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GROUND MOTION ATTENUATION RELATIONS FOR SHALLOW EARTHQUAKES IN GREECE

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ABSTRACT

In the present paper new attenuation relations are proposed based on 744 records of horizontal components for the peak ground acceleration, velocity and displacement for shallow earthquakes, using 474 strong motion recordings from earthquakes in the Greek area. The data set used consists of records from 142 mainly normal faulting earthquakes with magnitudes $4.5 \leq M_W \leq 7.0$ and epicentral distances $1\text{km} \leq R \leq 150\text{km}$. The data analysis incorporates the soil classification according to NEHRP (1994) [1]. Comparisons with other predictive relations from other regions are also carried out.

Keywords: Strong motion attenuation; shallow earthquakes; Greece;

INTRODUCTION

Seismic hazard assessment is commonly based on empirical predictive attenuation relations. Such relations are generally expressed as mathematical functions relating a dependent variable to parameters characterising the earthquake source, propagation path and local site conditions. To date many attenuation relations for peak ground acceleration, velocity and displacement have been published based on ever increasing number strong motion data from the Circum Pacific region [2-10], as well as from Europe and Middle East region [11-16].

Since the first installation of accelerographs in Greece – in early 1970's – strong motion data recordings are progressively increasing. Especially, during the last decade, the number of strong motion recordings has significantly increased due to digital instruments deployed both as permanent national networks and temporary arrays during aftershock sequences. Automatic digitization and new correction techniques have increased the reliability of strong motion data set particularly in the low frequency content (e.g. f<1Hz). In addition, more accurate earth structure models in Greece led to decreasing errors in hypocenter determination. Taking into account the aforementioned, based on the to date (1973-1999) available strong motion recordings from shallow earthquakes in Greece new attenuation relations of peak ground acceleration, velocity and displacement of horizontal strong ground motion are defined. These relations are compared with relevant recent ones proposed for Greece or for other regions with comparable seismotectonic environment.

DATA USED

The data used in the present study consist of 474 strong motion recordings, from 142 mainly normal faulting shallow earthquakes in Greece (ITSAK: www.itsak.gr and NOA: www.noa.gr). This data set come from all the available accelerograms in Greece, during the period 1973-1999, after satisfying at least one of the following criteria: (a) The earthquake which triggered the instrument has a moment magnitude of Mw≥4.5, (b) The strong motion record has a peak ground acceleration PGA≥0.05g independently of the earthquake magnitude and (c) The record has PGA<0.05g but there is another one with PGA≥0.05g which come from the same earthquake. All recordings of the data set used were automatically digitized and processed homogeneously [17]. Special attention was paid determining the digital filters of the data processing in order to estimate PGD. Data recorded in 4-story buildings and higher are excluded from this set. The finally chosen data set for regression analysis consist of 744 horizontal components. For the completeness of the database used in this study the epicenters of the earthquakes of a recent catalogue compiled by the Geophysical Laboratory of the Aristotle University of Thessaloniki were adopted [18]. The size of the earthquakes in this catalogue is expressed in a scale equivalent to the moment magnitude, M_w, which it was suggested to be a suitable independent variable in defining attenuation relations [19].

