Influence of site response and focal mechanism on predictive performance of peak ground motion prediction equations for the Greek region

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The predictive performance of ground motion prediction equations relative to peak horizontal acceleration (PHA) defined for the Greek region were found not to benefit from the inclusion of terms accounting for site response. This is in part due to an inadequacy of standard methods for site classification to evaluate the expected amount of PHA amplification. Indeed, the adoption of a new method to derive classification from the analysis of regression residuals seems able to improve the predictive performance. However, this improvement is limited by an intrinsic drawback of classification criteria, i.e. the implicit assumption that amplification be a site-specific property not depending on event characteristics. Instead, the inclusion of focal mechanism among the explanatory variables of equations both for PHA and for peak horizontal velocity (PHV) does not improve the predictive performances independently on how fault styles are categorized.

KEYWORDS

Ground Motion Prediction Equations; Peak Horizontal Acceleration; Peak Horizontal Velocity; focal mechanism; site classification; seismic hazard assessment.

Declarations of interest: none

Published on Soil Dynamics and Earthquake Engineering, doi: 10.1016/j.soildyn.2019.105745

1 INTRODUCTION

Empirical equations for ground motion prediction (GMPE) have several employments. They are used to quickly outline the impact of an earthquake in the first minutes of a seismic crisis, to define scenarios of future events expected within emergency preparedness planning and comprise one of the basic tools in the practice of probabilistic seismic hazard evaluation for long-term risk reduction policy. While the first equations proposed in literature had simple functional forms, which provided just a median estimate of basic ground motion parameters as function of source size and distance, in last decades considerable efforts have been addressed to refine prediction capacity adding explanatory variables and adopting more complex functional forms, also benefitting from the increasing availability of accelerometer data.

A debated question about such empirical equations is their areal validity: in principle, regional differences of seismic shakings could be observed, depending on source properties controlled by the tectonic regime and on wave propagation efficiency controlled by geological factors. These considerations motivated the introduction of regionalized equations derived from data acquired within restricted geographical areas, despite the doubts raised about its real need, considering, on the one hand, the resulting limitation of datasets used for regression and, on the other hand, the uncertain significance of inter-regional variability in comparison to the intra-regional one (cf. [1]).

The effectiveness of GMPEs depends on the accuracy of predictions of shakings for future events. Thus, an objective evaluation of whether the adoption of new more complex and/or regionally differentiated equations be justified should not simply rely on their capability of better fitting database used in regression analysis. Indeed, such an improvement may not reflect a real improvement of predictive performance for future events if the adopted models are unable to catch the real major sources of observation variability.

On the basis of such considerations, an updating of GMPEs relative to several ground motion parameters for the Greek area was recently conducted by us employing new available accelerometer data [2]. Several functional forms were tested and the most effective ones were identified from their accuracy in predicting the observations of a "validation" dataset different from that used to calculate equation coefficients through regressions. Such an approach also offered the possibility to compare the effectiveness of new equations in comparison to previously published ones and to evaluate if new equations really improve GMPE predictive performance.

One of the most intriguing outcome of the cited work [2] was the observation that, while for ground velocity-based equations the optimal functional forms include site effect terms, acceleration-based equations do not seem to benefit from the consideration of such effects. Furthermore, for almost all the shaking parameters considered, the prediction accuracy does not seem to improve if equations include terms to represent the influence of focal mechanism.

Therefore, in the present paper, these results are re-analysed, focusing on peak ground motion parameters, i.e. peak horizontal acceleration (PHA) and velocity (PHV). After having briefly recalled the main results obtained by our previous study [2], the results of new tests aimed at giving a better insight on regression results, are presented and the implications of the analysis outcome with regard to the optimization of GMPEs employed for hazard assessment are discussed.

2 REGRESSION METHODOLOGY AND DATASETS EMPLOYED

In our previous work [2], new GMPEs for the Greek area were calculated for PHA and PHV adopting a two-stage approach [3, 4], which separates the estimation of parameters that model the influence of source properties from those representing the effect of wave propagation. This approach is aimed at countering the bias due to the uneven sampling of magnitude-distance within the regression datasets: indeed, the prevalence in such datasets of weak events recorded at short distances and strong events at long distances can lead to underestimate attenuation rates (see [5]).

In the context of defining new GMPEs for the Greek area, several functional forms were tested starting from a general equation having the form

$$\log Y = a + b\,M + c\,log\sqrt{R^2 + h^2} + d\sqrt{R^2 + h^2} + \sum_{i\,=\,1,N} e_i s_i + \sum_{j\,=\,1,\,M} f_j m_j + \varepsilon_r + \varepsilon_e \quad (1)$$

where Y is the geometric mean of orthogonal horizontal components of PHA or PHV, M is the event moment magnitude, R the epicentral distance in km, s_i and m_j are N and M dummy variables accounting for the influence of site effect and focal mechanism, respectively. The prediction uncertainties related to unmodelled intra- and inter-event variability are expressed by ε_r and ε_e, respectively. In equation (1), two causes of ground motion reduction with distance are modelled, i.e. the geometrical spreading, represented by the 3rd term, and the inelastic attenuation, represented by the 4th one, while the coefficient h accounts for the saturation effect constraining Y to finite values as R tends to 0.

All the functional forms tested in regression analyses included the first three terms of the equation (1). Alternative forms were tested excluding one or more of the other terms or varying the number of the dummy variables. Tests were carried out on a general database of accelerometer recordings of 186 events, acquired in the Greek area between 1973 and 2014 (see Table S1 in [2]). From this database, two datasets were extracted: a first "training" dataset was used to determine, through non-linear regressions, the constants appearing in equation (1) and a distinct "validation" dataset was used to compare the effectiveness of different functional forms. For the latter purpose, equations resulting from regressions were applied to predict the logarithm of ground motion observations belonging to the validation dataset and the root mean square *rmsl* of the deviations of the predicted values from the observed ones was used to rank the predictive performance of different equations.

