# Use of Macroseismic Intensity Data to Validate the Ground Motion Prediction Model in Albania

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## ABSTRACT

Macroseismic observations are a valuable tool, that can be used for the verification of site response and attenuation. Hence, in the framework of a bilateral project supported by Central European Investment Fund and with the extensive support of Global Earthquake Model Foundation to update the national seismic hazard model of Albania, intensity maps that contained more than 6000 macroseismic observations for 168 shallow (h<40 km) medium up to large (3.74-6.94) earthquakes that occurred in Albania and the surrounding area between 1851 and 1990 were digitized and analysed. The Boxer methodology was used to redefine the location and magnitude of these events. Instrumental magnitudes used in the calibration, included both moment magnitudes derived from moment tensor solutions and proxy values, in order to ensure both a magnitude (or intensity) and temporal coverage as wide as possible.

As intensity is a qualitative measurement of ground motion, several attempts have also been made in previous studies to derive some more quantitative relationships between surface geology and local amplification, by proposing also relations between the average horizontal spectral amplification and the intensity increment, and peak ground motion values and macroseismic intensity. Hence, by taking into account these regressions applied to our macroseismic database, this study aims to evaluate whether the analysed macroseismic data show good agreement with the expected seismic response, referring to soil type categorization on a national scale and the Ground Motion Prediction Equations selected in previous studies.

**Keywords:** Macroseismic data, attenuation, Boxer, regression, peak ground acceleration

## 1. Introduction

Albania is an earthquake-prone country which saw destructive earthquakes resulting in casualties and large economical losses (Sulstarova et al. 1980, Muco et al. 2002, Kociu et al.2005, Wagner et al. 2012, Muceku et al. 2021). The 26th November earthquake demonstrated that there is a need for a critical review of the current seismic code or for the accelerated adoption of Eurocode, which could help to reduce the seismic risk associated with the future constructions (Duni et al. 2004, Freddi et al. 2021). In this perspective, Global Earthquake Model Foundation and Institute of Geosciences of Albania are currently implementing a 1-year project funded by the European Investment Fund and supported by the Electrical Corporation of Albania, to update Albania’s probabilistic seismic hazard model.

Appropriate selection of the ground motion prediction equations is fundamental for the overall accuracy of the national seismic hazard model. Previous PSHA studies in Albania (Fundo et al. 2012) and large-scale projects in the Balkans (Salic et al. 2018) have relied on GMMs developed for areas with similar geological and tectonic characteristics, because of the limitations of the database in the moderate-to-large magnitude and short distance ranges to develop a unique GMM for this region. In the current project the unique strong motion waveforms available from the BSHAP project were considered in addition to the ESM flatfile (Lanzano et al. 2019) for the period from 1986 to 2014. Residual analysis was performed to generate the best-fitting GMPE-s and their respective weights (Brooks et al. 2024).

Macroseismic observations that encompass an earlier period of significant seismic events, can be a valuable tool for an additional verification of attenuation. The geographic distribution of earthquake effects quantified in terms of macroseismic field, provides basic information for source characterization of pre-instrumental earthquakes, and it can be even used in the framework of seismic hazard analysis. As intensity is a qualitative measurement of ground motion, several attempts have also been made in previous studies to propose relations between the average horizontal spectral amplification and the intensity increment, and peak ground motion values and macroseismic intensity (Wald et al. 1999c, Tselenis et al. 2008, Faenza et al. 2010, Bilal et al. 2014, Oliveti et al. 2022). Hence, by taking into account the possibility of application of these regressions to our macroseismic database, this study aims to evaluate whether the analysed macroseismic data show good agreement with the expected seismic response, referring to soil type categorization on a national scale and the Ground Motion Prediction Equations selected in previous studies.

## 1.1. Macroseismic intensity database in Albania

The devastating effects of earthquakes have been witnessed continuously, therefore documentation of the observed effects of the induced shaking has been essential, starting from the historical chronicles of destroyed cities, up to the recent planning prevention politics. The characterization of earthquake effects has evolved considerably, resulting in different macroseismic scales, i.e., MCS (Sieberg, 1932); MSK (Medvedev et al. 1964) and EMS98 (Grünthal, 1998) (for Europe).

The macroseismic intensities of strong earthquakes in Albania and the surrounding area during the past 30 years, have been documented and studied from various researchers (Sulstarova et al. 1975,1980, Ivanovich et al. 1980, Kociaj et al. 1980, Papazachos et al. 1997,1998). However, most of the research consisted basically in publishing the datasets, or in the best case isoseismal maps were developed, namely the atlas of UNESCO (Shebalin, 1974) and in the two atlases published by the Geophysical Laboratory of the University of Thessaloniki (Papazachos et al. 1982, 1997). The report of a joint research project (Papazachos et al. 2008) presented the macroseismic information for 57 events that occurred in Albania and the surrounding area between 1851 and 1990, for shallow (h<60km), medium up to large (7.1>M≥4.5) earthquakes of this area. The authors have indirectly verified that the macroseismic observations are in the MSK-64 scale, therefore we adopted this deduction in our study as well.

