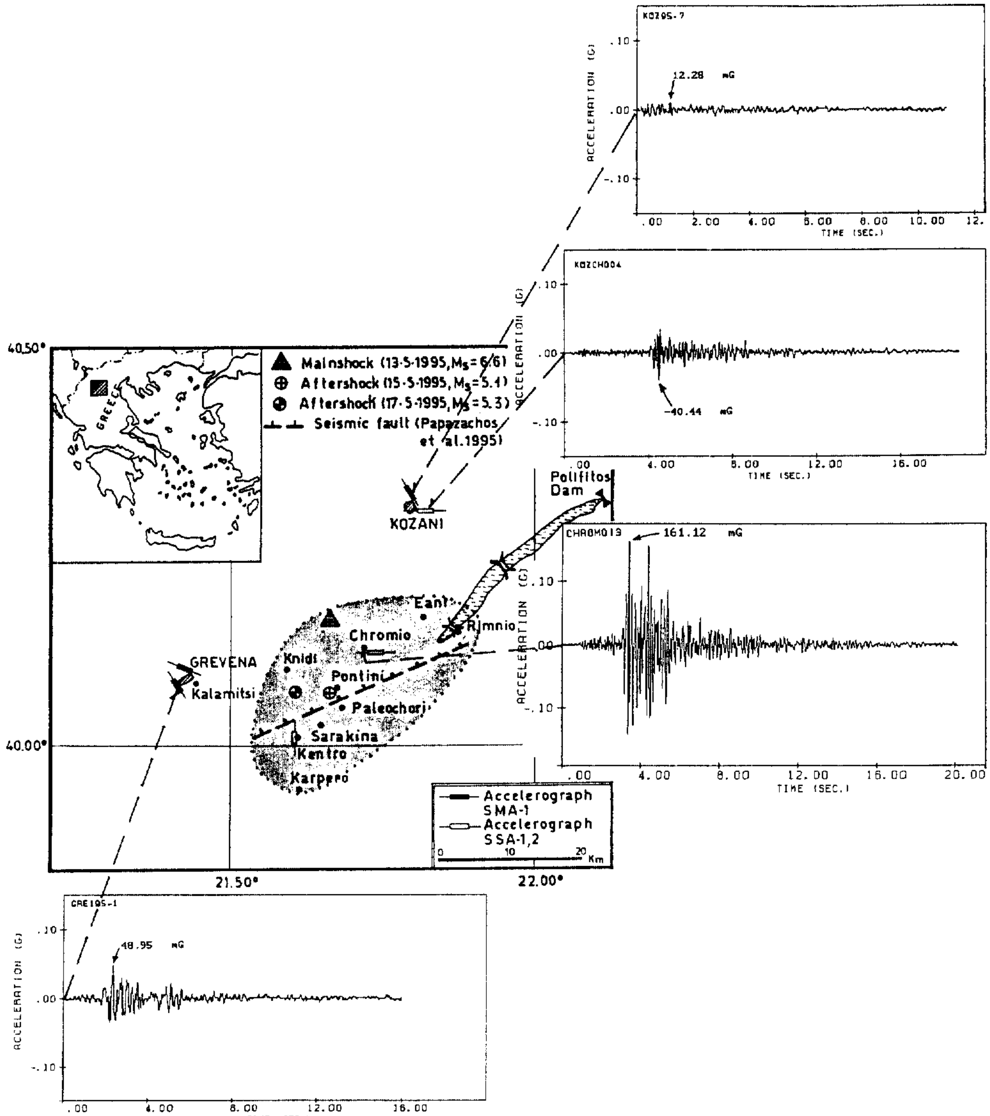


Fig. 1. Map of the broader area affected by the May 13, 1995 mainshock, showing the accelerographs installed by ITSAK and the meisoseismal area (shadowed zone). Horizontal components of the accelerograms recorded during the large aftershock of May 15, are also shown.

Greece, all belonging to the strong motion network run by the Institute of Engineering Seismology and Earthquake Engineering (ITSAK), recorded the mainshock at the towns of Kozani, Karditsa, Karpenisi, Larissa, Edessa, Kastoria, Veria and Florina. The highest acceleration, 0.21 g, was recorded in Kozani, whereas at the other locations it varied from 0.01 g to 0.03 g. Immediately after the mainshock, ITSAK and the Geophysical Laboratory of the Aristotle University of Thessaloniki installed and operated seven more accelerographs in the affected area.

In the present study, local (region-specific) strong-motion attenuation relations for the peak ground acceleration and velocity are derived, based mainly on the accelerograms recorded during the Kozani–Grevena seismic sequence as well as on the observed macroseismic intensities of the mainshock. Incorporating these relations in a seismic source model of the broader region, seismic hazard in the epicentral area ($\Delta \leqslant 20$ km) is assessed. Using the hazard analysis results, as well as the observed response spectra of the available strong-motion recordings, a set of elastic design spectra for the examined region is proposed.

## STRONG MOTION DATA AND LOCAL ATTENUATION RELATIONS

Strong-motion data recorded during the Kozani–Grevena, Northern Greece, large ($M = 6.6$) earthquake of May 13, 1995 and its aftershock activity are presented and discussed. A part of this data set is used for defining local attenuation relations. For this purpose an equation of the form

$$\ln Y = C_1 + C_2 M + C_3 \ln(\Delta + R_0) + C_4 S + C_5 P \qquad (1)$$

was adopted, where $Y$ is the peak ground acceleration or velocity, $M$ is the moment magnitude, $\Delta$ is the epicentral distance, $S$ represents the soil conditions, taking the value of 1 for bedrock and 0 for alluvium, and $P$ is the error term. Constants $R_0$ and $C_4$ cannot be reliably determined from a small data set, so the values $R_0 = 15$ km and $C_4 = 0.31$, determined for the area of Greece (Theodulidis and Papazachos, 1992), were used.