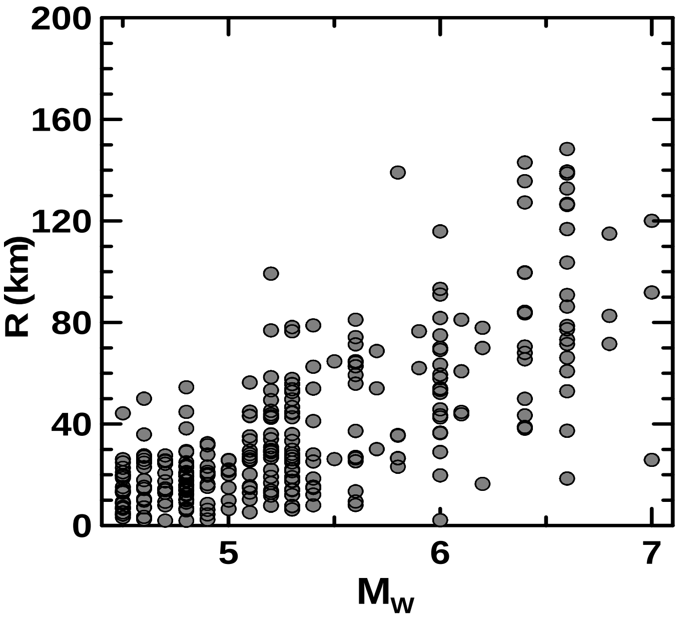


Figure 1: Distribution of epicentral distance (R) as a function of moment magnitude (Mw) of the strong motion records used in this study.

In Figure 1 the distribution of moment magnitude Mw with epicentral distance, (R), of the recordings used in this study is shown. It is observed that there is a correlation between these two parameters raising some difficulties in defining attenuation relations. In fact, for small magnitudes 4.5≤Mw≤5.0 recordings exist mainly in short, R≤ 40km, epicentral distances. On the contrary, large magnitude events are recorded at intermediate and long distances. For Mw>6.0 there is lack of observations in the near field, (R<20km).

Figure 2a and 2b show the distribution of PGA values as a function of epicentral distance and magnitude M_w. A dense area of points for distances up to 40km is observed for PGA values less than 0.1g. Similar remarks can be made, for $M_w<5.5$.

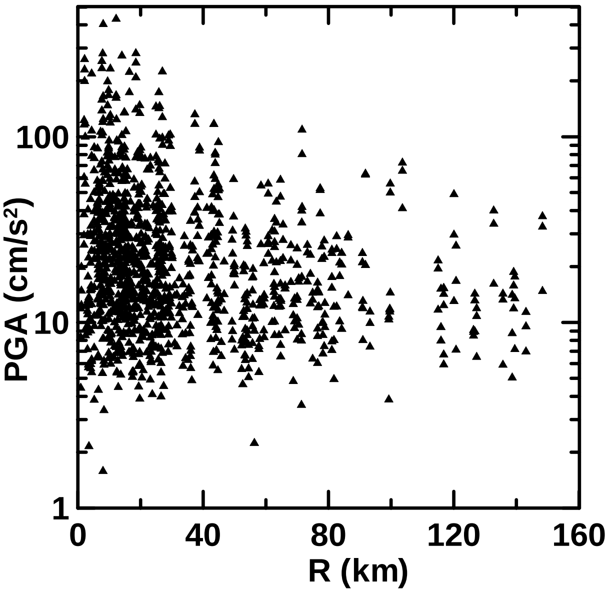


Figure 2a: Distribution of the peak ground accelerations (PGA) as a function of the epicentral distance (R) for the strong motion recordings used in the present work.

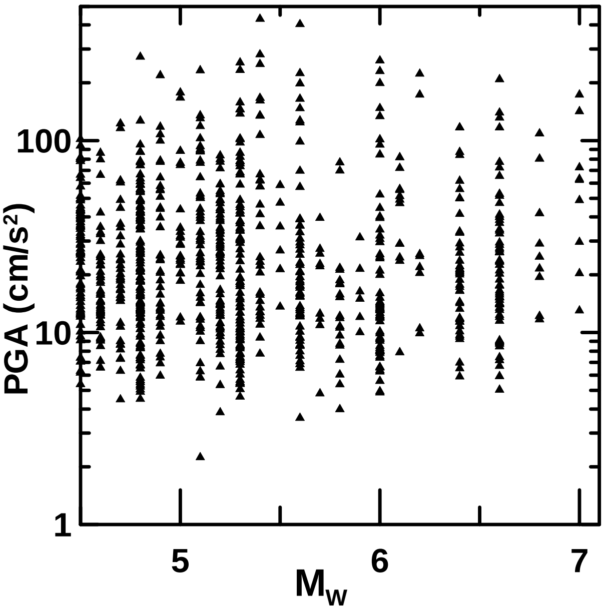


Figure 2b: Distribution of the peak ground accelerations (PGA) as a function of the moment magnitudes (M_W) for the strong motion recordings used in the present work.