Referring to the considerable large macroseismic database available for Albania, it was deemed necessary to refine the location and magnitude of events. In this perspective, the exiting literature was consulted for the available algorithms to perform these statistical analyses.

In a recent study (Provost et al. 2022), the intensity distributions of pre-instrumental earthquakes at the border between France and Italy were analysed using two alternative methods, Boxer (Gasperini et al. 1999) and QUake-MD (Provost et al. 2020). Differences between the resulting magnitude estimates and instrumental magnitudes show the same standard deviation for both methods and a lower mean residual for Boxer. Moreover, Boxer has been used for the verification of the calibration of historical earthquakes in the Earthquake Catalogue of Switzerland (ECOS2009) (Fäh et al. 2011) and also for Italian Parametric Earthquake Catalogue version CPTI15 release 1.5 (Rovida et al. 2016).

Therefore, Boxer methodology was selected to refine the location and the magnitude of the seismic events. Intensity maps that contained more than 6000 macroseismic observations for 168 shallow (h<40 km) medium up to large (3.74-6.94) earthquakes that occurred in Albania and the surrounding area between 1851 and 1990 were digitized and analysed. The method relies on the attenuation of macroseismic intensity as a function of the earthquake magnitude and the distance of every MDP from the epicentre. Instrumental magnitudes used in the calibration include both moment magnitudes derived from moment tensor solutions, and proxy values in order to ensure both a magnitude (or intensity) and temporal coverage as wide as possible. The last version of the Boxer computer code (Boxer 4.2.1) was used to provide the calibrated coefficients from the input dataset. Among the location methods available in the Boxer code, we selected "method 0" (Gasperini et al. 2010), which determines the epicentre as the barycentre of the data points with the highest intensities. Such a choice was driven by the verified stability of the method even with poor intensity distributions. In addition, the location "method 4" is also used. The uncertainty associated with the epicentral coordinates is calculated by Boxer with both "method 0" and "method 4". The macroseismic magnitudes are calculated with Boxer method, either with the isoseismal method and the new calibration derived for Albania, or with the new Io-to-Mw relation in the case of poor intensity distributions. Seven intensity classes, i.e. those with intensity between 5 and 9 plus intermediate uncertain values as an independent class, were calibrated to be used by Boxer in the formula by Sibol et al. (1987) Eq.1:

$$M_i = a_i + b_i \log^2(A_i) + c_i I_0^2 \qquad (1)$$

where M is magnitude, $A_i$ is the area of the i-th isoseismal, $I_0$ is epicentral intensity, and $a_i$, $b_i$, $c_i$ are the coefficients (Table 1).

**Table 1**. Coefficients obtained through the calibration of Boxer.

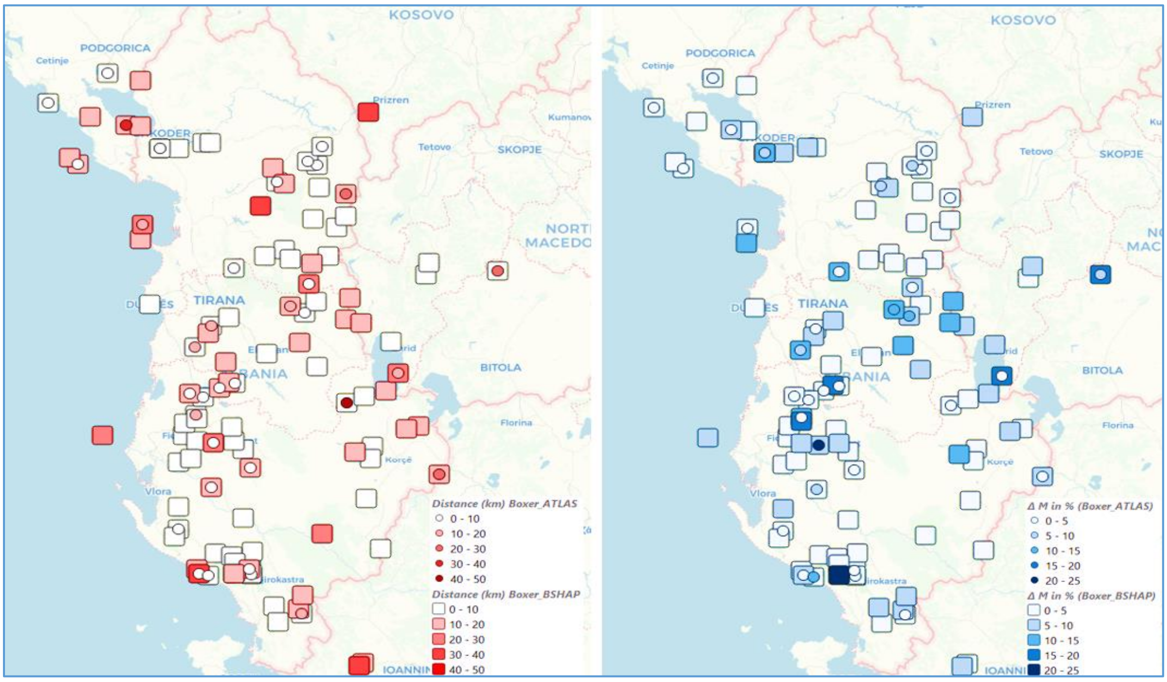
| I | $a_i$ | $b_i$ | $c_i$ | Std | Reg | DF |
|---|---|---|---|---|---|---|
| 5.0 | 3.1864 | 0.0850 | 0.0161 | 0.1778 | 19.1579 | 16 |
| 6.0 | 3.3916 | 0.1294 | 0.0000 | 0.2108 | 32.7632 | 36 |
| 7.0 | 4.0233 | 0.1169 | 0.0000 | 0.2777 | 19.6364 | 31 |
| 7-8 | 3.7692 | 0.0065 | 0.0358 | 0.3352 | 10.2083 | 21 |
| 8.0 | 3.7901 | 0.0695 | 0.0202 | 0.1957 | 14.1818 | 19 |
| 8-9 | 3.7937 | 0.0668 | 0.0224 | 0.1610 | 11.3529 | 14 |
| 9.0 | 4.2188 | 0.0825 | 0.0148 | 0.1053 | 11.0667 | 12 |