Figure 2 shows the distribution of the available accelerograms of the earthquake sequence with magnitude and epicentral distance. The magnitudes range between 3.1 and 6.6; the epicentral distances range from 1 km to about 140 km. In Fig. 3, peak ground acceleration values as a function of epicentral distance for three magnitude ranges, $3.1 \leqslant M \leqslant 4.5$, $4.5 < M \leqslant 5.5$ and $M > 5.5$, are given. Peak ground acceleration values vary between 0.004 g and 0.21 g. The variability of ground motion due to the $M = 5.1$ aftershock of May 15, 1995, as recorded by ITSAK's network is illustrated in Fig. 1. The influence of the attenuation of peak ground acceleration and local site conditions on strong motion are quite apparent in this figure.

Attenuation of peak ground acceleration and velocity is a critical factor in assessing seismic hazard at a site. Comparison of aftershock strong-motion data with attenuation relations proposed for the area of Greece gave some evidence of a significant disparity (Theodulidis and Lekidis, 1996). For this reason, and in order to have a realistic attenuation model, an attempt is made to define local acceleration and velocity attenuation relations in the following steps:

(i) The initial data set considered consisted of 16 time histories of horizontal acceleration recorded by ITSAK's permanent network during the mainshock of May 13, 1995. To expand the data set, the only recording of the October 25, 1984 quake, as well

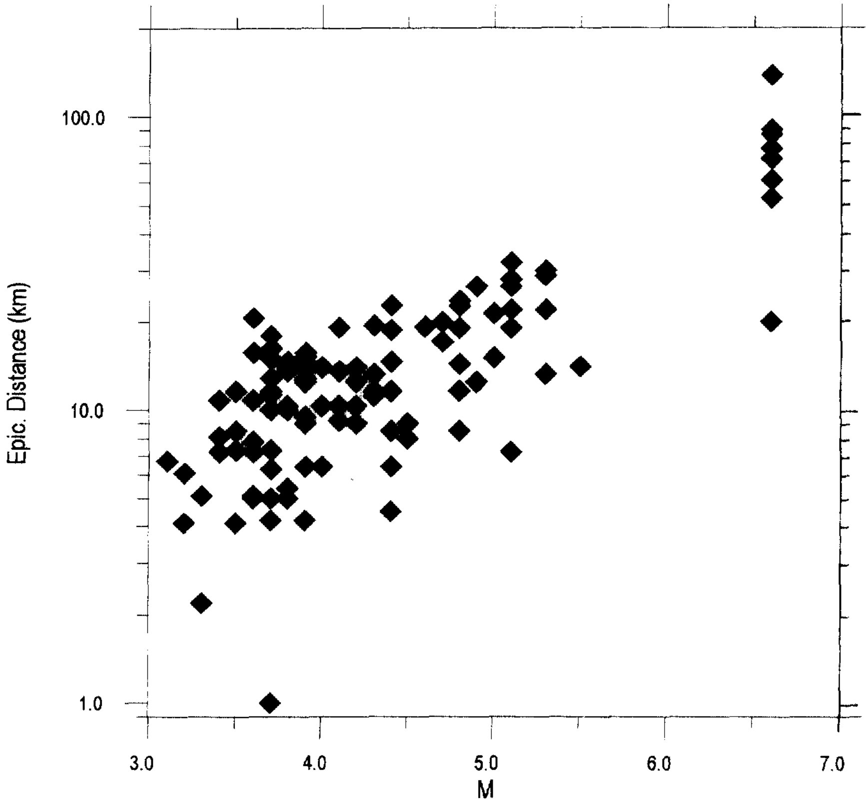


Fig. 2. Distribution of strong motion data recorded during the May 15, 1995 seismic sequence with magnitude and epicentral distance.

as the macroseismic information corresponding to both events, were also used. Observed macroseismic intensities were transformed into peak horizontal accelerations by means of the relation (Theodulidis and Papazachos, 1992)

$$\ln a_g = 0.28 + 0.67 I_{MM} + 0.42 S \tag{2}$$

where $I_{MM}$ is the modified Mercalli intensity and $S$ is the soil condition factor ($S = 0.5$ for intermediate soil conditions was assumed). Based on the data set obtained, the following relation between peak horizontal ground acceleration and epicentral distance was estimated:

$$\ln a_g = -1.90 \ln(\Delta + 15) + C \tag{3}$$

where $C$ is a quantity depending on earthquake magnitude and soil conditions.

(ii) For the determination of the coefficient $C$, 216 values of peak horizontal accelerations due to aftershock activity were additionally included into the analysis. Then, by considering $S = 0.5$ in Eq. (1), the data set was transformed to correspond to intermediate soil conditions and extrapolated to epicentral distance $\Delta = 0$ by using

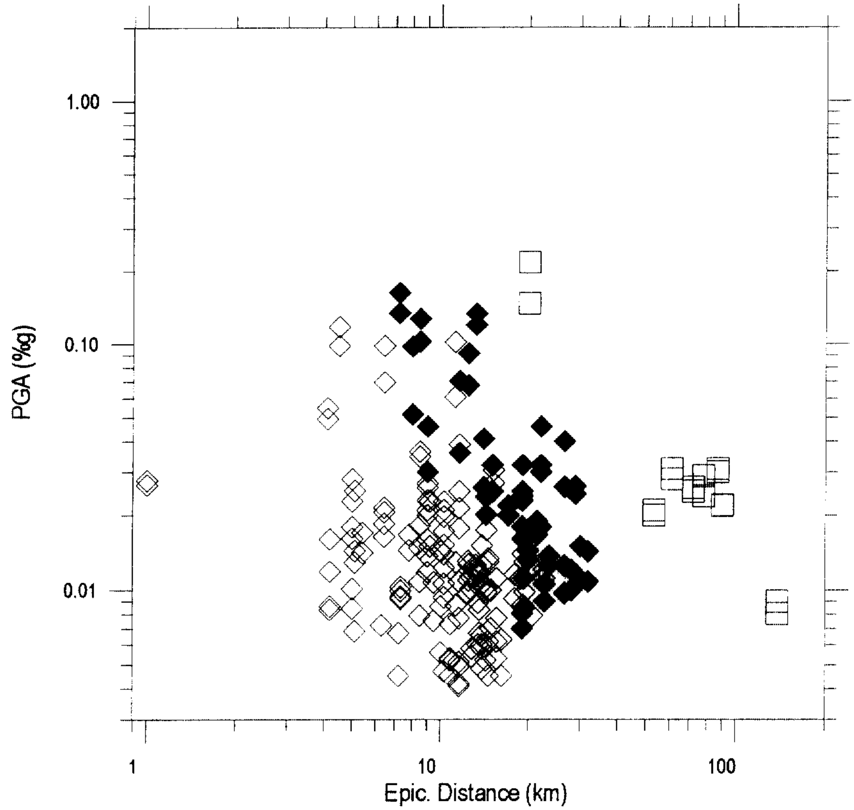


Fig. 3. Distribution of strong motion data recorded during the May 15, 1995 seismic sequence with epicentral distance and peak ground acceleration (open diamond: $3.1 \leqslant M \leqslant 4.5$, full diamond: $4.5 < M \leqslant 5.5$ and open square: $M = 6.6$).