Among the tested equations, the best predictive performances for PHA were provided by equations excluding terms for focal mechanism and site category classified according to the criteria defined by the United States National Earthquake Hazards Reduction Program (NEHRP: see [6]). With regard to PHV, the best equation was found to be the one excluding the terms for focal mechanism and inelastic attenuation, but including site effect modelled through a couple of binary variables set to (0, 0) for sites on rock (class B), (1, 0) for hard soils (class C) and (0,1) for less stiff soils (class D).

In the present paper, we investigate the reasons of these results, through a new series of tests carried out following the same approach. From the general database, two distinct "training" and "validation" datasets were extracted, the former, including 281 two-component accelerograms of 72 events recorded by 120 stations, was used for new regressions, and the latter, consisting of 112 two-component accelerograms of 109 events recorded by 44 stations, was used to compare equation predictive performances. For the requirements of the two-stage approach, the training

dataset was selected in such a way to include only events for which more than one recording are available. Both datasets comprise data relative to events of magnitude up to 6.8, recorded at distances up to about 200 km. Given the scarcity of short distance data in the training dataset, which implies a rather weak constraint for predictions at such distances, validation was carried out only on recordings acquired at distances longer than 5 kilometers. Figure 1 shows the magnitude/distance distribution of the recordings that form the two datasets.

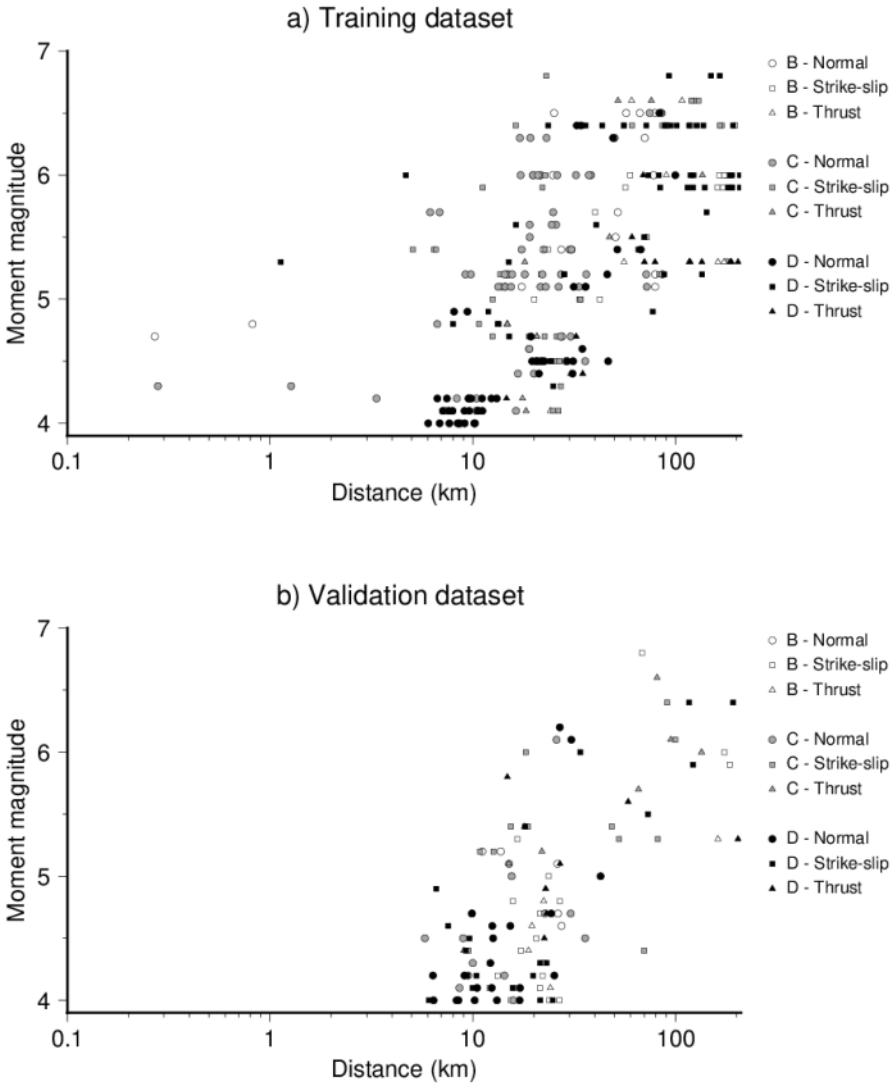

Fig. 1.Magnitude of recorded events as function of distance of the recording station for the "training" dataset (a), used in equation regressions, and for the "validation" dataset (b), used in the equation effectiveness evaluation. White, grey and black symbols are used for data acquired on sites of type B, C and D, respectively, whereas differences of source focal mechanisms are marked by symbol shape (circle = normal; square = strike-slip; triangle = thrust).

3 DATA ANALYSIS

The outcome of regressions carried out in [2] raised questions that stimulated a deeper analysis with the support of additional tests to get a better insight on the result implications. The two main questions were i) the different effectiveness of the introduction of terms accounting for site response in equations for PHA and PHV and ii) the lack of improvement in predictions provided by equations including terms to represent the influence of focal mechanism. Here, we re-examine these results through a more detailed analysis of residuals of equations derived for PHA and PHV.

3.1 Site Effect

The main difference between the equation forms that provided the best predictive performance for PHA and PHV (evaluated from the minimization of root mean square of residuals *rmsl* calculated on the validation dataset) is that, while the inclusion of terms representing site conditions improves significantly the GMPE predictions for PHV, the same does not happen for PHA. This is true not only for the best equation obtained for each ground motion parameter. Indeed, ordering equations by increasing values of *rmsl*, site class is present in the seven best GMPEs for PHV but not in the two best equations for PHA. Furthermore, any PHA equation including site effect terms gives a worse performance than that with the same functional form but without site terms and the use of a single variable distinguishing rock from soil sites gives better results than the use of two variables distinguishing also between more or less stiff soils (see Table S2 in [2]).