**Total number of earthquakes used: 46*

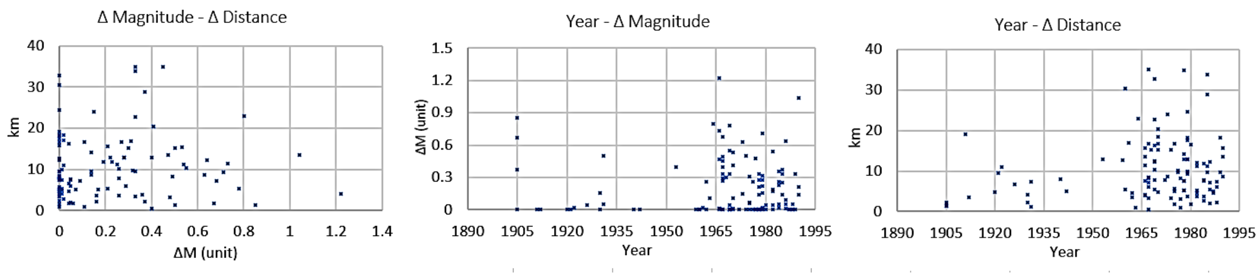
The events having more than 15 MDPIs were compared with the catalogue used for the seismic hazard evaluation of western Balkans – NATO SfP 984374 (BSHAP2), 2015 and the events present in the study of Papazachos, B. et al. 2008, (hereafter referred as "BSHAP" and "Atlas") (Fig.1). The difference in magnitude varies up to 23.28% for BSHAP and 24.37% for Atlas. There is no observed spatial or temporal trend for the differences (Figure 1.b), neither a proportionality between the magnitude to location differences. However, it can be noted that differences in location derived from Atlas dataset are larger. Despite the fact that these differences are present in a percentage as low as ~3%, they exceed 40km.

## 1.2. Strong-motion database of Albania and neighboring countries

The strong motion network in Albania has been established for the first time in 1985 and at the end of 1986, thirty SMA-1 accelerographs were distributed around the country.




(a)




(b)

**Figure 1.** Difference in magnitude (unit %) and location (km) of Boxer results compared to "BSHAP" and "Atlas" (a) in space (b) in time

This network operated normally up to 1988, then due to various reasons the monitoring was stopped for a period of four years, to start again in 2002 (Duni et al. 2010). The first strong motion flatfile developed to perform a GMPE selection analysis, within the scope of seismic hazard evaluation, for Albania and the neighbouring countries, was compiled during the BSHAP project.

The majority of the recordings in this database are related to shallow earthquakes in small-to-moderate magnitude range 4<Mw<6, with hypocentral depth ranging between 0-17.5 km.

In the current bilateral project between IGEO and GEM for updating the national seismic model of Albania, the unique strong motion waveforms available from the BSHAP project were considered in addition to the ESM flatfile (Lanzano et al. 2019) for the period from 1986 to 2014. Residual analysis was performed to generate the best-fitting GMPE-s and their respective weights (Brooks et al. 2024).