Eq. (3). The scaled peak ground acceleration values and the magnitudes of the earthquake sequence were found to be related as (Fig. 4):

$$\ln a_{0g} = 1.06M + C' \tag{4}$$

where $C'$ is a quantity depending on the soil conditions. The value of the slope of Eq. (4) is very close to the value of 1.02 obtained for a data set covering most of the Greek territory and hence representing an 'average' value (Theodulidis, 1991). Because of this proximity and the relatively small number of data generated by the earthquake sequence which presented a gap in the magnitude range from 5.5 to 6.6, the 'average' value, $C_2 = 1.02$, in the attenuation relation was used.

(iii) Finally, using the entire data set of 232 values of peak horizontal acceleration, the constant, $C_1$ of Eq. (1), was found to be equal to 4.85 and the mean square error 0.50. Thus, the local attenuation relation for the horizontal peak ground acceleration is:

$$\ln a_g = 4.85 + 1.02M - 1.90 \ln(\Delta + 15) + 0.31S + 0.50P \tag{5}$$

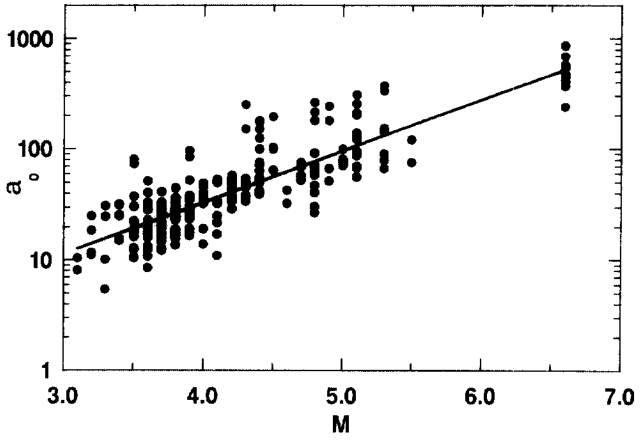


Fig. 4. Scaled peak ground accelerations at zero distance as a function of magnitude and their fit to equation (4).

A similar procedure applied to the peak ground velocity resulted in the following attenuation relation:

$$\ln v_g = -0.61 + 1.29M - 1.65\ln(\Delta + 10) - 0.22S + 0.63P \qquad (6)$$

The observed peak ground acceleration or converted intensity-to-acceleration or velocity data can be seen in Figs 5 and 6, where a reasonable fit to the proposed local acceleration and velocity attenuation relations can be observed.

## SEISMIC HAZARD ASSESSMENT

Seismic hazard assessment at a given site is a critical element in earthquake engineering. The basic steps involved in seismic hazard assessment are:

(i) determination of an adequate model that represents seismic sources with potential to affect the site of interest,
(ii) definition of an appropriate earthquake recurrence model to supplement the seismic source model and
(iii) derivation of a realistic attenuation relation to transfer the ground motion from the source to the site of interest.

The method proposed by Cornell (1968) provides a probabilistic estimate of seismic hazard, as it can incorporate historical seismicity data as well as geophysical and seismotectonic information into the seismic source model. In the present study, a modification of Cornell's method due to McGuire (1976) and the corresponding computer code "EQRISK"—properly modified—were used. The following expected strong-motion parameters were estimated: the modified Mercalli intensity, $I_{MM}$; peak ground acceleration, $a_g$; peak ground velocity, $v_g$; bracketed duration, *BD*; and spectral pseudoacceleration, *PSA*. Here, bracketed duration is defined as the time between the first and the last excursion of ground acceleration above the level of 0.05 g (Bolt, 1974). Seismic hazard estimates are presented in terms of expected values of the above strong-motion parameters for various mean return periods of occurrence.