At present, the sites of the Greek accelerometer stations are classified according to the NEHRP criteria, based on the mean velocity of shear waves in the top 30 meter of soil (Vs_{30}). This parameter shows some correlation with site conditions responsible for resonance phenomena, even though, the use of this parameter alone for site response characterization presents limits and drawbacks (cf. [7]). Additionally, it can be observed that PHV reflects better than PHA the shaking properties responsible for damaging effects (cf. [8]). Indeed, high PHA values for short-duration high-frequency shakings typically do not produce significant damages on engineering structures, whereas PHV, deriving from an integration of ground acceleration, tends to reach higher values for longer and relatively lower-frequency shakings, responsible for more severe damages.

These considerations suggest the possible need of using distinct site classification criteria to be used for equations predicting PHA and PHV values. Thus, we experimented a reclassification of stations of the Greek accelerometer network, aimed at improving the prediction of the site effect influence on PHA values. This reclassification was based on a cluster analysis of regression residuals aimed at grouping the station sites into a number of distinct classes. Such an approach relies on the consideration that ground motions observed for given magnitudes and distances should differ from median values predicted by a GMPE that does not consider site effect by amount depending on site amplification. Thus, large positive residuals can be expected at sites affected by resonance phenomena (e.g. on soft soils) and negative ones at sites not affected by amplification (e.g. on compact rocks).

The method we propose consists of using preliminarly a GMPE not including site effect terms to calculate median ground motion expected for magnitudes and epicentral distances corresponding

to those of events recorded by accelerometer stations. Only stations are selected for which two or more recordings are available and the average of residuals is calculated for each of these stations. They are then ordered by increasing values of average and the optimal grouping into classes is obtained by looking for the class limits that minimize the root mean square of deviations of residuals of each recording from the average of residuals of stations belonging to the same class of the recording station.

In order to compare the predictive performance of equations excluding site effect terms with those including site response classified according to both the NEHRP criteria and the new approach, regressions were carried out for each equation on a subset of the training dataset of Fig. 1a, comprising only stations for which more than one recording are available. This subset includes 220 two-component recordings acquired by 63 stations for 59 events. The equation obtained with the functional form excluding site response terms is

$$\log PHA = 0.410 + 0.513\,M - 0.896\,log\sqrt{R^2 + 5.002^2} - 0.0054\sqrt{R^2 + 5.002^2} \pm 0.265 \quad (2),$$

where 0.265 is the total standard deviation estimated, given by the quadratic mean of ε_r and ε_s. With regard to equations including site classes, all stations in the training dataset are classified in one of three NEHRP classes (B - rock, C – hard soil and D – relatively softer soil). Thus, two dummy variables s_C and s_D were used to distinguish among the three categories, setting them to (0, 0), (1, 0) and (0, 1) for site class B, C and D, respectively. Using the NEHRP criteria to assign the accelerometer sites to the three classes, the resulting equation is:

$$\log PHA = 0.171 + 0.524\,M - 0.921 log\sqrt{R^2 + 4.941^2} - 0.0051\sqrt{R^2 + 4.941^2} + 0.191 \cdot s_C + 0.251\,s_D \pm 0.251 \quad (3)$$

The residuals of the regression provided by equation (2) were used to reclassify the station sites into three classes B′, C′ and D′. Figure 2 shows the residuals distribution and the site class grouping obtained from the cluster analysis, whereas Tab. 1 reports a comparison between the original classification (based on the NEHRP criteria) and that resulting from the cluster analysis. The three classes are characterized by mean residuals equal to -0.387±0.222 (class B), -0.086±0.220 (class C) and 0.220±0.257, which are results consistent with the expected increase of ground motion passing from rock site to more and less stiff soils.

In Table 1, in order to highlight classification differences, cell reporting classes with different ranking in terms of expected amplification level are marked with different grey shades (from white for B/ B′ to dark grey for D/D′). One can notice that the new classification agrees with the NEHRP one only for about half of the stations examined (33 out of 63). For 25 sites, the reclassification moves the site by one level above or below that of the NEHRP class. In some cases, this can depend on a slight shift of the class limit (e.g. KOZ2 and NOAA, which exchanges their belonging to rock and stiffer soil classes in the old and new classification, are both located close to the boundary between class B′ and C′). However, in some other cases, the observed residuals are inconsistent with the NEHRP classification (e.g. E02 and LCHA, which NEHRP criteria assign to class D, show residuals near the limit between class B′ and C′), and in five cases (FRM, KYP1, RIOA, VLSA and ZARA) classification varies by two levels (from B to D′ or from D to B′).