## 2. Conversion of macroseismic database to strong motion parameters

The strong motion data used to derive the selected GMPE should encompass the largest and smallest earthquake magnitudes and source-to-site distances that are included in the seismic source model. Macroseismic observations that encompass an earlier period of significant seismic events, can be a valuable tool for the verification of attenuation.

Several efforts have been made to re-construct the distribution of the ground shaking for historical events at global (Allen et al. 2008) and local scales (Faenza et al. 2013). Moreover, the use of macroseismic data as a reference for the selection of the most appropriate ground motion model in low-to-moderate seismicity areas (Villani et al. 2019, Tang et al. 2019) can be an important application to constrain the GMPE selection from strong motion data. In this perspective, the macroseismic intensities of our database are converted to peak ground acceleration (PGA), SA(0.3), SA(1.0) and are statistically compared with the respective parameters predicted by the GMPEs.

In this study we use the reversible relationships (Equation 2) between macroseismic intensity (I) and peak ground acceleration (PGA), spectral acceleration (SA) at 0.3 and 1.0s [SA(0.3) and SA(1.0)], which were developed for Italy [20], and the respective parameters are presented in Table 2.

$$I = a + b\log PGM + c\log 2PGM \quad (2)$$

| PGM | a | b | c |
|---|---|---|---|
| PGA | 3.01 | – | 0.86 |
| SA(0.3) | 2.77 | – | 0.68 |
| SA(1.0) | 3.00 | 0.91 | 0.51 |

**Table 2**.Regression coefficients (a, b, c) of the PGM parameters for all intensity classes (the coefficients standard deviation σa, σb, σc in Olivetti, et al., 2022)

For consistency of the results, 58 events with more than 10 respective MDPIs were selected from the original database. The first step was to determine the soil category of each reported intensity, using the Soil Category Map of Albania according to EC8.

An event example is presented in Figure 2.a and it is noted that in some cases, despite the same distance from the event hypocenter, different intensities are recorded, probably due to the different soil conditions.

There is a plausible distribution of magnitude to distance as presented in Figure 2.b and Figure 3.a, which highlights the relevance for the inclusion of this dataset in the procedure for selection of the GMPEs. The plot in Figure 3.b presents two cases: original PGA derived from original intensities, and modified PGA, which is obtained by reducing the original PGA with the respective amplification factor (considering the soil category of the location of the reported intensities).

It is evident form the large extent of the amplification effect in this dataset, that a macroseismic database without the corresponding soil category, would produce a misleading constraint to the GMPE set selection. Then $V_{s,30}$ was assigned to each MDPI, as the lower level of the respective soil category according to Eurocode classification, in order to be more conservative (Figure 2.b).