Regarding the local site conditions the classification proposed by NEHRP [1] and UBC [20] was used. Based on existing geotechnical data site conditions at the recording stations were classified in 5 categories, namely, A, B, C, D, E. In our case the vast majority of data corresponds only to the categories B, C and D that were finally adopted in this study. As a result from the total of 1488 horizontal components used, 290 belong to category B, 756 to C and 442 to D.

EMPIRICAL PREDICTIVE MODELS AND RESULTS

For the definition of the predictive relations optimization technique was used. The optimization procedure was based on the least square method in one step by using the singular value decomposition method. Such an analysis allows the stability control of the final solution and was adopted because of the observed correlation in our data set between magnitude and epicentral distance (Fig. 1).

The following two equations were examined in the regression analysis,

$$\ln Y= c_0 + c_1 M_W + c_2 \ln(R+R_0) + c_3 S \quad (1)$$

$$\ln Y= c_0 + c_1 M_W + c_2 \ln(R^2+h_0^2)^{1/2} + c_3 S \quad (2)$$

where Y is the strong motion parameter to be predicted, M_w is the moment magnitude, R is the epicentral distance, S is a variable which takes the value 0 for the soil category B, 1 for the C and 2 for the D. Scaling coefficients c_0 , c_1 , c_2 , c_3 are to be determined from regression analysis. Coefficient R_0 of Eq(1) accounts for saturation in the near field, while h_0 is known as "effective" depth of an event, that is, depth where seismic energy is released. Both Eq(1) and Eq(2) are practically similar apart from the fact that the former has a simple term for distance [21] and in the near field they give slightly different results.

A two step regression analysis was followed [22,23]. In the first step using all recordings of the data set scaling coefficient of magnitude, c_1, was determined. In the second step scaling coefficients c_0, c_2, c_3, were determined using recordings from earthquakes with $Mw \geq 5.0$. The "effective" depth, h_0, or the parameter R_0 is difficult to be determined directly by regression analysis on the available data given its strong correlation with scaling coefficient c_2, as it was shown using appropriate Monte-Carlo simulations [24]. For this reason values of R_0=6km and h_0=7km were adopted for PGA attenuation relation, that correspond to the average focal depth of the events used in the present study as well as to the average "effective" depth calculated using Eq(1), Eq(2), respectively, and macroseismic data for the area of Greece [25]. In a similar way for PGVand PGD attenuation relations values of R_0=5km and h_0=6km were adopted for Eq(1) and Eq(2), respectively.

Following the aforementioned method the following pairs [Eq(1), Eq(2)] attenuation relations were defined for horizontal PGA(cm/sec^2), PGV(cm/sec) and PGD(cm), respectively:

$$\ln PGA=4.16+0.69M_W-1.24\ln(R+6)+0.12S\pm0.70 \quad (3)$$

$$\ln PGA=3.52+0.70M_W-1.14\ln(R^2+7^2)^{1/2}+0.12S\pm0.70 \quad (4)$$

$$\ln PGV=-1.51+1.11M_W-1.20\ln(R+5)+0.29S\pm0.80 \quad (5)$$

$$\ln PGV=-2.08+1.13M_W-1.11\ln(R^2+6^2)^{1/2}+0.29S\pm0.80 \quad (6)$$

$$\ln PGD=-6.63+1.66M_W-1.34\ln(R+5)+0.50S\pm1.08 \quad (7)$$

$$\ln PGD=-7.26+1.68M_W-1.24\ln(R^2+6^2)^{1/2}+0.50S\pm1.08 \quad (8)$$

The last term gives the ±1 standard deviation of each relation. In Figure 3 the mean ±2 standard deviations of horizontal PGA attenuation relation proposed in this study is shown as a function of distance along with data normalized to Mw=6.5. It can be observed that the vast majority of the data are enveloped between ±2σ, showing the validity of the proposed relation. Residuals of the horizontal PGA, PGV and PGD are plotted against distance, R, using Eq(2) in Figure 4. No apparent trend of the residuals is observed.

