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THE DEPENDENCE OF PEAK HORIZONTAL ACCELERATION ON MAGNITUDE AND DISTANCE FOR SMALL MAGNITUDE EARTHQUAKES IN GREECE

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SUMMARY

Eight hundred nineteen recordings, mainly of aftershock sequences ($1.7 \le \mathbf{M} \le 5.1$) in Greece, at epicentral distances $3\text{km} \le R \le 40\text{km}$, are used to gain some insight into the engineering characteristics of small-magnitude, normal-faulting earthquakes in Greece. The dependence of peak horizontal ground acceleration on magnitude and distance is examined and predictive relations are derived and compared with similar ones proposed for California. Furthermore, predictive relations obtained on the basis of larger magnitude earthquakes ($\mathbf{M} \ge 4.5$) in Greece are compared with those derived in the present work and striking differences are discussed. The results obtained in this work suggest that peak ground acceleration (PGA) of moderate-to-low magnitude events ($\mathbf{M}<5.0$) cannot be predicted using available predictive equations derived from larger events data and that the scaling law of earthquakes in the low-magnitude range needs to be properly defined. In addition, given the fact that small-magnitude events are used in engineering seismology to simulate large events (empirical Green's function method; Hartzell [1]), one should carefully take into account a possible insufficiency of the scaling law of intermediate-to-low magnitude earthquakes in realistically assessing seismic hazard.

INTRODUCTION

A large number of predictive relations of peak ground motion have been proposed by several researchers worldwide, referring either to large geographical regions (e.g. West USA, Europe) or smaller regions or countries (e.g. Italy, Greece). The reference point in all these relations is the data set used, which consists of accelerograms produced from moderate-to-large magnitude earthquakes ($\mathbf{M} \geq 4.5$) and for a wide range of epicentral distances ($5 \leq R \leq 150$ Km). This one-way direction in the estimation of predictive relations of peak ground motions is imposed by the needs of the way that cities are built during the last decades (tall buildings, complex constructions) and by critical constructions, such as power plants, which are built near populated areas. The previously mentioned constructions are mostly affected by large earthquakes, which

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are generally more destructive, but in some cases small to moderate magnitude earthquakes in near-field distances have also caused serious damage in buildings or interrupted the operation of power plants (Campell [2]).

A small number of researchers have dealt with the study of small to moderate magnitude earthquakes recorded at near-field distances in order to derive predictive relations of peak ground motion (Fletcher [3], Campell [2], Costa [4], Theodulidis [5], Bommer [6], Boatwright [7]). It was shown that the previous predictive relations reveal different attenuation characteristics in near-field distances compared to the proposed relations for larger magnitude earthquakes and epicentral distances. This comparison suggests that peak ground motions of events with low magnitude (**M**<5.0) cannot be reliably predicted using available relations and that the scaling law in low magnitude range needs to be properly defined.

Even after these studies, properties of strong ground motion attenuation of small magnitude earthquakes are still under research. In the present study an effort to closely examine these properties is made, using a proper data set (i.e. small to moderate magnitude (1.7≤**M**≤5.1) earthquakes recorded at near-field distances in Greece).

DATA USED

Data used in this paper consist of 819 strong motion recordings, corresponding to 423, mainly normal faulting, shallow earthquakes in Greece. This data set was selected from the strong-motion database of the Institute of Engineering Seismology and Earthquake Engineering (ITSAK) of Greece, which includes accelerograms of earthquakes that occurred in Greece during the period 1986-1999. The selected records correspond to earthquakes of low-to moderate magnitudes, which cover the range of 1.7≤**M**≤5.1 and were recorded at epicentral distances 3km≤*R*≤40km from permanent, as well as temporary monitoring accelerograph networks, operated by ITSAK. A significant number (208) of the waveforms used were recorded within the Euroseistest area in Northern Greece during the period from 1994 to 1997. In Figure 1 a regional map showing the distribution of the recording stations, as well as the epicenters of the selected earthquakes is depicted.