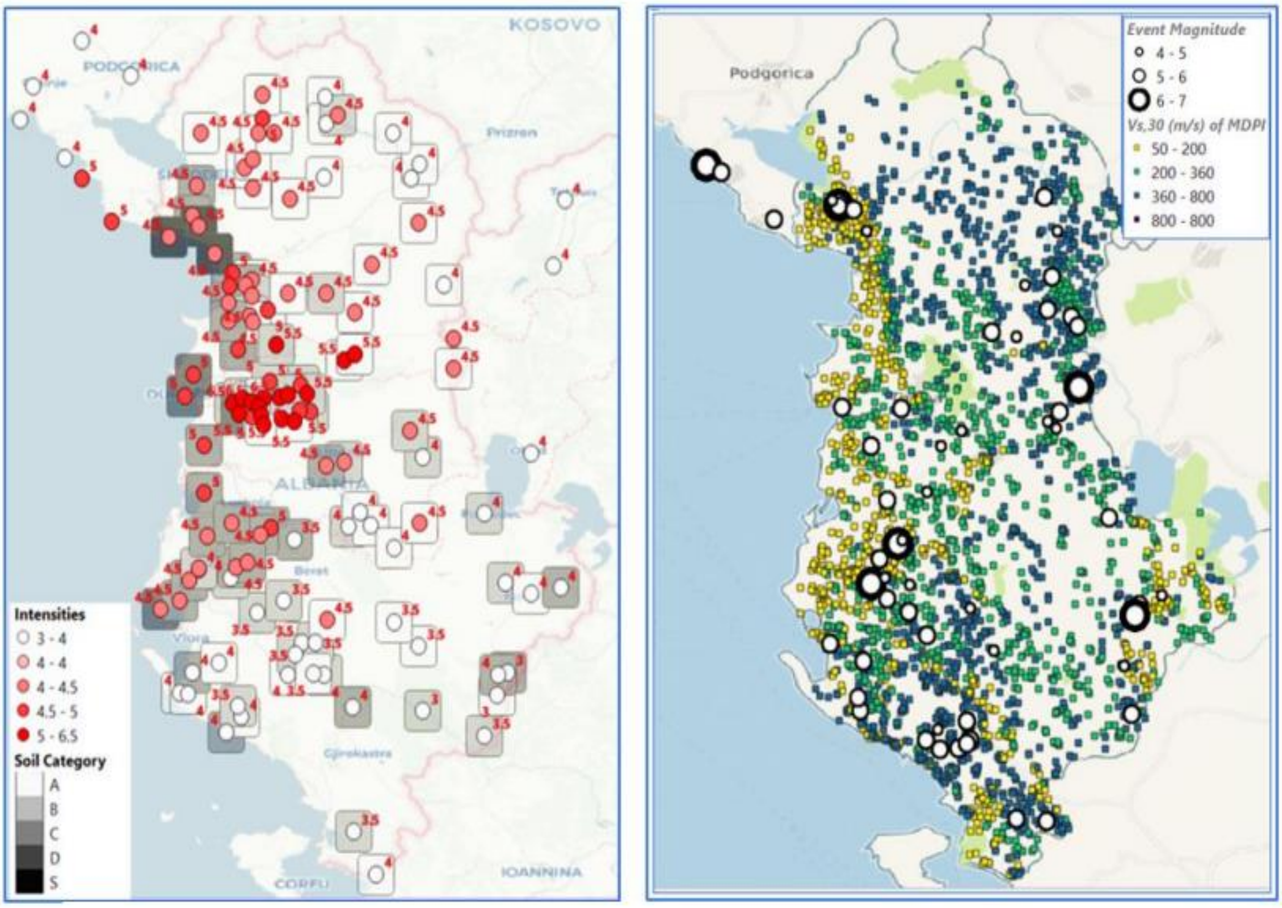



**Figure 2.** (a) Intensities distribution and the corresponding soil category of each MDPIs location of event 1988_01_09_40.273_20.681 (b) Magnitude distribution of all events used for residual analysis and the respective $v_{s,30}$ of each MDPIs location

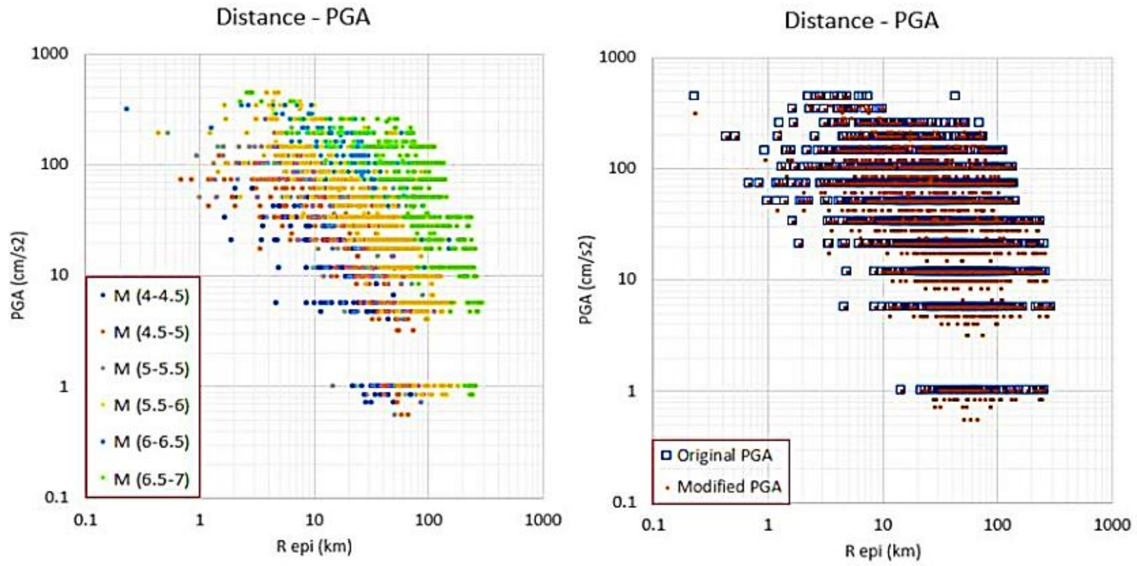



**Figure 3.** (a) Magnitude – Distance distribution of events used for residual analysis (b) Effect of amplification in PGA distribution of the current dataset

## 2.1. Residual analysis to check the GMPE set compatibility

The suggested GMMs from the residual analysis of the strong motion database against a set of 10 GMMs in a recent work (Brooks et al. 2024), have been adopted in our statistical analysis, namely CY14 (Youngs et al., 2014), B20 (Boore et al. 2020), K20 (Kotha et al. 2020) and L19 (Lanzano et al.2019). Moreover, referring to the GMC logic tree considered in BSHAP-2 (Gulerce et al. 2015), Boore et al. (2014) is tested as well.