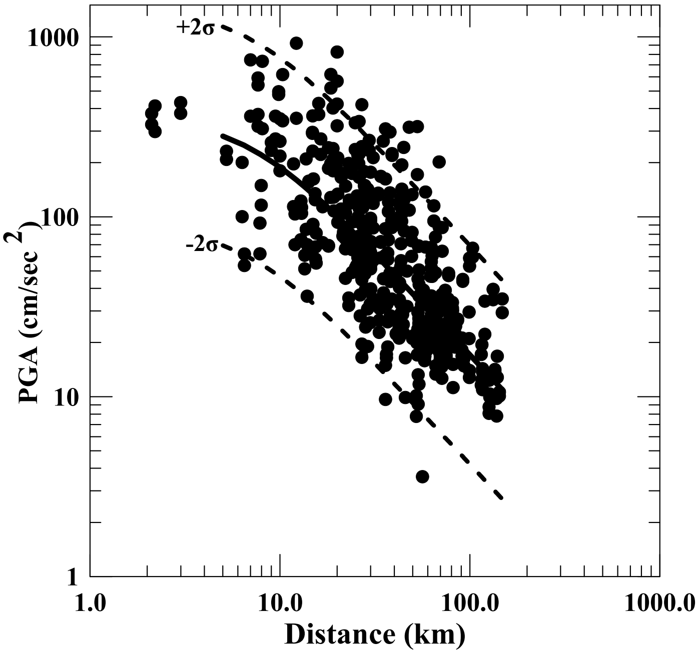


Figure 3: Comparison of the horizontal PGA empirical relation with ± 2σ with the observed values scaled to M=6.5.

From Eqs. (3) to (8) it is concluded that there is a systematic increase of predicted strong ground motion going from "hard" to "soft" soil conditions. Such an increase seems to be more intense for velocity and even more for displacement than for acceleration as is generally expected. Although a simple linear correspondence between soil categories B→S=0, C→S=1, D→S=2 has been chosen based on geotechnical data and the available shear wave velocities of the surficial layers of the recording stations, it seems to work reasonably when quantifying soil influence on strong ground motion.

COMPARISON WITH SIMILAR ATTENUATION RELATIONS AND DISCUSSION

Comparison of the proposed horizontal PGA attenuation relations with those previously proposed for the area of Greece [26], for soil category C→S=1, are shown in Figure 5. Significant differences are observed mainly for large magnitudes with the latter giving higher values of about 60%-90% than the former. This is mainly due to relatively high scaling coefficient of magnitude, $1.01 \leq c_1 \leq 1.12$, of the relations proposed by Theodulidis [26].

In Figure 6 comparison of the horizontal PGA relations with those proposed by Ambraseys [15], for "rock" (S=0) soil conditions, is shown. For distances up to about 30km a good agreement is observed whereas for longer distances the latter relations give higher PGA values. Such a deviation may be due to different data sets used in regression analyses. For instance, Ambraseys used data from various seismotectonic environments that extend to long site-to-source distances [15].