The data set mainly consists of digital accelerograms recorded by ETNA-K2, SSA1 and SSA2 accelerographs and very few analogue instruments (SMA1), which recorded only a small fragment of the data set. The filtering processing of the records to eliminate digitization noise was divided into two parts. Analogue recordings were processed and filtered following the technique proposed by Skarlatoudis [8]. Digital recordings' noise is imposed by the accelerograph characteristics and more specifically by the analogue to digital converter of the recording instrument. The only parameter that affects the noise level in the digital accelerograms is the earthquake magnitude as, in general, small-magnitude earthquakes have different frequency content from large-magnitude earthquakes and usually their PGA values are shifted towards higher frequencies. After studying the frequency content of all the records in the presently compiled data set and applying band-pass filters with different low and high characteristic frequencies, the band-pass filters presented in Table 1 were finally selected for the processing of the digital accelerograms. In Figure 2 an example of the validity of the filtering method applied in the digital recordings is shown. The Fourier amplitude spectra (FAS) of the strong motion part of the two horizontal components are plotted together with the FAS of equal duration post event noise for three different recordings (egote048, egote008 and filia004) derived from earthquakes with **M**=2.5, **M**=3.5 and **M**=5.0 respectively. The comparison showed that the filters applied with the procedure described above, for the range of magnitudes used in the present study, adequately remove the digitization noise from the accelerograms included in our data set.

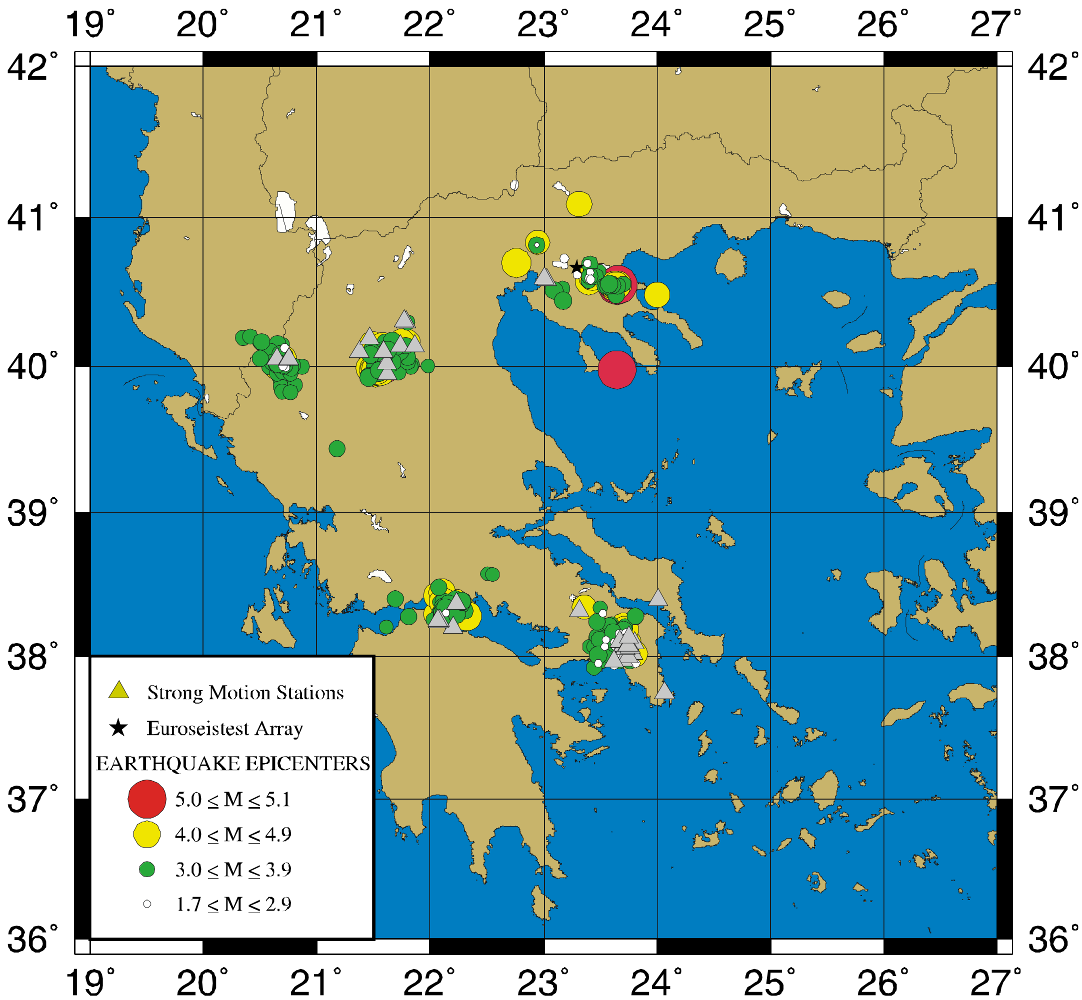

Figure 1: Regional map showing the distribution of the recording stations and earthquake epicenters used in this study *[Star denotes the EUROSEISTEST array]*.