Figure 4 provides the results of the empirical distribution of total residuals for peak-ground acceleration (PGA) for B14, B20, CY14, K20 and L20, whereas Figure 5 presents the variation of total residuals with Joyner-Boore distance for all the above-mentioned GMM. There is a moderately good fit between the empirical and the standard normal distribution for all GMPEs, especially for B20 (Figure 4), whereas Figure 5 shows better performance of CY14 in terms of closer to zero residual, for the whole range of distances.

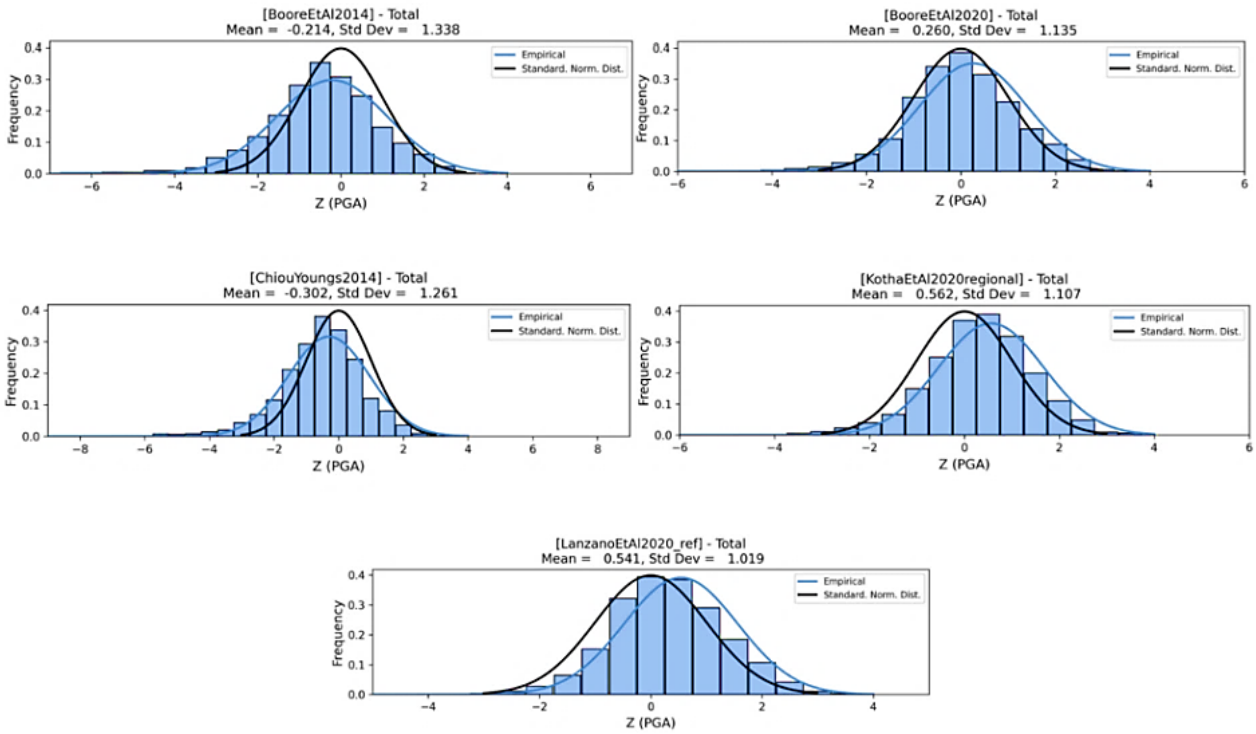



**Figure 4.** Comparison of the theoretical and empirical distributions of residuals B[14], B[20], CY[14], K[20] and L[20]