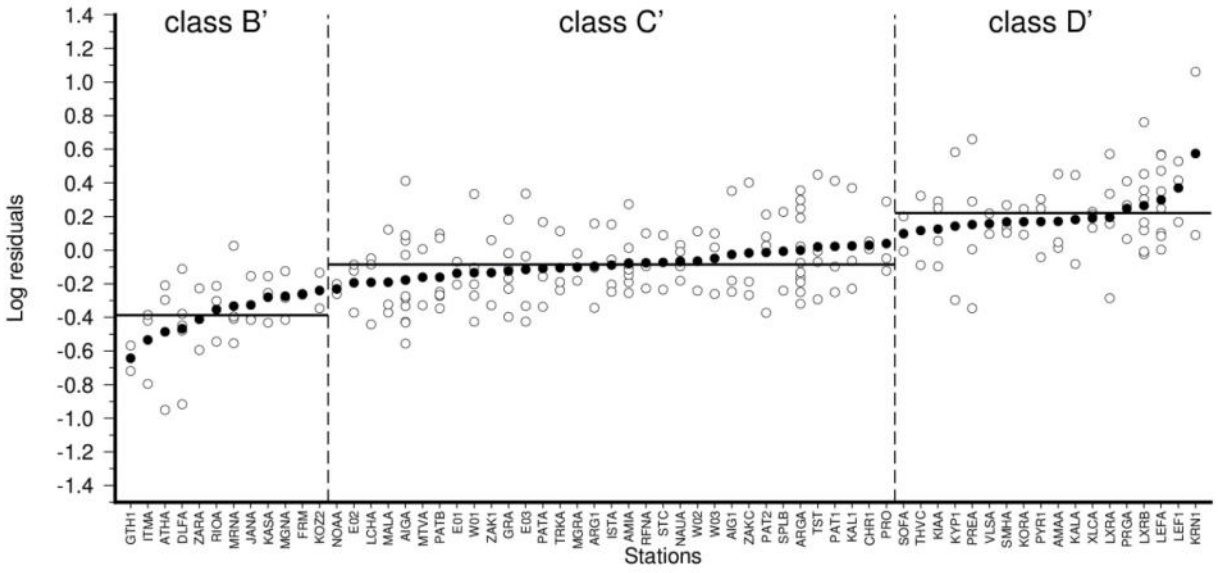

Fig. 2. Results of the site reclassification based on the residuals of the regression of PHA values according to the equation (2). Open circles represent residuals of single recordings at each station of the training dataset, black dots correspond to the mean value of residuals for each station, vertical dashed lines separate the stations classified in different site classes and horizontal solid lines mark the average of residuals for the stations of each site class.

Using the new station classification, a new equation was calculated by regression on the same dataset, adopting a functional form where site classes are expressed through two dummy variables $s_{C'}$ and $s_{D'}$. The result is:

$$\log PHA = 0.097 + 0.481\, M - 0.763 log \sqrt{R^2 + 4.686^2} - 0.0058\sqrt{R^2 + 4.686^2} + 0.263 \cdot s_{C'} + 0.531\, s_{D'} \pm 0.190 \quad (4),$$

which is characterized by a considerable lower standard deviation than the previous equations. This was expected, because the new classification is correlated to residuals of equation (2) better than the classification used in equation (3), so that equation (4) can explain in terms of site response a larger amount of the observed ground motion variability.
In order to verify if the reduction of standard deviation is due to a real improvement of the predictive performance and not just to an "overfitting" of the dataset used for regressions, the predictions of the three equations were compared with the observations of a different dataset. This consists of a subset of the validation dataset of Fig. 1b, including only recordings acquired at the sites for which the cluster analysis provided the new classification, i.e., 88 recordings acquired by 24 stations for 86 events. Applied to these data, the three equation provides estimated errors whose root mean square *rmsl* (calculated on the logarithm of PHA) was found 0.299 for equation (2), 0.321 for equation (3) and 0.287 for equation (4).

Table1.Comparison between accelerometer site classes derived from the NEHRP criteria and from a reclassification based on cluster analysis. For each station, geographic coordinates and the available number of recordings are reported.

Code	Lat	Lon	N. rec	NEHRP	Reclass	Code	Lat	Lon	N. rec	NEHRP	Reclass
AIG1	38.250	22.067	3	C	C′	**MGNA**	38.656	20.791	3	B	B′
AIGA	38.251	22.085	11	C	C′	**MGRA**	37.996	23.345	2	C	C′
AMAA	37.795	21.350	3	D	D′	**MRNA**	38.525	22.117	4	C	B′
AMIA	38.528	22.378	8	C	C′	**MTVA**	39.770	21.183	2	D	C′
ARG1	38.167	20.483	3	C	C′	**NAUA**	38.394	21.833	5	B	C′
ARGA	38.177	20.479	11	C	C′	**NOAA**	37.973	23.718	2	B	C′
ATHA	38.001	23.774	3	C	B′	**PAT1**	38.250	21.733	3	C	C′
CHR1	40.133	21.733	2	C	C′	**PAT2**	38.238	21.738	4	C	C′
DLFA	38.478	22.496	5	B	B′	**PATA**	38.250	21.730	3	C	C′
E01	40.671	23.307	2	D	C′	**PATB**	38.239	21.727	6	D	C′
E02	40.674	23.316	3	D	C′	**PREA**	38.956	20.753	4	C	D′
E03	40.676	23.324	4	D	C′	**PRGA**	39.286	20.402	3	D	D′
FRM	40.655	23.298	2	D	B′	**PRO**	40.688	23.276	3	C	C′
GRA	40.675	23.289	6	D	C′	**PYR1**	37.670	21.438	3	D	D′
GTH1	36.754	22.567	2	B	B′	**RFNA**	38.020	23.987	3	C	C′
ISTA	38.953	23.155	4	D	C′	**RIOA**	38.296	21.791	3	D	B′
ITMA	37.178	21.925	3	B	B′	**SMHA**	38.251	20.648	3	C	D′
JANA	39.656	20.849	3	B	B′	**SOFA**	39.338	22.097	2	D	D′
KAL1	37.033	22.100	3	C	C′	**SPLB**	38.004	23.710	2	C	C′
KALA	37.030	22.120	2	C	D′	**STC**	40.649	23.305	2	C	C′
KASA	39.746	19.936	3	B	B′	**THVC**	38.319	23.318	2	C	D′
KIAA	38.014	22.750	4	D	D′	**TRKA**	39.553	21.766	3	D	C′
KORA	37.939	22.931	2	D	D′	**TST**	40.664	23.291	4	D	C′
KOZ2	40.300	21.790	2	C	B′	**VLSA**	38.177	20.589	2	B	D′
KRN1	36.802	21.961	2	C	D′	**W01**	40.665	23.274	5	D	C′
KYP1	37.250	21.667	2	B	D′	**W02**	40.661	23.260	2	D	C′
LCHA	37.938	21.264	3	D	C′	**W03**	40.660	23.251	3	D	C′
LEF1	38.826	20.702	3	D	D′	**XLCA**	38.078	22.631	3	D	D′
LEFA	38.833	20.704	8	D	D′	**ZAK1**	37.784	20.898	2	D	C′
LXRA	38.200	20.437	4	D	D′	**ZAKC**	37.784	20.898	3	D	C′
LXRB	38.200	20.437	8	D	D′	**ZARA**	37.487	21.649	2	D	B′
MALA	38.622	23.232	3	C	C′						

It is noteworthy that the *rmsl* calculated on the regression dataset was found equal to 0.307, 0.292 and 0.236, for (2), (3) and (4), respectively. Thus, equation (3), which adopts the NEHRP classification, while, in comparison to equation (2), slightly improves the fitting with the

regression dataset, shows a worse performance in predicting the observations of the validation dataset. This result is consistent with what was observed in [2], and confirms that the reduction of standard deviation depends only on an "overfitting" of data, without providing an improvement of prediction accuracy on independent data. On the other hand, in comparison to the basic equation (2), the equation (4), which adopts the new classification, shows an improvement of prediction accuracy, which is however much smaller than that observed when applied to the regression dataset. This suggests that the improvement obtained in PHA prediction with a classification more specific for this parameter is rather weak.