Table 1: Magnitude dependent roll-off and cut-off frequencies used for data filtering in the present study.

M	f_r (Hz)	f_c (Hz)
$2 \leq \mathbf{M} < 3$	0.95	1.0
$3 \leq \mathbf{M} < 4$	0.65	0.7
$4 \leq \mathbf{M} < 5$	0.35	0.4

Source parameters of the earthquakes included in our database were taken from various previously published studies that were based on high-quality data from local networks (Bernard [9], Hatzfeld [10], Theodulidis [5], Panou [11], Papazachos [12]). The magnitudes of the earthquakes were taken from the catalogue of the Geophysical Laboratory of the Aristotle University of Thessaloniki (Papazachos [13]) and the revised catalogue of the Institute of Geodynamics of the National Observatory of Athens (Papanastassiou [14]). The size of the earthquakes in our catalogue, combined from the previously mentioned catalogues, is expressed in a scale equal or equivalent to the moment magnitude, **M** (Papazachos [15]). Moment magnitude was confirmed to be a suitable independent variable in defining attenuation relations for the Aegean area (Papazachos [16]), in agreement with similar observations worldwide (Joyner and Boore [17]). Preliminary site classification of the recording stations was also attempted in four categories (A,B,C,D) proposed by the NEHRP[23] and UBC [24].