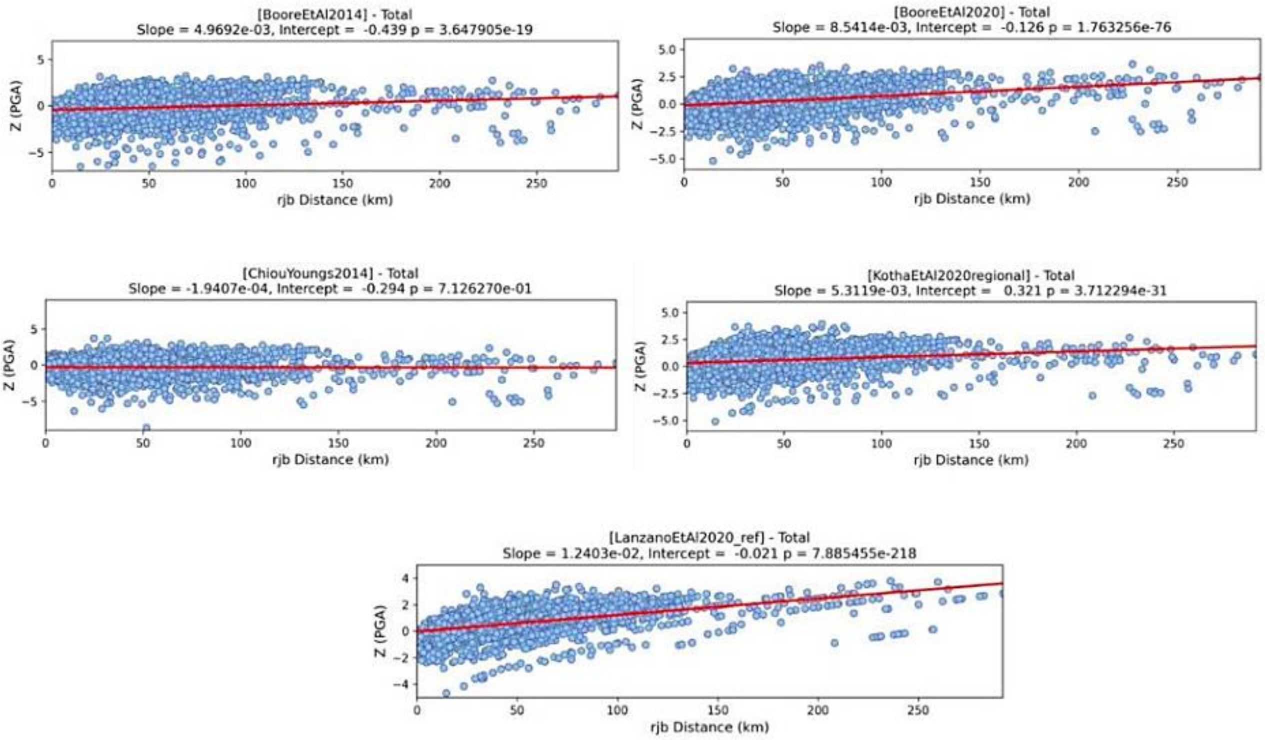



**Figure 5.** The normalised and model residuals with respect to Joyner-Boore distance for B[14], B[20], CY[14], K[20] and L[20]

The variation of total residuals with Joyner-Boore distance, show a tendency for under-prediction by other GMPEs in the large distance domain.

Despite the outlined statistical scores, it was deemed necessary to basically plot the database over the respective Attenuation curves (Figure 6), to have another representation dimension of the best/worst fitting domain in terms of magnitude, distance and PGA/SA intervals.

No single event of a certain magnitude was chosen, rather a database corresponding to a range of magnitudes encompassing the levels predefined in the plots (M=5, M=6 and M=7) was selected. Generally, all plots confirm that the datasets fit the +/-3σ interval, with a specifically better fit for the range of Magnitudes 5.5-6.5 for all three spectral parameters and along the full distance range.

Whereas for the stronger earthquakes, L[20] seems to better capture the database trend for the large distance domain, in all three spectral parameters.

The results in the Sammon's maps are used to exclude any GMPE, performing similar to other GMPEs, or to keep it if performs differently from other GMPEs for all three spectral parameters. From the plots in Figure 7 it is clear that CY[14] performs similar to B[20] for PGA and SA[0.3], whereas for SA[1.0] has a more unique performance.

Another important observation from this plot, is that B[14] performs identical to B[20] for SA[0.3] and SA[1.0], therefore is can be discarded from the final set.

## 3. Conclusion

The macroseismic intensities available for earthquakes in Albania and the surrounding area between 1851 and 1990, are converted to peak ground acceleration (PGA), SA(0.3), SA(1.0) and are statistically compared with the respective parameters predicted by the GMPEs. Generally, all attenuation plots confirm that the datasets fit the +/-3σ interval, with a specifically better fit for the range of magnitudes 5.5-6.5 for all three spectral parameters and along the full distance range. The GMPE set suggested from the statistical analysis of the strong motion database, namely CY14 (Youngs et al., 2014), B20 (Boore et al. 2020), K20 (Kotha et al. 2020) and L19 (Lanzano et al.2019) is exhaustive and represents relatively well both the strong motion and macroseismic database.