A possible explanation of the limited efficacy of the inclusion of site class as explanatory variable is the implicit assumption of common GMPEs that site amplification, apart from fluctuations related to casual factors (e.g. seismic wave incidence angle at the surface) is a site-specific property independent on seismic source properties. Indeed, its modelling with binary dummy variables implies that the amplification amount is on average the same for any event of different magnitude and distance. However, experimental observations indicate that amplification may not be independent on source size and distance, because these factors influence the spectral distribution of shaking energy, which generates a different response according to the site resonance frequency. It was observed, for instance (see [9]), that, in case of events of magnitude and distance below a certain threshold, PHA at reference sites on rock can be even larger than on nearby sites on soil known to be affected by amplification. This is likely due to a major concentration of seismic shaking energy, for low-magnitude short-distance events, at frequencies that are higher than those of soil site resonance and are more efficiently transmitted through rock materials.

Therefore, to investigate the reason of the limited effectiveness of site class for the prediction of PHA, we examined how residuals of GMPE excluding site terms vary with distance and magnitude for site classified according to the NEHRP criteria. Figure 3 (left side) shows the results of this analysis applied to the residuals of the regression of equation (2). A running average was calculated over the residuals of 11 consecutive observations of the regression dataset ordered by increasing distance (top) and magnitude (bottom), so to reduce the influence of fluctuations related to other factors that can randomly influence the results. It is apparent that residuals do not show significant systematic differences between sites classified into NEHRP classes C and D, whereas sites of class B shows, as expected, PHA values below the average and clearly smaller than sites C and D, but only at distances larger than 30 km and magnitudes over 5.2. This indicate that at short distances from moderate magnitude events, sites classified into classes B, C and D do not show significant differences of the PHA amplification factor. The same occurs for any distance and magnitude for sites of class C and D, which additionally explains the mentioned observation that equations including two dummy variables were found not to perform better than those using just one variable for site classification.

For comparison, a similar analysis was carried out also on the PHV values of the same dataset. A regression was performed using a functional form without site class term and without inelastic attenuation term (which according to the results of the previous study[2], was found to have a negligible influence on PHV prediction accuracy). The resulting equation is

$$\log PHV = -1.064 + 0.681\,M - 1.459\,log\sqrt{R^2 + 6.606^2} \pm 0.290 \qquad (5),$$

and the running averages of residuals as function of distance and magnitude are reported in the right part of Fig. 3.

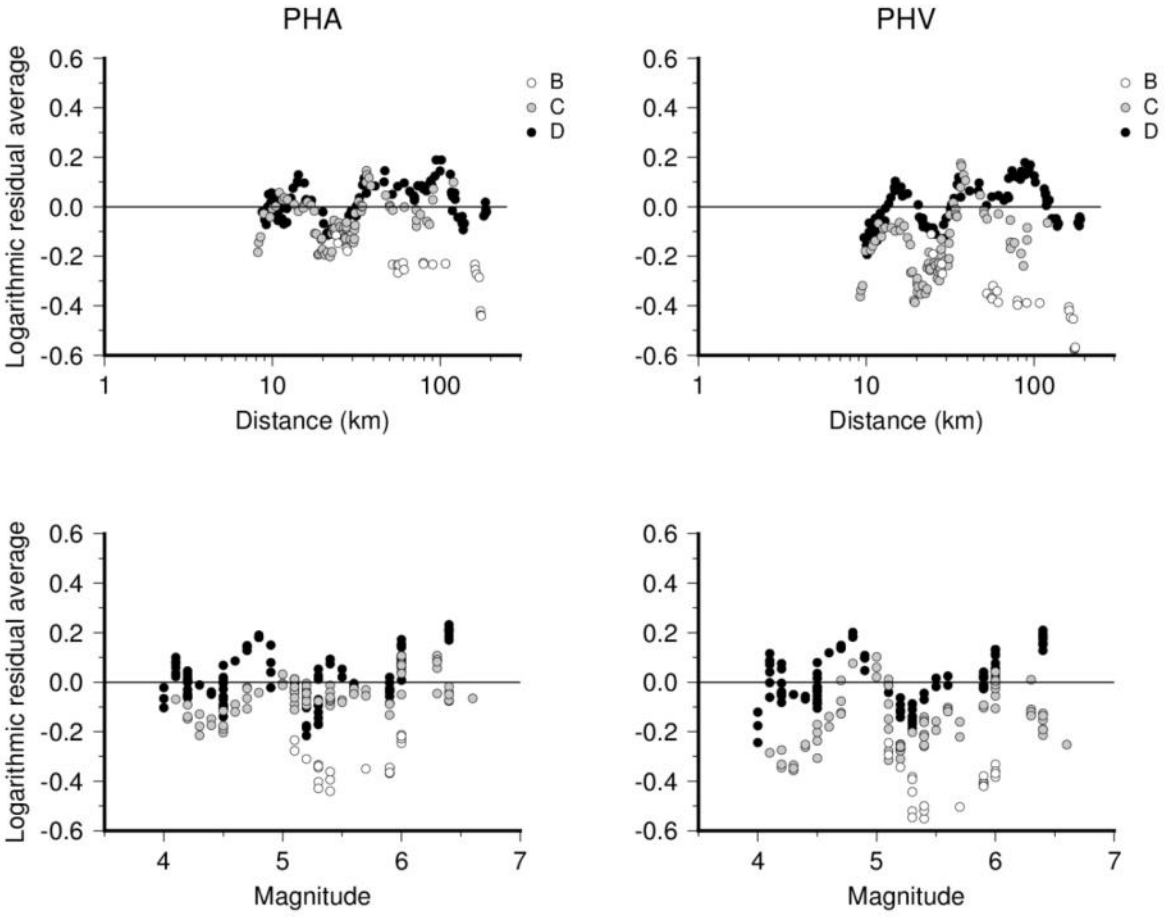

Fig. 3. Running averages of logarithmic residuals of GMPE not including site class term, as function of distance (top) and magnitude (bottom), for peak acceleration (left) and velocity (right). Data relative to different site classes are represented with different grey shade, according to the legend.