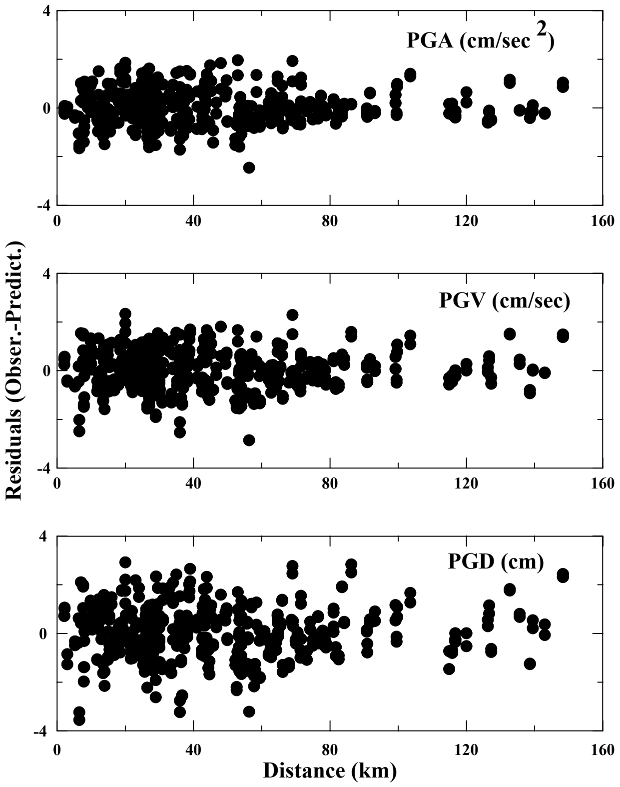


Figure 4: Distribution of the residuals of the peak ground acceleration, velocity and displacement in terms of distance.

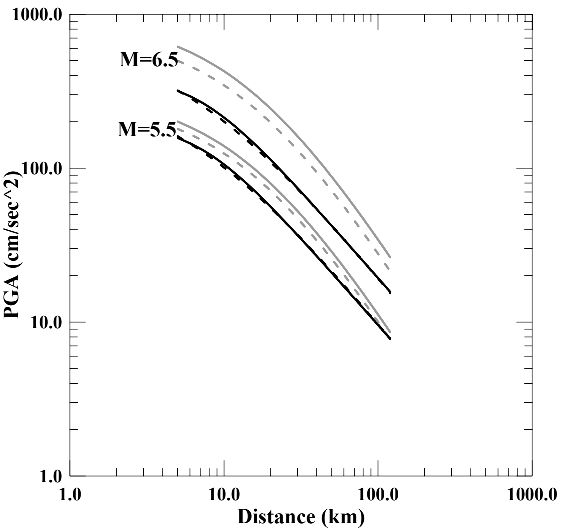


Figure 5: Comparison of the PGA empirical relations, Eqs. (3) (black continuous line) and (4) (black dashed line) with those proposed by Theodulidis [26] for Greek data (grey dashed line) and Greek data enriched with other strong motion data (grey continuous line).

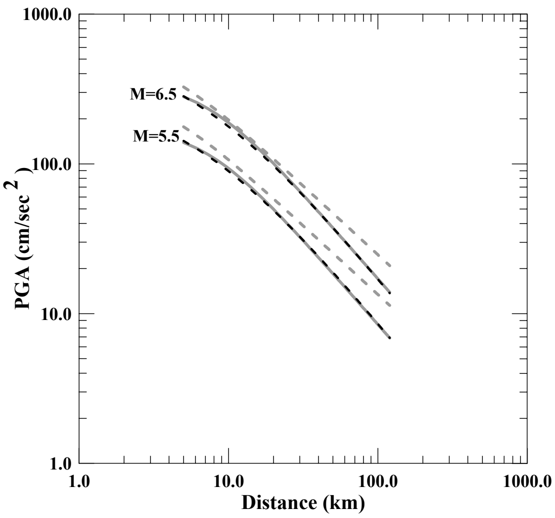


Figure 6: Comparison of the PGA empirical relations, Eqs. (3) (grey continuous line) and (4) (black dashed line) with those proposed by Ambraseys [15] (grey dashed line) for M=5.5 and 6.5 and rock soil conditions.

Sabetta and Pugliese based on strong motion data from normal and thrust faulting-type earthquakes occurred in Italy, proposed horizontal PGA and PGV attenuation relations [14]. In Figure 7 comparison of their horizontal PGA attenuation relation with those presented in this study, for “rock”(S=0) soil conditions, shows systematically higher values of the former. This difference may be due to the fact that Italian data come from both normal and thrust faulting events while the Greek data mainly from normal faulting. Spudich based on strong motion data from normal faulting earthquakes proposed horizontal PGA attenuation relation, [23], that is compared with PGA attenuation relation of this study, for “rock”(S=0) soil conditions (Figure 8). For magnitude Mw=6.5 there is good agreement between the two relations while for Mw=5.5 divergence mainly in long distances is observed.