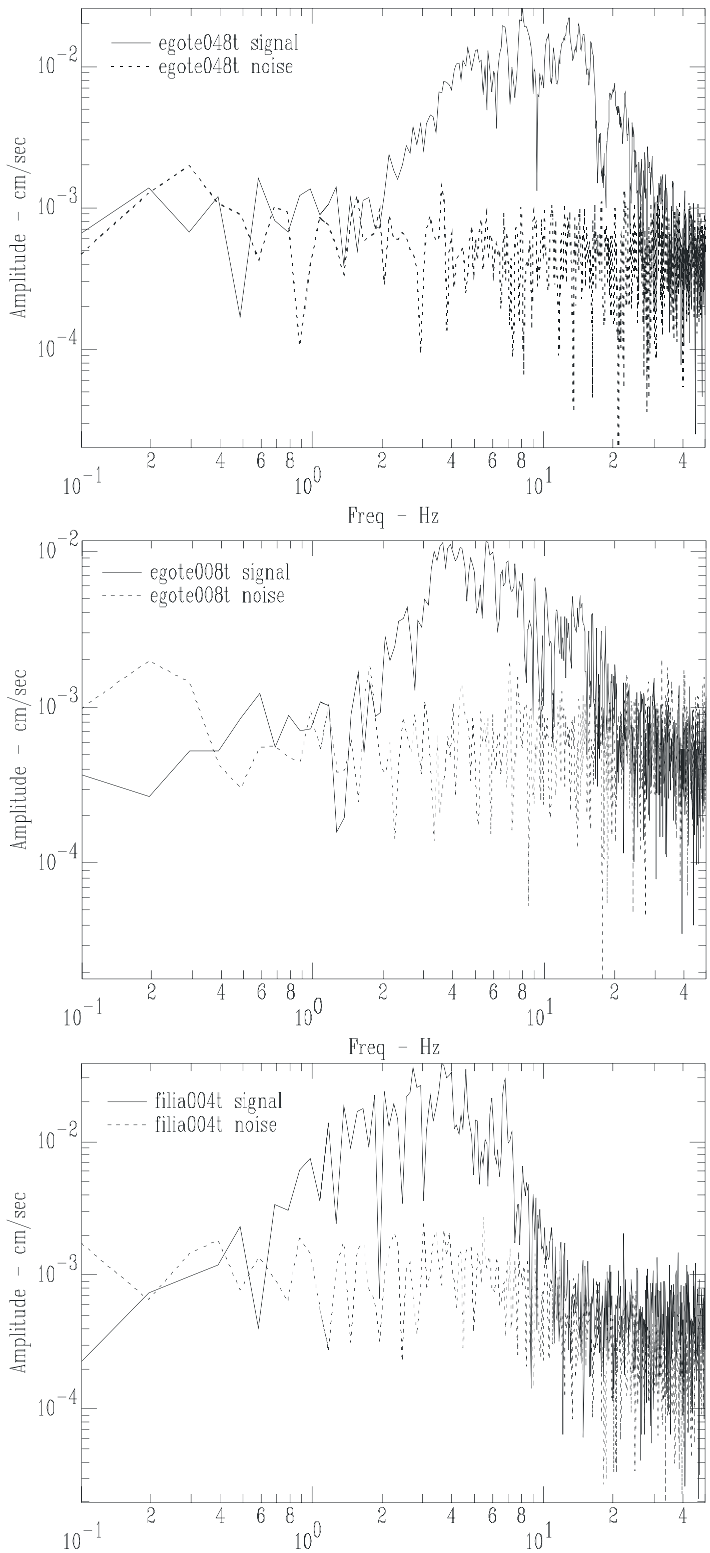

Figure 2: Fourier amplitude spectra (FAS) of the strong motion part of the transversal horizontal component, plotted together with the FAS of equal duration post event noise for three different recordings egote048, egote008 and filia004 (from top to bottom) derived from earthquakes with M=2.5, M=3.5 and M=5.0 respectively.

DATA REGRESSION

In order to define the possible boundary in the epicentral distances range where PGA predictive equations show different properties compared to equations proposed for larger magnitude earthquake data sets, we examined different data sub-sets by successively allowing data recorded up to 40 Km epicentral distance in the regression analysis. The limit of 40 Km was selected because only a few recordings (3%) exist for larger distances. In addition, the selection of a larger distance limit would result in studying properties of predictive equations in far-field distances, which is not the aim of this study. In Figures 3a and 3b, the distribution of PGA values is plotted as a function of epicentral distance, *R*, and magnitude **M** respectively.

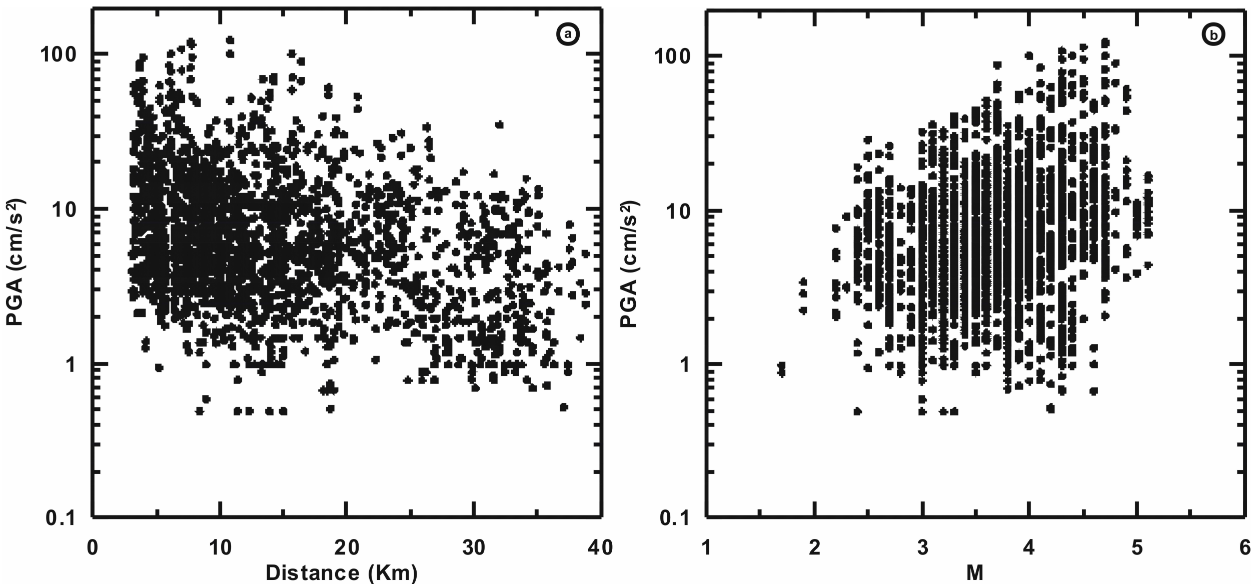

Figure 3: Distribution of peak ground acceleration, PGA, values derived from the strong motion records used in the present work as a function of, a) epicentral distance, *R* and, b) moment magnitude, M.

The equations examined in the regression analysis have the following general form:

$$\log Y = c_0 + c_1\mathbf{M} + c_2 \log\left(R^2 + h^2\right)^{1/2} \qquad (1a)$$

$$\log Y = c_0 + c_1\mathbf{M} + c_2 \log\left(R + c_3\right) \qquad (1b)$$

where *Y* is the strong motion parameter to be predicted, **M** is the moment magnitude, *R* is the epicentral distance and *h* is the focal depth of each earthquake. Scaling coefficients c_0, c_1 and c_2 are to be determined from regression analysis. Coefficient c_3 in equation (1b) accounts for saturation in the near-field and 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 (Papazachos [18], Papazachos [19]). For this reason, a value of c_3=6km was adopted, as suggested by Margaris [20], which roughly corresponds to the average focal depth of the events used in the present study.