One can notice that, for PHV, residuals relative to sites of class C are prevailingly quite below those of sites D and those of sites B below those of both of them, even though, as for PHA, differences between sites B and C tends to reduce for distances shorter than 30 km and magnitude smaller than 5.2. Overall, the distribution of residuals for PHV estimations appears more consistent with the expected increase of ground motion passing from a rock site to a hard soil and to a less stiff ground. This can explain why GMPEs for peak velocity seem to benefit more from the introduction of a representation of site conditions through two variables. A similar result had been previously obtained for GMPE predicting Arias intensity [10], which supported the reliability of the existing site classification for ground motion parameter related to the total shaking energy.

These results, however, indicate also that the site classification based on residual analysis can be influenced by the combination of magnitude and distances that are prevailing for the recordings of a given station. For instance, a site on rock reporting recordings only for short-distance/lower-magnitude events, will show residuals comparable with those observed for sites on soil, and

could then be classified together to them. Thus for generic predictions of PHA, the distinction between site classes does not seem useful, unless new kind of site effect modelling be introduced assuming this effect as depending on magnitude/distance combinations (which, however, would require a larger amount of data for regressions).

3.2 Focal Mechanism

A second question examined is the apparent insignificance of focal mechanism as explanatory variable, which implies that, according to the comparative tests carried out on the validation dataset, fault mechanism is not a factor that needs to be taken into account for prediction optimization. We carried out some additional tests to verify if this result could depend on an inadequate association of focal mechanisms to dummy variables. In our previous work [2], the categorization of event focal mechanisms had been simplified unifying strike-slip and thrust fault types, following the outcome of previous studies [11], thus a single dummy variable *m* had been included in equation (1), setting its value to 0 for normal faults and to 1 otherwise. Therefore, we carried out new regressions on the entire training dataset of Fig. 1a. In a first regression we used again a single dummy variable, named m_T, but set to 1 for thrust faults and to 0 otherwise, whereas in a second regression the three basic mechanism types were separated by using two dummy variables m_S and m_T, set to (0,0), (1,0) and (0,1) for normal, strike-slip and thrust mechanisms, respectively. For comparison homogeneity, the same dataset was used also to recalculate equations without focal mechanism terms and with a single dummy variable m_{ST}, set to 0 for normal faults and to 1 otherwise (as in [2]).
The equations resulting from regressions are, for PHA:

$$\log PHA = 0.396 + 0.522\,M - 0.952\,log\sqrt{R^2 + 5.379^2} - 0.0047\sqrt{R^2 + 5.379^2} \pm 0.262 \quad (6)$$

$$\log PHA = 0.420 + 0.499\,M - 0.952\,log\sqrt{R^2 + 5.379^2} - 0.0047\sqrt{R^2 + 5.379^2} + 0.236\,m_{ST} \pm 0.255 \quad (7)$$

$$\log PHA = 0.364 + 0.531\,M - 0.952 log\sqrt{R^2 + 5.379^2} - 0.0047\sqrt{R^2 + 5.379^2} + 0.246\,m_T \pm 0.259 \quad (8)$$

$$\log PHA = 0.402 + 0.507\,M - 0.952 log\sqrt{R^2 + 5.379^2} - 0.0047\sqrt{R^2 + 5.379^2} + 0.203 \cdot m_S + 0.326\,m_T \pm 0.255 \quad (9).$$

Taking into account the results reported in the previous section about the significant influence of site effects for the prediction of PHV, test relative to this parameter were carried out adopting a functional form including the dummy variables s_C and s_D to distinguish among sites of class B, C and D. Instead, following the outcome of the previous work [2] about the insignificance of inelastic attenuation, the relative term was omitted. The equations obtained by regressions are:

$$\log PHV = -1.526 + 0.710\,M - 1.438\,log\sqrt{R^2 + 6.405^2} + 0.198\,s_C + 0.355\,s_D \pm 0.259 \quad (10)$$

$$\log PHV = -1.483 + 0.691\,M - 1.438\,log\sqrt{R^2 + 6.405^2} + 0.198\,s_C + 0.355\,s_D + 0.178\,m_{ST} \pm 0.256 \quad (11)$$

$$\log PHV = -1.591 + 0.720\,M - 1.438\,log\sqrt{R^2 + 6.405^2} + 0.198\,s_C + 0.355\,s_D + 0.275 m_T \pm 0.256 \quad (12)$$

$$\log PHV = -1.545 + 0.705\,M - 1.438\,log\sqrt{R^2 + 6.405^2} + 0.198\,s_C + 0.355\,s_D + 0.123\,m_S + 0.326\,m_T \pm 0.255 \quad (13).$$

One can notice that the coefficients of terms accounting for attenuation (geometric or inelastic) and site effect (when present) are the same for all the equations relative to the same ground motion parameter. This is a consequence of the two-stage approach, since the coefficients of these terms are all calculated in the first stage, which is independent from source properties. On the contrary, the other coefficients, depending on magnitude and focal mechanism, differ because are calculated in the second stage by using regression equations of different form. Despite the slightly lower value of regression standard deviation for equations that include focal mechanism terms, when these equations are applied to the entire validation dataset of Fig. 1b, the resulting root mean square of logarithmic errors (*rmsl*) is higher. With regard to PHA, for equation (6) the resulting *rmsl* is 0.305, against 0.315 for (7), 0.309 for (8) and 0.317 for (9). For PHV, the equation (10) gives *rmsl* = 0.317, whereas equations (11), (12) and (13) give 0.342, 0.324 and 0.340, respectively. Both for PHA and PHV, the distinction of thrust faults alone (equations 8 and 12) from the other types seems to give better predictions than other mechanism combinations, but, in any case, these predictions are worse than those obtained totally neglecting the fault type influence.