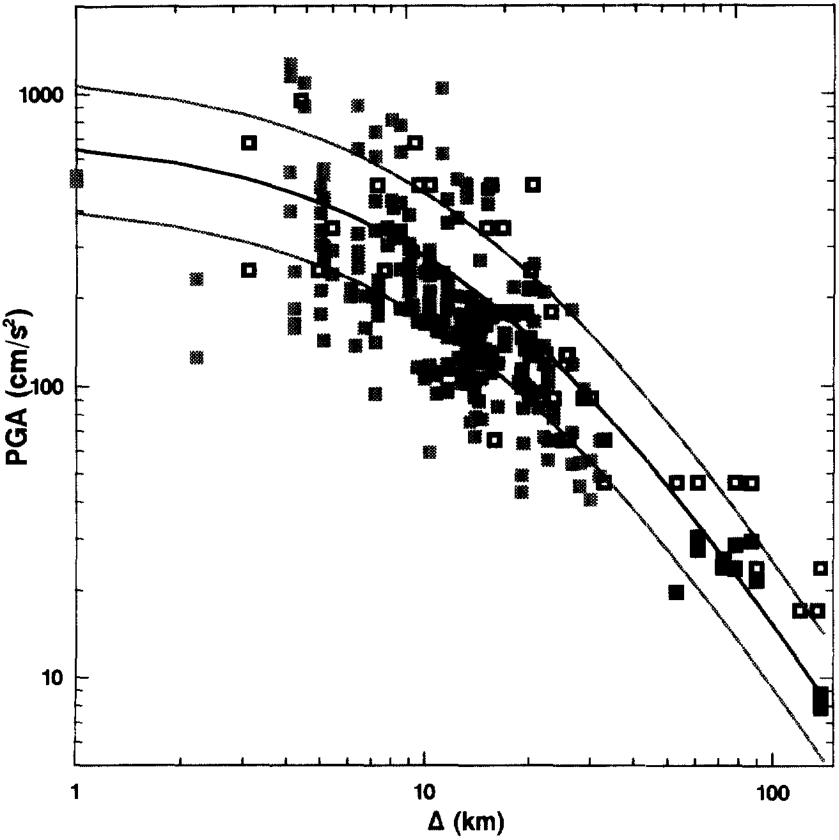


Fig. 5. Observed peak ground acceleration values (solid square:main events of 13–5–95 and 25–10–84, open square: converted intensities, grey square: aftershocks of the 13–5–95 sequence) as a function of epicentral distance Δ. All values have been reduced to $M = 6.6$ using equation (5) whose mean $\pm 1$ standard deviation curves are also plotted.

The seismicity of the region of Western Macedonia, which dominates the seismic hazard of the study area, was modeled by Hatzidimitriou and Papazachos (1995) as being due to two distinct seismic sources. For each source they estimated the occurrence rate for earthquakes with $M \geqslant 5.0$, the largest expected magnitude and the constants $a$ and $b$ of the Gutenberg and Richter (1944) relations. In the seismic hazard analysis a Poissonian model of occurrence is adopted, *i.e.*, a random distribution of events in space and in time (Cornell, 1968), and this is combined with an anisotropic radiation model of strong ground motion proposed for the area of Greece by Papazachos (1992), Margaris (1994) and Margaris and Papazachos (1994).

In order to assess seismic hazard in the area of interest, the previously determined attenuation relations for peak horizontal acceleration and velocity (Eqs 5 and 6), the relation proposed by Papazachos *et al.* (1992) for bracketed duration and the relations for spectral pseudovelocity (Theodulidis and Papazachos, 1994a) were used. Seismic hazard was assessed for most of the affected villages close to the epicentral area as well as for the towns of Kozani and Grevena. As the values obtained were practically similar, the use of

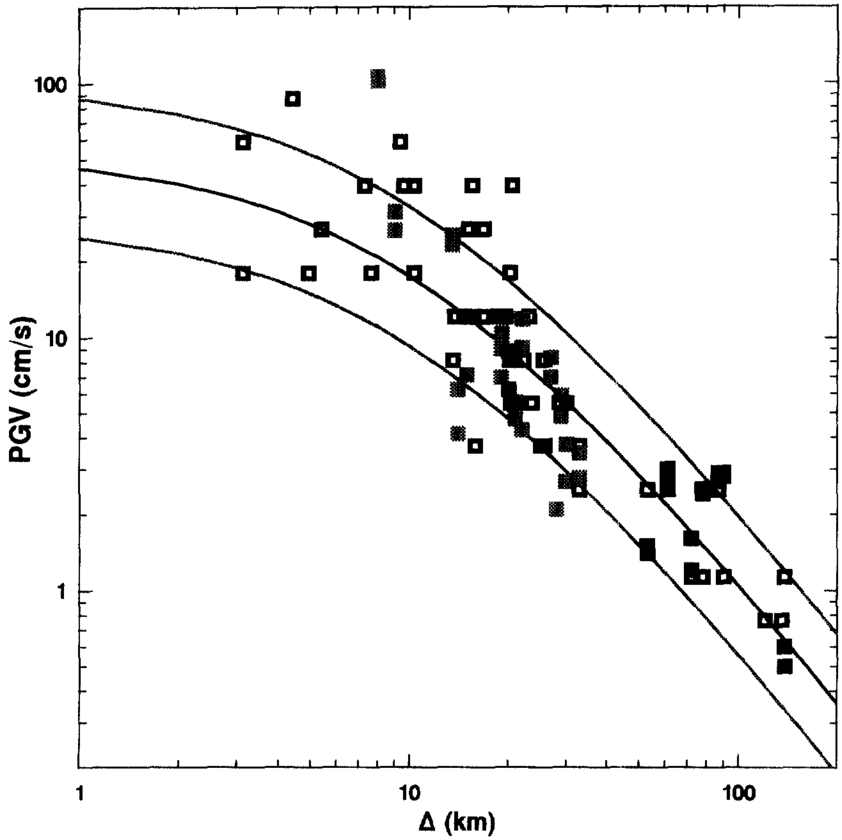


Fig. 6. Observed peak ground velocity values (solid square: main events of 13–5–95 and 25–10–84, open square: converted intensities, grey square: aftershocks of the 13–5–95 sequence) as a function of epicentral distance Δ. All values have been reduced to $M = 6.6$ using equation (6) whose mean ±1 standard deviation curves are also plotted.

an 'average' site was decided and probabilistic estimates of seismic hazard for various mean return periods, $T_M = 10, 50, 100, 200, 475, 950, 1900$ and $4750$ years, were made. Seismic hazard estimates are given in Table 1. According to Weichert and Milne (1979), seismic hazard assessment for mean return periods above 1000 years should be based mainly on deterministic methods if adequate data exists. Consequently, estimated peak ground-motion values for very low annual probabilities of occurrence ($<0.001$) should be considered only as indicative ones. A more realistic step in low-probability seismic hazard estimates in the study area may be based on complete historical, archeological and neotectonic information.

In Fig. 7, the expected values of peak ground acceleration as a function of the mean return period for two categories of soil conditions, namely rock and alluvium, are presented. In order to stress the necessity of using local attenuation relations, the curves corresponding to the 'average' attenuation relation derived for the entire territory of Greece (Theodulidis, 1991) are plotted together with the local ones. From Fig. 7 it is clear that the 'average' relation leads to a considerable overestimation of the expected acceleration values in the examined area.