The fact that focal parameters of the earthquakes used in this study were computed from different institutes, using different location techniques and software, may result in an inhomogeneously processed data set. Furthermore, errors in phase picking during routine location procedures of small-magnitude earthquakes (indistinct first arrivals) lead to less accuracy in the computed focal parameters compared to corresponding parameters of large-magnitude earthquakes, and especially in the focal depth. On the other hand, most of the events were recorded by local, dense, seismological networks providing good azimuthal coverage of their epicenters and acceptable errors in their focal parameters. However, in order to minimize the effects of the focal parameters uncertainties in the regression analysis, the focal depth was considered constant and set equal to the "effective" depth that is the average depth where seismic energy is released. In the area of Greece the value that corresponds to the average focal depth is estimated to be h_0=7 Km (Papazachos [18], Papazachos [19]), which is also equal to the average depth of the earthquakes used in this study.

Influence of the recording station site conditions was also examined using c_4 as scaling coefficient in equation (1) and showed practically no effect ($c_4 \approx 0$). Thus, site effect scaling coefficient on PGA was neglected and regression analysis performed only for scaling coefficients c_0, c_1 and c_2.

The regression analysis followed in the present study is based on the least squares' method in one step using the Singular Value Decomposition (SVD) method (Lanczos [21]), as described in detail in Skarlatoudis et al. (2003b).

RESULTS

In order to reveal the different characteristics between the predicting relations of small-to-moderate and moderate-to-large earthquakes, and the magnitude threshold where these differences become dominant, the data set used in this study and the one used in Skarlatoudis [22] were combined and processed using the method described above. The results of this joined inversion are presented in the following equation:

$$\log PGA = 0.67 + 0.43\mathbf{M} - 1.08\log\left(R^2 + 7^2\right)^{1/2} \pm 0.35 \qquad (2)$$

In Figure 4a a comparison between the observed values and our relation for PGA versus distance reduced to a magnitude **M**=3.5, plotted together with the $\pm$1 standard deviation curves, is presented. A significant number of data is outside the $\pm$1 standard deviation curves, roughly denoting the insufficiency of this "joint" relation to adequately describe both data sets. This conclusion is becoming more evident when plotting the average PGA residuals for each magnitude, against magnitude in Figure 4b. It is clear that for magnitudes larger than **M**$\geq$5 Equation 2 is insufficient to describe the data set by systematically underestimating the observed values.

The previous observations motivate the derivation of another predictive relation, for predicting PGA values of small to moderate earthquakes. The same procedure as above was applied in the data set compiled in the present study and the results are summarized in the following equations:

$$\log PGA = 1.03 + 0.32\mathbf{M} - 1.11\log\left(R^2 + 7^2\right)^{1/2} \pm 0.34 \qquad (3a)$$

$$\log PGA = 1.24 + 0.33\mathbf{M} - 1.20\log(R + 6) \pm 0.34 \qquad (3b)$$

The last term in the above equations expresses the standard deviation of the predicted value for each relation.