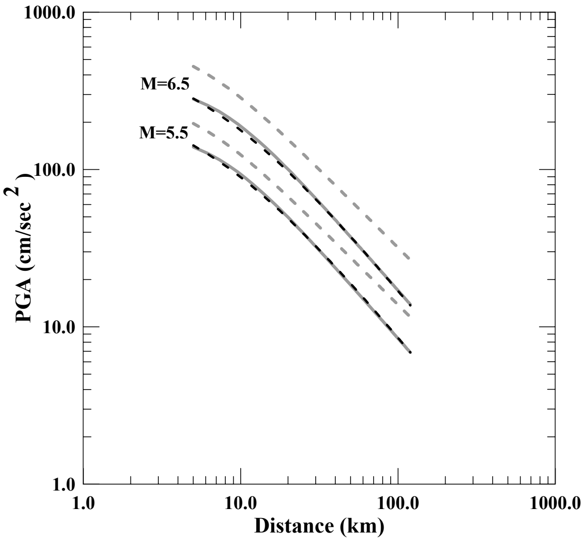


Figure 7: Comparison of the PGA empirical relations Eqs. (3) (grey continuous line) and (4) (black dashed line) with those proposed by Sabetta and Pugliese [14], (grey dashed line) for M=5.5 and 6.5 and rock soil conditions.

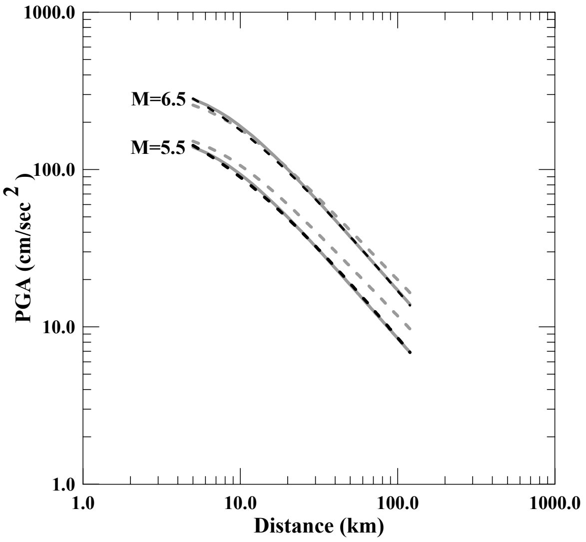
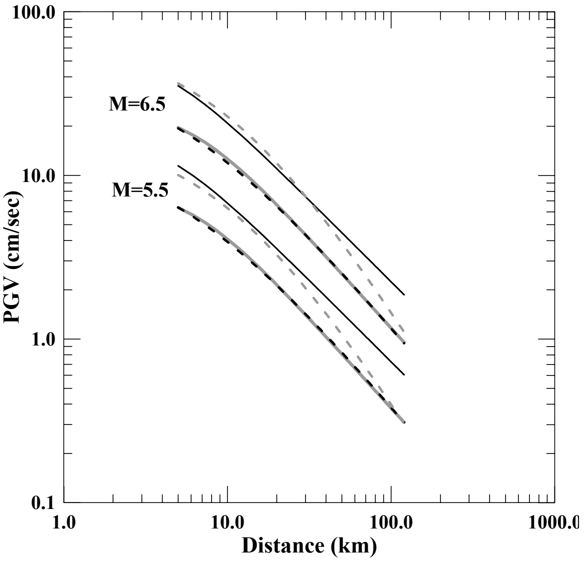


Figure 8: Comparison of the PGA empirical relations Eqs. (3) (grey continuous line) and (4) (black dashed line) with those proposed by Spudich [23], (grey dashed line) for M=5.5 and 6.5 and rock soil conditions.