Table 1. Expected values of macroseismic intensity, $I_{MM}$, peak ground acceleration, $a_g$, velocity, $v_g$, and bracketed duration, $BD$, ($\geq 0.05$ g) for various mean return periods, $T_M$, and two soil categories (rock: $S = 1$, alluvium: $S = 0$)

| $T_M$ (yrs) | 10 | 50 | 100 | 200 | 475 | 950 | 1900 | 4750 |
|---|---|---|---|---|---|---|---|---|
| $I_{MM}$ | 6.1 | 6.9 | 7.3 | 7.6 | 8.0 | 8.2 | 8.5 | 8.7 |
| | | | $a_g$ (cm/sec$^2$) | | | | | |
| $S = 1$ | 49 | 97 | 126 | 160 | 209 | 254 | 293 | 355 |
| $S = 0$ | 36 | 71 | 92 | 117 | 154 | 184 | 218 | 248 |
| | | | $v_g$ (cm/sec) | | | | | |
| $S = 1$ | 1.6 | 3.5 | 4.8 | 6.4 | 8.8 | 10.9 | 13.3 | 17.2 |
| $S = 0$ | 2.0 | 4.4 | 6.0 | 7.9 | 10.9 | 13.7 | 17.0 | 21.0 |
| | | | $BD$ (sec) | | | | | |
| $S = 1$ | 2.4 | 3.9 | 4.7 | 5.5 | 6.6 | 7.4 | 8.2 | 9.3 |
| $S = 0$ | 2.9 | 4.7 | 5.6 | 6.7 | 7.9 | 8.9 | 10.1 | 11.1 |

Expected spectral values of pseudoacceleration for two site conditions and three mean return periods, $T_M = 50$, 475 and 950 years, were calculated by employing a relevant attenuation model proposed for the area of Greece (Theodulidis and Papazachos, 1994a). To account for anisotropic source radiation, the elliptic model in seismic hazard assessment developed for the area of Greece (Margaris and Papazachos, 1994) was adopted. In Fig. 8, expected pseudoacceleration spectra for three return periods $T_M = 50$, 475 and 950 years and two soil conditions, are plotted along with the horizontal acceleration response spectra of the mainshock recorded at the town of Kozani. It is apparent that the observed spectra are well covered by the probabilistic spectra for mean return periods between 475 and 950 years.

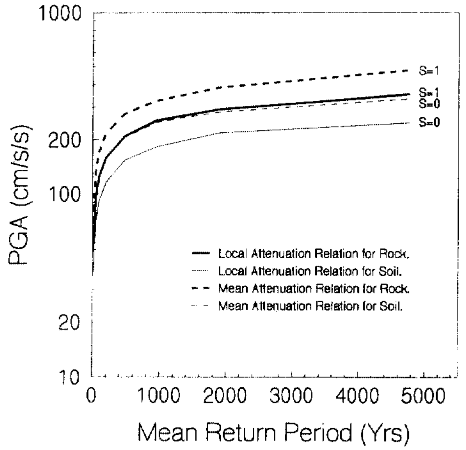


Fig. 7. Expected peak ground acceleration for the study area for two soil categories (rock: thick line, alluvium: thin line) using local and 'mean' (valid for entire Greece) attenuation relations of peak ground acceleration.

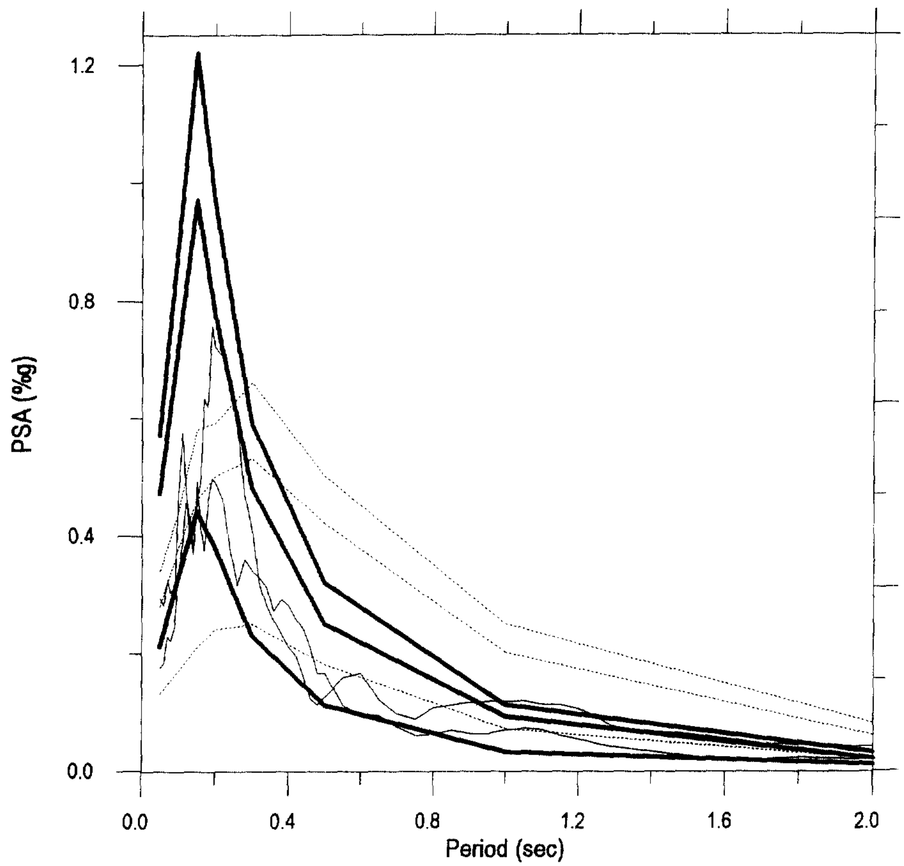


Fig. 8. Expected, 5% damped, acceleration response spectra for two soil categories (rock: thick line, alluvium: dotted line) for mean return periods of 50, 475 and 950 years. Mainshock's recorded response spectra of horizontal components at Kozani are also plotted (thin line).