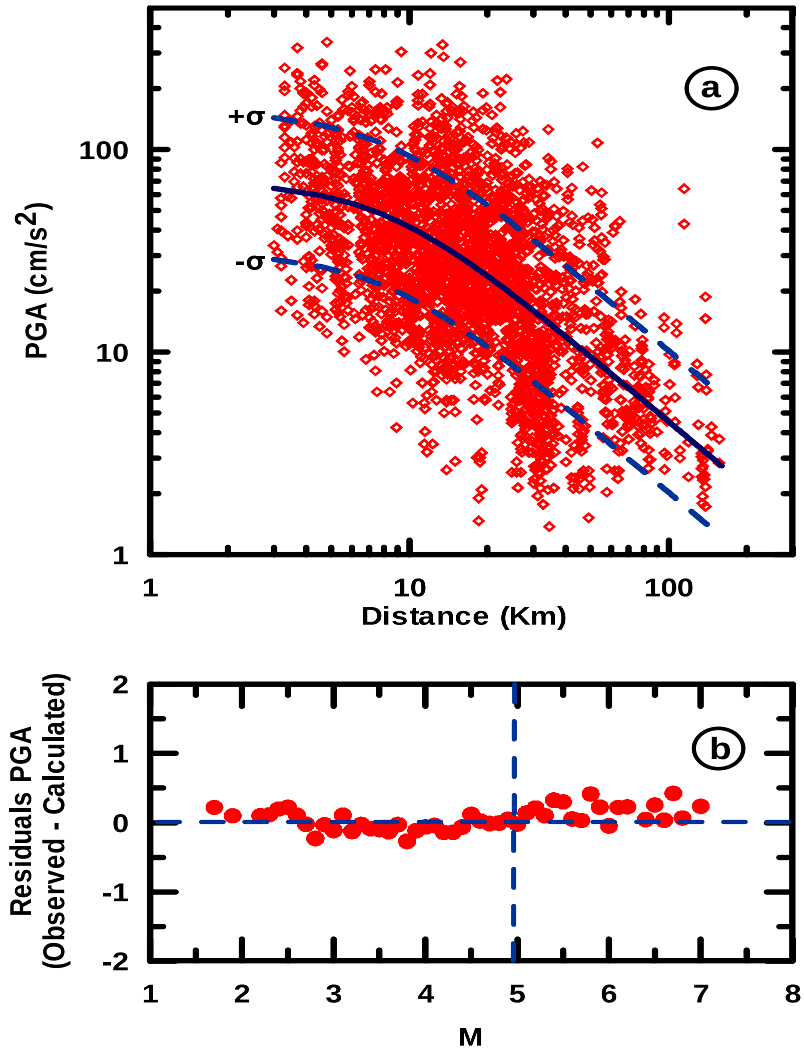

Figure 4: a) Comparison of the horizontal PGA empirical relation with the observed values scaled to M=5.0, plotted along with the ± 1 standard deviation (s.d.) curves, b) Distribution of the average peak ground acceleration residual at each magnitude versus moment magnitude M.

In Figure 5a a comparison of the observed values and our relations for PGA versus distance reduced to a magnitude **M**=3.5, together with the ±1 standard deviation curves, is presented. The examination of Figure 5a allows a rough visual inspection of the data fit to the proposed relations. However it is not safe to draw an absolute conclusion regarding the quality of the fit based on these figures, as the reduction of all data to a common magnitude (**M**=3.5) neglects the magnitude-PGA correlation (Figure 3b). The quality of the fit of the proposed relations is to be evaluated from the RMS error of each relation. The examination of the residuals resulting from the regression analysis, for each of the variables used in the regression model did not show any systematic variations as a function of the remaining variables. In Figures 5b the distribution of the resulting residuals for the proposed relation is plotted against magnitude and distance. It is obvious that no apparent trend can be identified in the residuals.