The absence of any improvement with the inclusion of focal mechanism among the explanatory variable reflects the absence of any correlation between the mechanisms of the recorded events and the residuals of observations obtained from the equations not including focal mechanism terms. Figure 4 shows that, for different events of different magnitude, one can find large residuals both positive and negative for the same fault type, without any preferential concentration around a mean level changing from one mechanism to the other, also taking into account the possible different influence of site effects on the ground motion recording.

This is confirmed also using the best equations obtained in the previous study [2] to calculate the PHA and PHV values of the validation dataset. Examining the averages of residuals relative to recordings acquired under similar site conditions for events of different source type (Fig. 5), no systematic variation is recognizable passing from normal to strike-slip or thrust fault mechanisms. Although, based on this test alone, one cannot exclude that such a result can depends on an incorrect station site classification, the results of the tests reported in section 3.1 about site effect influence let us exclude such an explanation at least for PHV. Thus, data indicate that, within the magnitude interval covered by the regression dataset (from 4.0 to 6.8), the employment of focal mechanism as explanatory variable to predict peak ground motion parameters for the Greek area does not seem justified, and the influence of source properties can be represented by magnitude alone.

4 DISCUSSION AND CONCLUSION

The results of data analysis reported in previous sections have some implications about the use of GMPE in hazard assessment, especially when aimed at providing elements required for the definition of building codes in seismic regions. According to a generally recommended practice, the definition of design spectrum for elastic analysis is anchored to the results of a "base" hazard assessment, expressed in terms of design ground acceleration (DGA). This parameter is given by the PHA value with a defined exceedance probability calculated at sites where the presence of outcropping compact rocks is assumed (e.g. site of class A, according to the Eurocode 8: see [12]). The consideration of the real local site conditions is subsequently taken into account by calculating the increase of seismic actions due to site response, either through simplified methods, as reported in [12], or through numerical modelling.

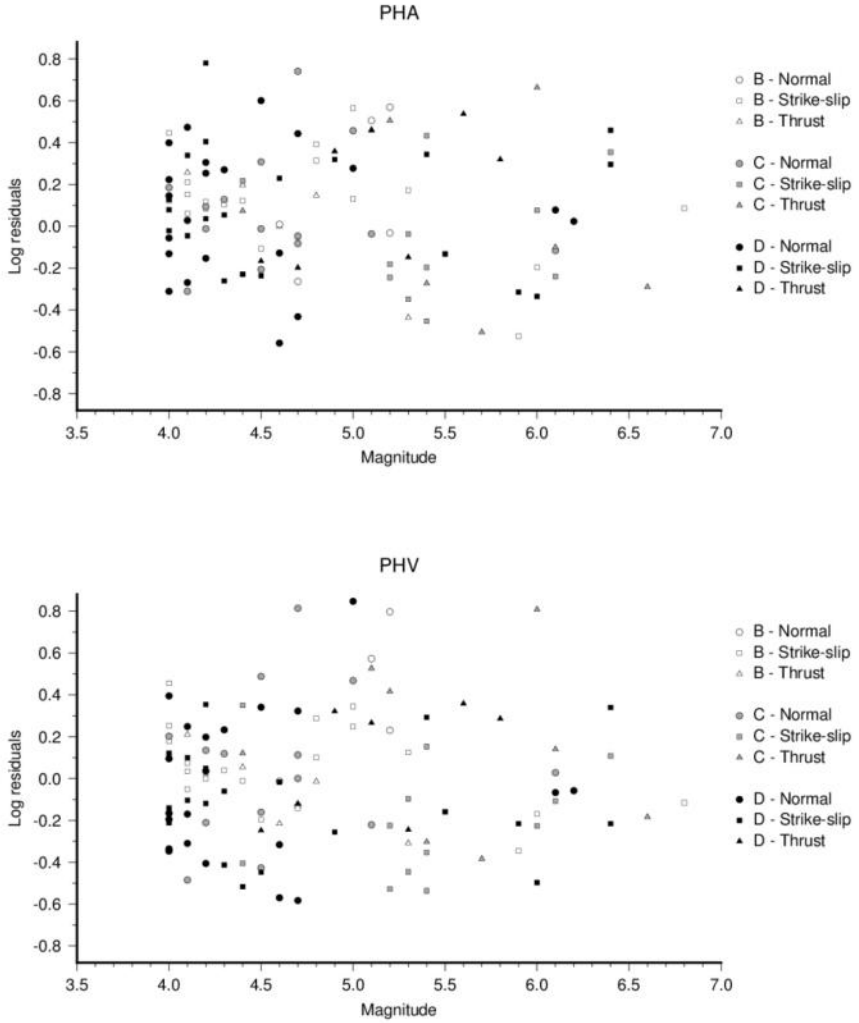

Fig. 4 Residuals of the application of the equations (6) and (10) (excluding focal mechanism) to predict PHA (top) and PHV (bottom) values of the validation dataset. Data relative to recordings of events with different focal mechanism, acquired at sites of different type, are represented through different symbols and grey shades, according to the legend.