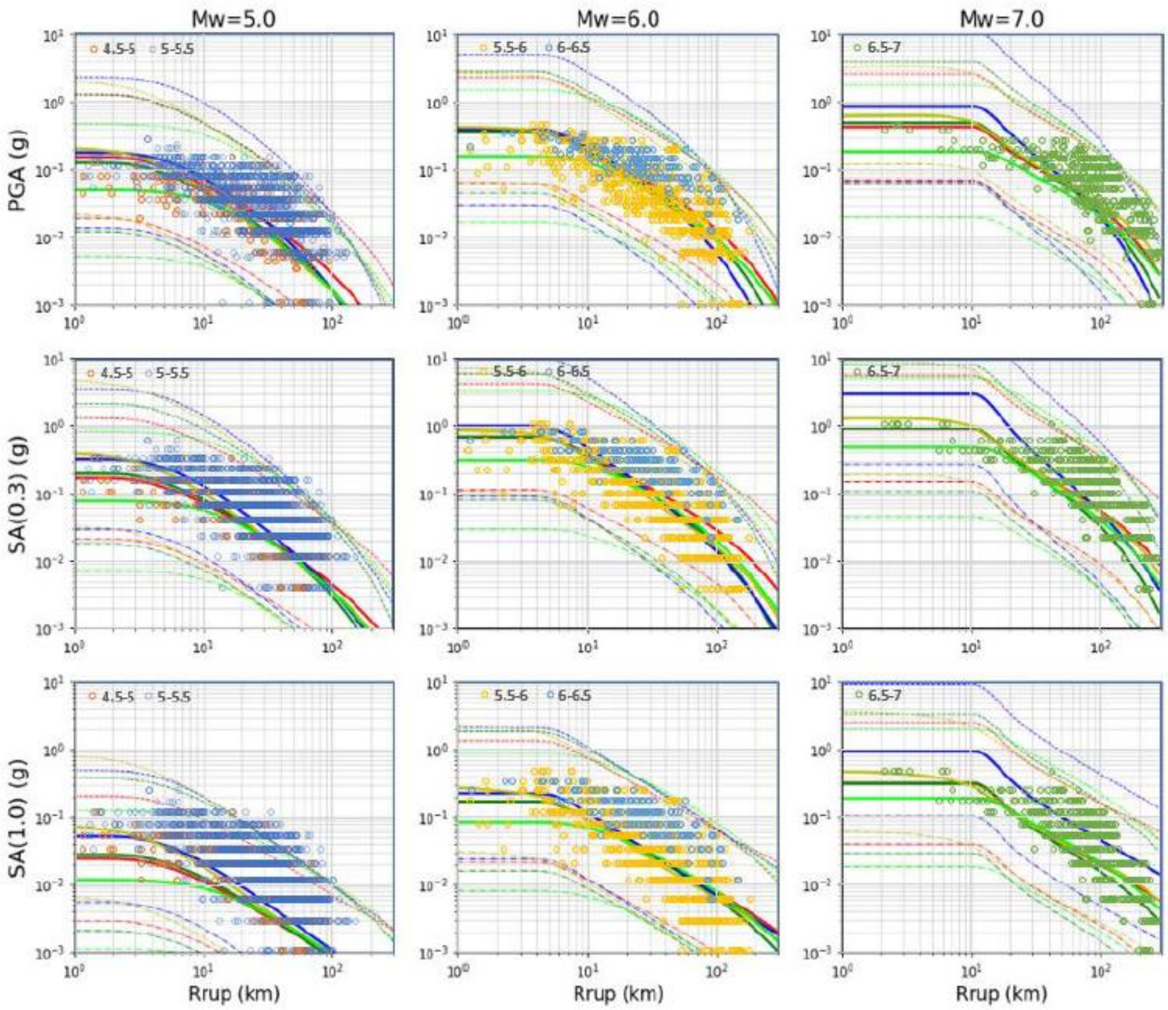



**Figure 6.** Attenuation curves [PGA, SA(0.3), SA(1.0) vs Rrup (km)] for selected GMPE (+/-3σ) with the dataset of the respective magnitude range derived from macroseismic database

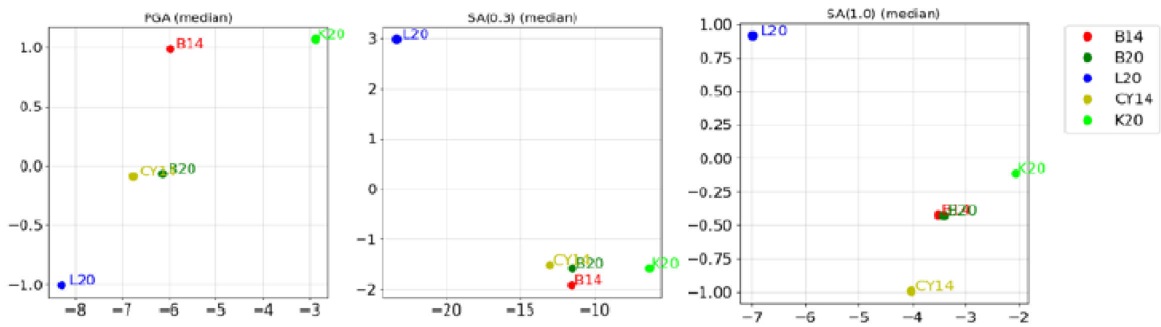



**Figure 7.** Sammon's maps representation for the median value

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