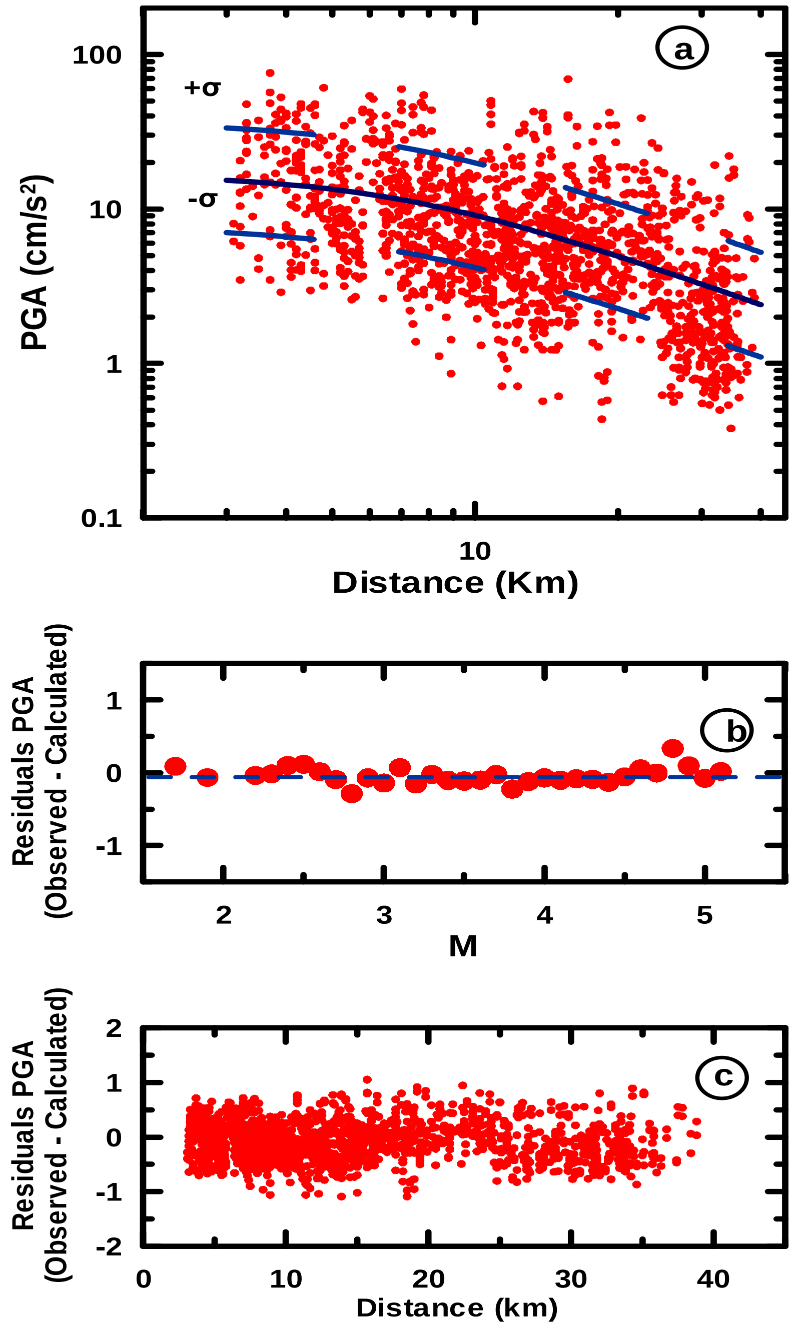

Figure 5: a) Comparison of the horizontal PGA empirical relation with the observed values scaled to M=3.5, plotted along with the ± 1 standard deviation (s.d.) curves, b) Distribution of the average peak ground acceleration residual at each magnitude value versus moment magnitude M, c) Distribution of peak ground acceleration residuals versus epicentral distance R.

DISCUSSION-CONCLUSIONS

Eight hundred nineteen recordings, mainly from aftershock sequences (1.7≤**M**≤5.1), acquired from normal-faulting events in Greece, at epicentral distances 3km≤*R*≤40km, are used to gain some insight into the engineering characteristics of small-magnitude earthquakes in Greece. These recordings came from digital and analogue instruments operated by ITSAK and were processed with a homogeneous method. Although focal parameters and magnitudes of the corresponding earthquakes were computed with various methods, a homogeneous database with focal parameters and magnitudes based on the published catalogues of the Geophysical Laboratory of the Aristotle University of Thessaloniki (Papazachos [13]) and the revised catalogue of the Institute of Geodynamics of the National Observatory of Athens (Papanastasiou [14]), as well as on several previously published studies (Bernard [9], Hatzfeld [10], Theodulidis [5], Panou [11], Papazachos [12]), was compiled.

The regression analysis of the data set, taking into account the previously mentioned obstacles and the massive processing and filtering of the data set resulted in a very good fit and its quality is shown through the RMS and further statistical analysis.

A comparison of the predictive relations defined in this paper, with those proposed by Campbell [2], Theodulidis [5] and Skarlatoudis [22], is shown in Figure 6. All relations are scaled at the epicentral distance of 20 Km and plotted against magnitude. Skarlatoudis [22] relation is plotted for site category C, using the classification proposed by NEHRP [23] and UBC [24]. It must be pointed out that in Skarlatoudis [22], Theodulidis [5] and in the present study the magnitude scale used was the moment magnitude **M** or equivalent moment magnitude when moment magnitude was not available. Plotting against magnitude would reveal a proper definition of the scaling law that rules the predictive relations in low magnitude range. The expected results from this kind of comparison would be continuous curves for the entire range of magnitudes. On the contrary, we concluded the existence of a "step" in the predicted levels of PGA around the magnitude of **M**=4.5, as can be seen in Fig. 6.