For those villages most heavily damaged by the earthquake of May 13, 1995, namely Karpero, Chromio, Knidi and Kentro, where accelerographs were installed shortly after the mainshock, as well as for the towns of Kozani and Grevena, the horizontal-to-vertical spectral ratio technique was applied in order to evaluate local site effects. This technique was introduced by Nakamura (1989), who applied it to noise recordings and discovered that the ratio of the Fourier spectra of the horizontal components to the spectrum of the vertical component reveals the soil's principal resonance frequencies. Encouraging results were later obtained from strong-motion recordings (Lermo and Chavez-Garcia, 1993; Theodulidis and Bard, 1995). Strong-motion data recorded during the Kozani–Grevena sequence showed that the local site conditions in Karpero and Chromio villages favour resonances at lower frequencies (0.5 Hz–1.0 Hz) than in Kentro (1.5 Hz–2.5 Hz) or in Knidi villages (2.5 Hz–8.0 Hz) (Fig. 9). This implies thicker and/or softer soil deposits under the Karpero and Chromio villages. On the other hand, all four sites, particularly Knidi, exhibit high amplification in the frequency band 4.0 Hz–8.0 Hz (corresponding to the period range

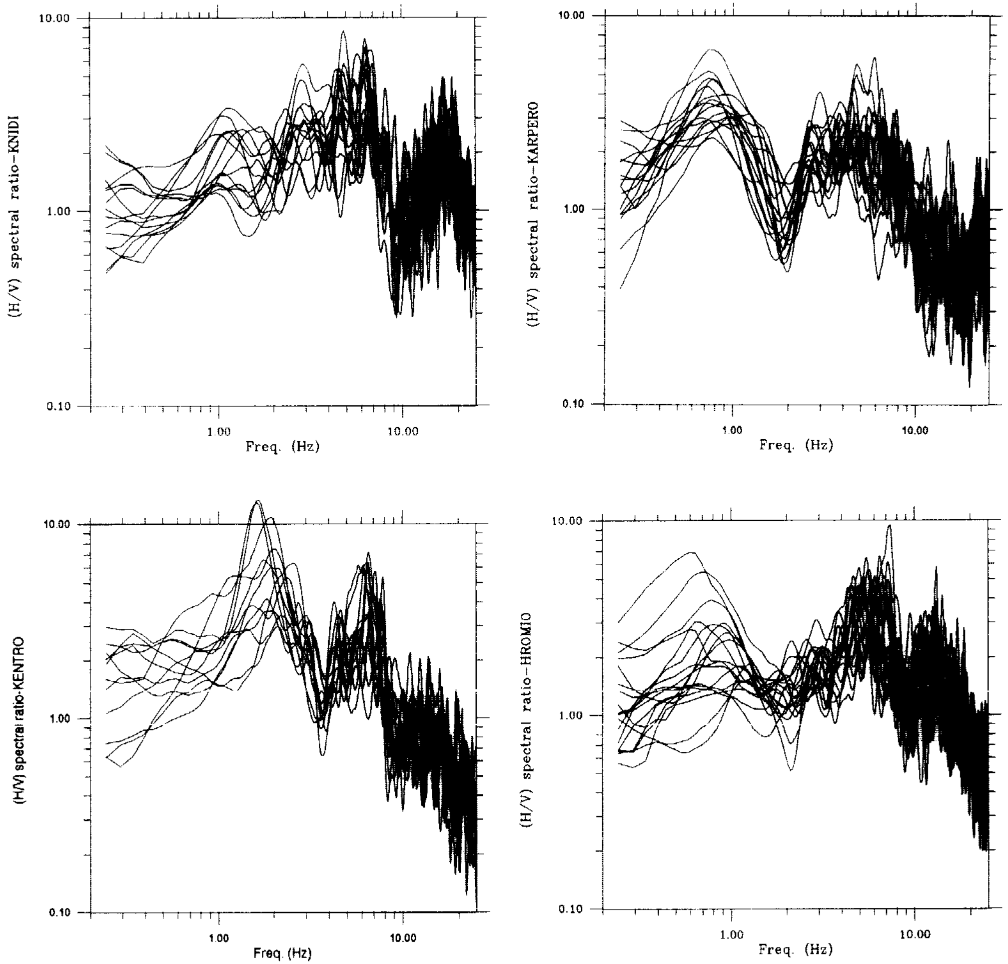


Fig. 9. Horizontal-to-vertical spectral ratio estimates on the basis of recorded accelerograms in four villages close to seismic fault.

0.13 sec–0.25 sec) which could, in part, explain the large damage inflicted upon rigid buildings in the area. Similar spectral ratio estimates at two separate sites in the towns of Kozani and Grevena showed different amplification and resonance frequencies (Fig. 10), thus implying the necessity for microzonation studies.

## ESTIMATION OF ELASTIC DESIGN SPECTRA

The Kozani and Grevena prefectures belong to zone I of the new Greek seismic code (NEAK) with the lowest effective acceleration of 0.12 g. Although the peak ground acceleration recorded in Kozani during the mainshock was 0.21 g in the longitudinal and 0.15 g in the transversal component, the mean effective acceleration of the horizontal motion calculated according to FEMA (1985) is equal to 0.14 g. This value falls between the proposed horizontal accelerations for NEAK's seismic zones I and II, respectively 0.12 g and 0.16 g. However, the elastic design spectra proposed by NEAK for the affected area are insufficient when compared with the observed response spectra of the May 13, 1995 mainshock, particularly in the low natural-period range, 0.1 sec–0.4 sec (Theodulidis and Lekidis, 1996). In that period range, the spectral-acceleration amplification factors, defined as the 5% damped response spectrum normalized to peak ground acceleration, calculated for the mainshock and the large aftershock of May 15, have average values around 3.0 in the town of Kozani and in the village of Chromio, and 2.75 in the town of Grevena (Fig. 11). These values are higher than that of 2.5 proposed by NEAK for all soil types, suggesting that the latter can not be considered adequate, at least for the broader epicentral area. An analogous observation, i.e. that the design spectra proposed by NEAK tend to systematically underestimate the spectral-acceleration amplification factors, especially in the low natural-period range, was made earlier in a study of a strong-motion data set corresponding mainly to strong shallow earthquakes in Greece (Theodulidis and Papazachos, 1994b).

Taking into account the calculated spectral-acceleration amplification factors and the peak ground-acceleration values estimated by seismic hazard analysis, elastic design spectra for rock and alluvium site conditions, with amplification factors of 3.0 and 2.75, respectively, are proposed (Fig. 12). In the same figure, probabilistic spectra for a mean return period of 475 years are plotted. It is seen that there is a reasonably good agreement between the proposed design spectra and the probabilistic ones, implying that the adoption of higher spectral-acceleration amplification factors may lead to more realistic design values.