In Figure 9 a comparison between horizontal PGV attenuation relations of the present study and those of Theodulidis [26] and Sabetta [14], shows that the latter gives up to 60% higher values for the whole distance range. That of Theodulidis although gives higher values for R<50km, at longer distances is in quite good agreement with the PGV attenuation relation of this study.

Empirical PGD attenuation relations to date have been rarely defined. This was mainly due to limited reliable data set since in low frequency strong ground motion a lot of errors (instrumental, processing, etc.) were incorporated. However, some PGD attenuation relations have been published among which those of Kawashima [6] for Japan, Theodulidis [26] for Greece and Gregor [27] for USA. Their divergence is shown in Figure 10 that reaches to about one order of magnitude at distances R>100km. Horizontal PGD values predicted by the relation of this study are in good agreement with those predicted by that of Theodulidis [26], for distances R>30km. However, in shorter distances the latter gives up to 2.5 times higher PGD values.



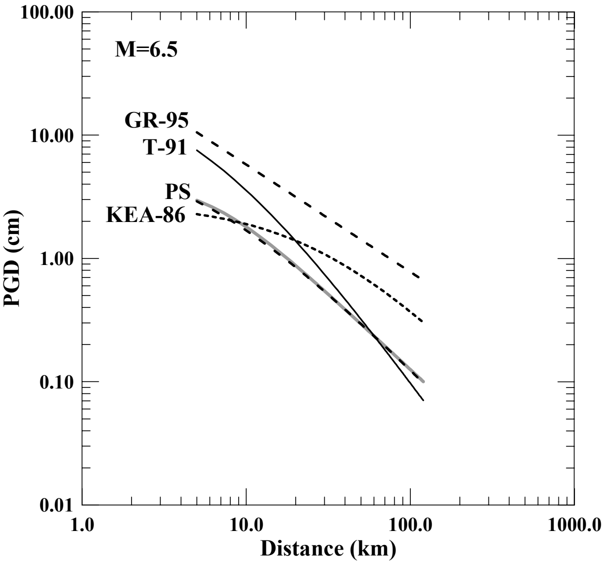


Figure 9: Comparison of the PGV empirical relations, Eqs. (5) (grey continuous line) and (6) (black dashed line) with those proposed by Sabetta [14] (black solid line) and Theodulidis [26] (grey dashed line) for M=5.5 and 6.5 and rock soil conditions.

Figure 10: Comparison of the PGD empirical relations, Eqs. (7) (grey continuous line) and (8) (black dashed line), PS, with those proposed by Theodulidis [26], (black continuous line, T-91), Gregor [27], (grey dashed line, GR-95) and Kawashima [6] (black dashed line, KEA-86), for M=6.5 and rock soil conditions.

CONCLUSIONS

Predictive empirical relations of horizontal and vertical PGA, PGV, PGD proposed in this study were based on an extended data set of strong motion recordings. From the data distribution (see Figures 1,2,3) it can be concluded that the range of validity of the attenuation relations for the epicentral distance is 5km≤R≤120km and for moment magnitude is 4.5≤Mw≤7.0.

Predictive relations [Eq(3) to Eq(14)] have been compared with similar ones from other seismotectonic environments. Good agreement of horizontal PGA attenuation was found with those predicted by the relation of Spudich that was based on worldwide data from normal faulting earthquakes [23]. The data set of the present study comes mainly from normal and some strike-slip faulting type earthquakes. Quite good agreement of the attenuation relation of this study was also observed for horizontal PGV and PGD - especially in intermediate and large epicentral distances, with those proposed by Thedulidis [26].

Predictive relations of horizontal PGA, PGV, PGD defined in this study were based on a satisfactory data set of strong motion recordings in Greece and may be considered as representative of the strong motion attenuation in this area. However, deployment of a denser strong motion network in regions of Greece where thrust faulting dominates could significantly increase in the future the data set used in the present study.

ACKNOWLEDGEMENTS

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