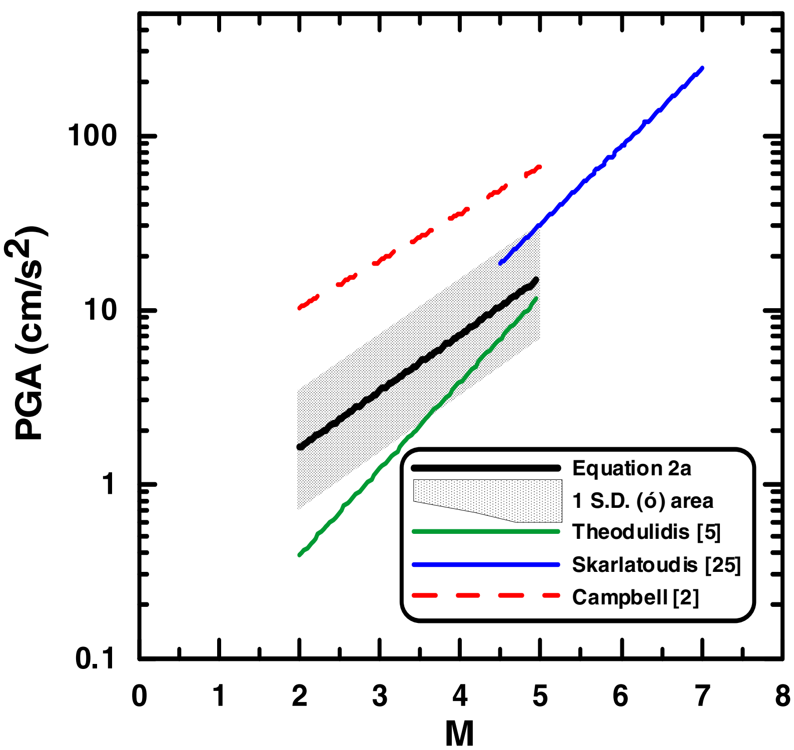

Figure 6: Comparison of the PGA empirical relations (black continuous line), with those proposed by Campbell [2] (red dashed line), Theodulidis [5] (light green dashed) and Skarlatoudis [22] (light blue continuous line) for epicentral distance R=20 Km.

Comparisons among the relations proposed in the present study and the relations proposed by Costa [4] and Ambraseys [25] were also attempted. In Costa [4], the M_D magnitude scale calibrated with the Wood-Anderson instrument of Trieste station was used, while in Ambraseys [25] the M_S magnitude scale was used. Due to the different magnitude scale used, a direct comparison among the previous relations and the relation proposed in the present study is meaningless. For this reason, in Figure 6 we did not include the specific relations. However, comparisons among proposed relations derived from small to moderate magnitude earthquakes data sets (Costa [4], Theodulidis [5]) showed similar gross characteristics; smaller predicted PGA values compared to the corresponding ones from large magnitude earthquakes are noticed. Such a high attenuation of PGA with distance probably results from the frequency content of the corresponding small-to-moderate magnitude earthquakes. Peak ground motions of smaller magnitude earthquakes are usually observed at higher frequencies compared to corresponding peak values of larger magnitude earthquakes. Different levels of predicted PGA values from the different proposed relations are shown in Figure 6. The main feature of this comparison though, is the discrepancy among the relations derived from small earthquakes data set and the relation proposed by Skarlatoudis [22], around the values of magnitude **M**=4.5. A noticeable difference in the slope of the relations and a discontinuity in the predicted levels of PGA between the "two types" of predictive relations are observed. Such major differences were also observed by Theodulidis [5] and Costa [4] and they were attributed either to the different frequency content or stress drop differences between small-to-moderate and moderate-to-large earthquakes.

A possible reason justifying the differences in predicted PGA levels between the "two types" of relations could be the effect of filtering procedure used in the present study and more specifically in the low-pass frequency range used (25 – 27 Hz). Having in mind that PGA values in small-to-moderate magnitude earthquakes usually appear in higher frequencies than in larger-magnitude earthquakes, the PGA predominant frequencies were measured in our data set. All the measured frequencies where smaller than 15 Hz, suggesting that low predicted PGA values from the equations proposed in this study are not affected by the low-pass filtering applied.

A predominant characteristic of the data set used, which is common with Theodulidis [5] and Costa et al. [4] data sets, is the absolute PGA values used in the regression analysis. In all three studies, the vast majority of the data used had PGA values less than 10 cm/s^2 (approximately 10 mg) unlike Campbell [2] and Boatwright et al. [7], who used data with PGA values greater than 30 cm/sec^2. This contrast among the data sets could be one of the reasons producing differences between the predicted PGA levels. Still, this is a precarious argument and attributing the aforementioned discrepancies solely to this contrast is rather risky.

All previous facts enforce the argument that peak ground acceleration of events with low magnitude (**M**<5.0) cannot be reliably predicted using available predictive laws based on moderate-to-large magnitude earthquakes. Taking under consideration the aforementioned, the necessity for further and detailed research is posed in order to specify the actual cause of these differences in the predicted levels of PGA between the "two types" of predictive relations compared.

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