## DISCUSSION AND CONCLUSIONS

The attenuation relations of peak ground acceleration and velocity derived in this study for the Kozani–Grevena area yielded a geometric-anelastic attenuation coefficient of 1.90. This is smaller than the average value of 1.65 obtained for the entire area of Greece (Theodulidis and Papazachos, 1992). This result implies a higher-than-average attenuation rate in the study area.

Seismic hazard analysis and recorded strong ground motion showed that, for the town of Kozani, the earthquake of May 13, 1995 can be considered to have a mean return period between 500 and 1000 years.

It became evident that a timely installation of a strong motion array in the epicentral area of large events can produce a sufficient amount of strong-motion data from the

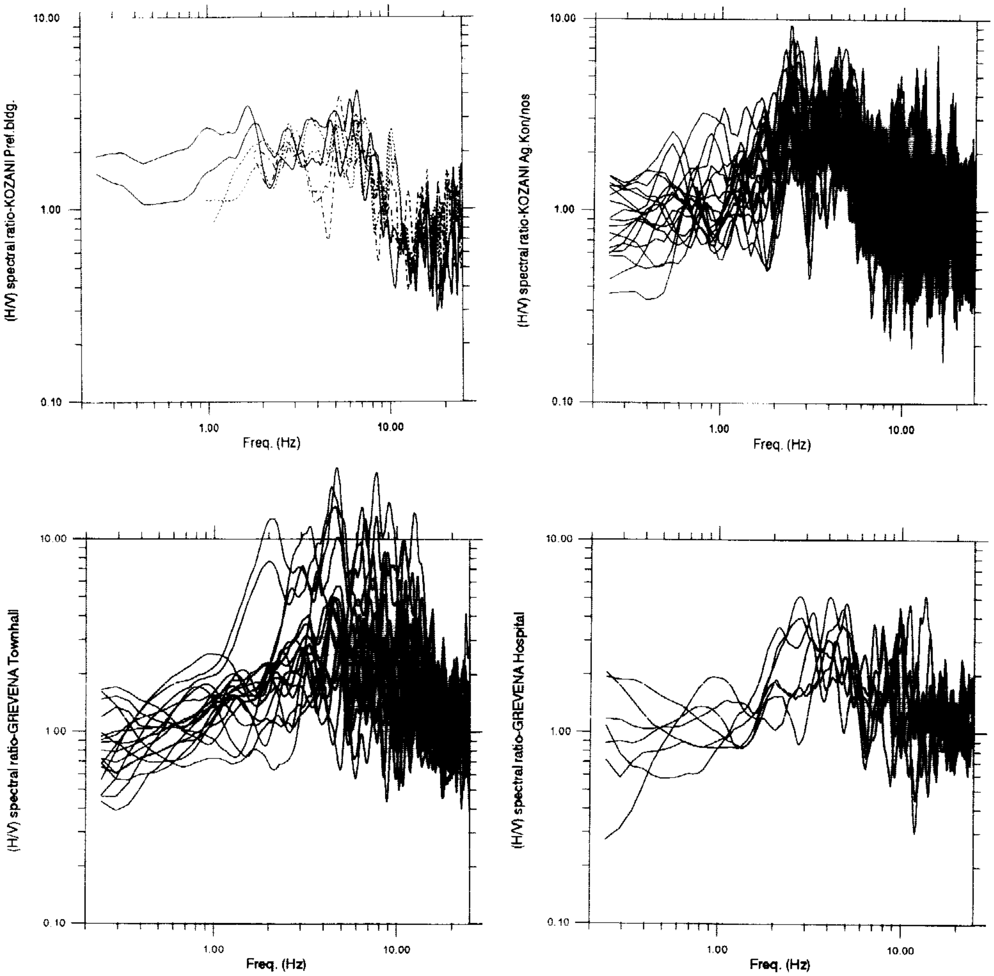
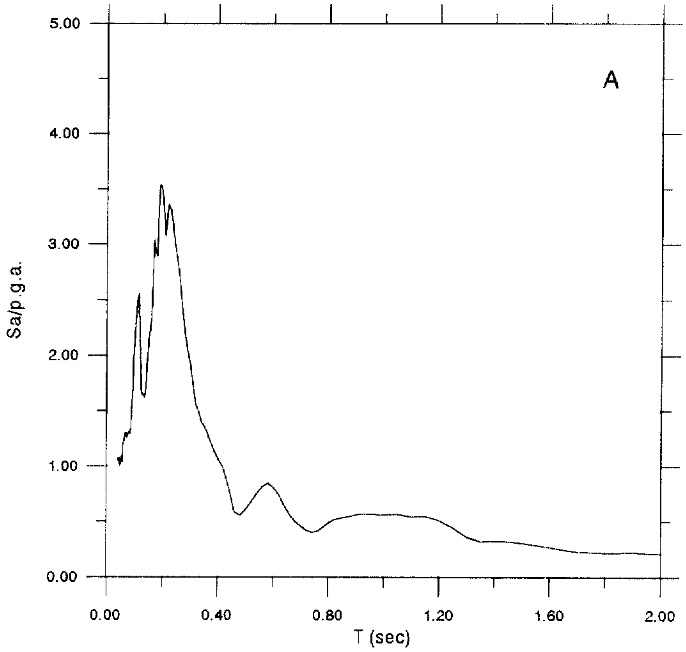


Fig. 10. Horizontal-to-vertical spectral ratio estimates on the basis of recorded accelerograms in two different sites in the towns of Kozani and Grevena.