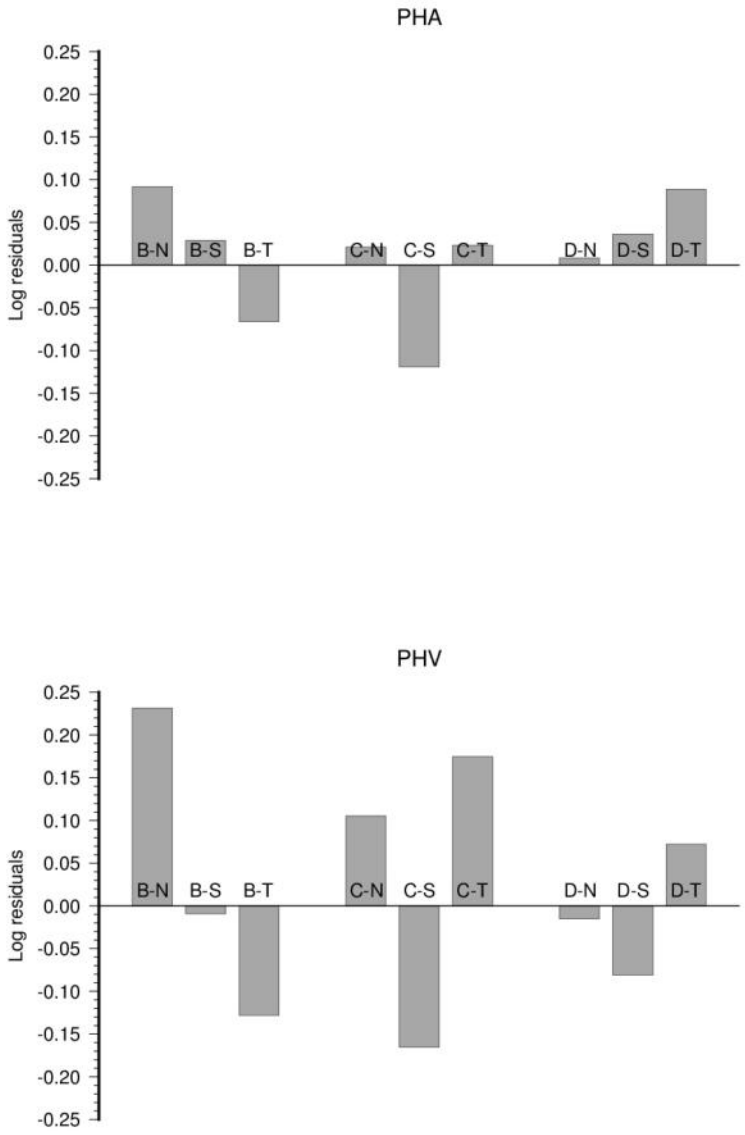

Fig. 5 Averages of logarithmic residuals derived applying the best equations obtained by [2] *to predict PHA (top) and PHV (bottom) values of the validation dataset. Data relative to recordings of events with different focal mechanism, acquired at sites of different type are labelled with B, C and D (indicating the site class of the recording stations), followed by N, S and T, for normal, strike-slip and thrust mechanisms, respectively.*

Therefore, for the calculations of DGA, once the probability of earthquake occurrence has been evaluated for seismic events occurring within relevant seismogenic zones, a GMPE is used to estimate the probability distribution of ground motion expected at sites on rock. For this purpose, GMPE calibrated on accelerometer database are generally employed, setting the site effect terms to the values for rock site conditions. The results of tests shown in the present study, however,

suggest that GMPEs calibrated on data of accelerometer stations classified according to standard criteria (e.g. based on simplified parameters like Vs_{30}) might provide unreliable estimations. Therefore, in assigning class to accelerometer stations whose data are to be used in GMPE regressions, it is advisable to adopt criteria more specific for PHA estimates, for instance following the approach outlined in section 3.1. Although such a method cannot be of general use for site classification, being applicable only where accelerometer recordings are available, and despite the results of classification can be influenced by the prevailing magnitude/distance combination for the recordings available at different stations, stations classified as B′ are in any case representative of site conditions not affected by amplification. Thus, having built a database for GMPE regression by using a classification based on PHA residual analysis, the use of the resulting equation, once the site terms are set to the values for class B′, allows estimating the PHA values expected in absence of amplification, which is just what required for "base" hazard assessment.

Another indication deriving from our study is that, for hazard assessment, it is not worthwhile employing GMPEs that model the influence of focal mechanism on PHA, which, moreover, require a differentiations of calculations for seismogenic zones characterized by different focal mechanisms. Indeed, our tests indicate that the inclusion of fault style among the GMPE explanatory variables does not improve the accuracy of PHA prediction. This consideration also simplifies the use of GMPE in hazard assessment procedures that define seismicity rates without the need of a preliminary identification of seismotectonic zones distinct by prevailing fault style (as in [13]).

Overall, some main learnings can be derived from the comparative analyses of the performance of ground motion prediction equations calculated for the Greek region. In the present study, performance analysis was based on the examination of the distribution of residuals deriving from GMPE application to a set of observations distinct from those used in regressions. Results indicate that, for a generic use of prediction equations in the examined area, there is no reason for using site effect terms for PHA and focal mechanism terms for both PHA and PHV, at least within the range of magnitudes (4.0-6.8) and distances (up to 200 km) investigated.

With regard to the site effect, the ineffectiveness of its consideration for PHA estimates can be in part due to a poor consistency between site classification based on the shear wave velocity of the top 30 meter of soil (Vs_{30}) and the relative amplification factors observed for peak horizontal acceleration. Indeed, the adoption of classification criteria directly based on the PHA observations, through the analysis of residuals from equations excluding site effect terms, seems able to slightly improve the predictive performance of the resulting equations. However, an additional factor that deteriorates the equation performance is also a possible inadequacy of site amplification modelling as a purely site-specific property, regardless of event magnitude and distance. Indeed the combination of these two factors controls the spectral energy distribution, thus significantly modifying the site response for different events, in dependence on the site resonance frequencies. Unless magnitude/distance–dependent modelling of site effect can be introduced (relying on an adequate amount of data), the fairest solution is simply to make use of median estimators of PHA neglecting the influence of site response.

With regard to the use of GMPE specifically for hazard assessment, however, there is the need of defining equations specifically predicting PHA at sites on rock. For this purpose, the use of database for which site classification is directly derived from the analysis of PHA residuals could give equations that are better representative of site conditions unaffected by amplification,

according to the requirement of "base" hazard assessment, independently on the "geological" correctness of classification.

Acknowledgements

This study was carried out with the financial support of Italian Ministry of Education, University and Research.

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