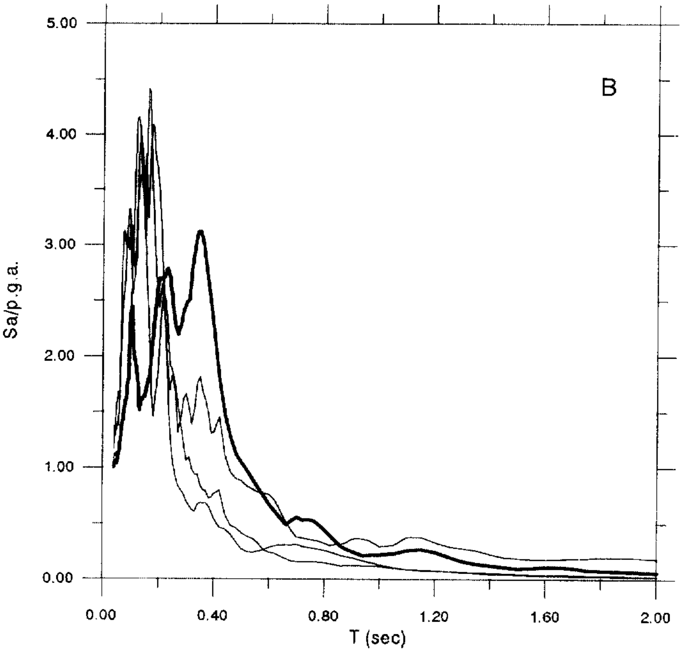


Fig. 11. (a) Spectral-acceleration amplification factors due to May 13, 1995 mainshock observed at the town of Kozani. (b) Spectral-acceleration amplification factors due to May 15, 1995 aftershock observed at two site of the Kozani town and at Chromio village (thin line) and at the town of Grevena (thick line).

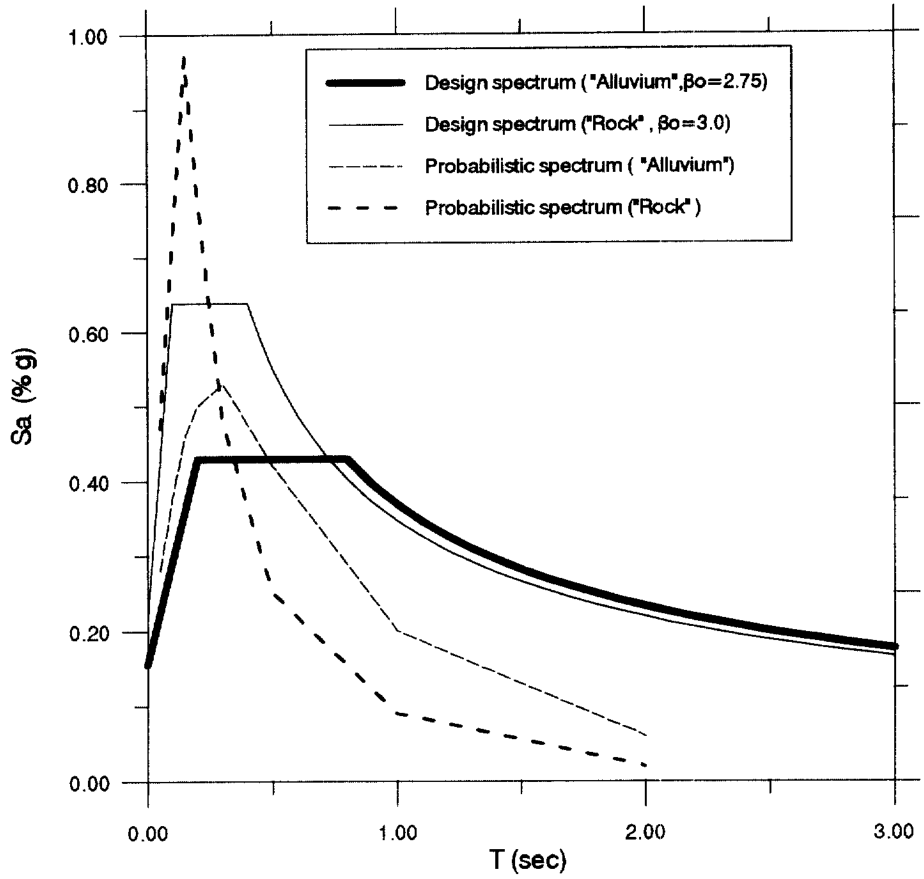


Fig. 12. Proposed design spectra for the study area in comparison with probabilistic ones with mean return perion of 475 years.

aftershock activity to permit derivation of local attenuation relations. The use of local attenuation relations in seismic hazard analyses is preferable to the use of 'average' attenuation relations, which inevitably incorporate propagation-path effects from different seismotectonic regions.

For the region of Kozani–Grevena, it has been shown that correcting NEAK's typical spectral shape, according to the spectral-acceleration amplification factors calculated from recorded strong-motion data, region-specific design spectra consistent with the results of seismic-hazard analysis are obtained. It seems that, in certain cases, adoption of region-specific spectral shapes may give more consistent and accurate estimates of seismic design values. By implication, a careful reevaluation of spectral-acceleration amplification factors for those seismic zones of NEAK where sufficient strong-motion data exists, would be a promising effort towards realistic estimation of design spectra.

In this area of Greece, there are seismic faults close to urban areas. Some of these faults may be unknown or may be considered non-active but still capable of generating short-duration high-acceleration destructive ground motion, as has been observed during recent small and/or moderate earthquakes (Anagnostopoulos *et al.*, 1987; Lekidis *et al.*, 1996a, 1996b; Theodulidis and Lekidis, 1996). The event of May 13, 1995 in the Kozani–Grevena region also constitutes such an example, suggesting a new look at the results of seismic-hazard assessment and related seismic zonation studies. In view of this and taking into account ground accelerations recorded during recent destructive shocks in Greece, careful reevaluation of the effective accelerations of NEAK, for at least the first three seismic zones, should be attempted. Such reevaluation would probably lead to higher levels of effective acceleration and result in more realistic and certainly safer seismic design values.

Damage distribution due to the May 13, 1995 mainshock close to the seismic fault, where the destructive impact of ground motion was the strongest, implies that high ductility demands were imposed on structures (Alexandris, 1995; Theodulidis and Lekidis, 1996). To cope with these demands, a significant increase of ductility factors over those proposed in NEAK for all types of structures built close to active faults would improve their energy-dissipation capacity and hence increase their resistance to seismic loads. Such a measure would contribute to safer buildings and, more generally, to seismic risk mitigation in the vicinity of seismic faults.

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