Constraints on Ground Motion Models for Seismic Hazard Assessment in Active and Stable Regions of Western Iberia

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15 WCEE
LISBOA 2012

SUMMARY:
Ground motion prediction equations (GMPEs) have long been known to critically influence the seismic hazard assessment. In Western Iberia its importance is particularly relevant due to the relative contributions of offshore distant-interplate earthquakes and onshore-local-intraplate earthquakes. Western Iberia is a stable continental region that is under the influence of the Azores-Gibraltar plate boundary, which has a recognized potential to generate very large magnitude earthquakes (e.g., 1755 Lisbon earthquake). In this paper we discuss the applicability of broad-scope GMPEs, developed for different tectonic environments, to the western Iberian region. We compare published GMPEs with both ground-motion data and intensity observations from regional earthquakes through visual inspection and residual analysis. The results show that models developed for stable continental regions are better suited to represent regional ground motions than models developed for active tectonic regions, while highlighting the importance of epistemic uncertainty in ground motions for moderate magnitude earthquakes at short distances.

Keywords: ground-motion, attenuation, seismic-hazard, response-spectra.

1. INTRODUCTION

Seismic hazard is critically influenced by the ground motion prediction equations (GMPEs) used in the assessment. Because instrumental ground motions that may be representative of the magnitudes and distances ranges of engineering interest are seldom available for a particular region, efforts have been made to address and quantify the applicability of GMPEs derived for one region to another. The broad-scope GMPEs aim to describe the ground motion attenuation within particular tectonic domains – such as active tectonic regions, stable continental regions and subduction zones – because specific characteristics of the lithosphere that influence the anelastic attenuation vary according to the tectonic regime.

Iberia is geographically located in the vicinity of Azores-Gibraltar plate boundary that separates the Eurasian plate from the African plate. While within the oceanic lithosphere the plate boundary runs along the strike-slip Gloria Fault, once the lithosphere becomes transitional and then continental, the boundary becomes diffuse and complex. Moment tensors and GPS data show a transpressional regime distributed over a broad belt, driven by NW-SE oblique convergence of the plates (e.g., Serpelloni et al., 2007). The rate of convergence is on the order of 5-6 mm/y according to plate kinematics modeling (e.g., Fernandes et al., 2003) and both seismicity and geodetic studies report no evidence of subduction of any of the plates (Borges et al. 2001; Stich et al., 2006). This complex region has recognized potential to nucleate very strong earthquakes, such as the M8.5-8.7 1775.11.01 Lisbon earthquake and the M7.8 1969.02.28 earthquake.

On the other hand, most Iberia (the exceptions being the Pyrenees and the Betics) classifies as stable continental region according to the geological criteria defined by Johnston (1989) based on the age of last major tectonic episodes. The largest magnitude estimates for past intraplate earthquakes are in the range Mw6.9-7.1 from historical data (Vilanova and Fonseca, 2007) and in the range Mw7.1-7.3 from paleoseimological evidence (Rockwell, et al., 2009). The latest damaging earthquake was the Benavente earthquake of 1909 (e.g., Fonseca and Vilanova, 2010) with magnitude estimates of Mw6.0-6.2 based on early instrumental records (e.g., Stich et al., 2005).

Vilanova and Fonseca (2007) identified the uncertainty pertaining to the GMPEs as the main contributor to the uncertainty in probabilistic seismic hazard assessment at 10% exceedance probability in 50 years: the maximum PGA expected to be exceeded would vary from 0.05g to 0.35g using respectively GMPEs developed for active and for stable continental zones. In addition, studies on seismic hazard deaggregation show contrasting results: Pelaez Montilla et al. (2002) conclude that seismic hazard for 10% exceedance probability in 50 years is dominated by intraplate local seismicity, whereas Sousa and Campos Costa (2009) attribute it to the offshore interplate seismicity. Striking differences between onshore and offshore GMPEs may explain these contrasting results (see Fonseca and Vilanova, 2011, Fonseca and Vilanova, this issue, for a detailed discussion on this subject).

During the last decade, the Portuguese seismic networks experienced a dramatic improvement. Therefore, the occurrence of moderate offshore earthquakes in February 12 2007, and December 17 2009 provided an unprecedented amount of regional ground motions.

A first objective of the study is to understand which class of GMPEs, active tectonics or stable tectonics, would better represent the instrumental set of regional ground motion data from offshore plate-boundary earthquakes of western Iberia. These earthquakes are generated in an old oceanic/continental transition region with seismogenic depths down to 60~km, but the propagation towards Iberia occurs mainly within stable continental crust. The second objective is to understand to what extent available data support different attenuation models for offshore and onshore earthquakes of western Iberia. Both, early-instrumental data from the M7.8 1969 earthquake and macroseismic intensity observations for moderate to large magnitude earthquakes, were be used to evaluate the robustness of the results for larger magnitudes.

2. DATA AND METHODS

2.1. Offshore Interplate Earthquakes

As stated above, the offshore region of Iberia is tectonically active, but the propagation of ground-motion towards Iberia occurs predominantly in stable continental crust. Since most studies report no evidence of subduction in that region, we will analyse GMPEs derived for both shallow active tectonic regions and stable continental regions. The Next Generation Attenuation (NGA) Boore and Atkinson (2008) model (NGA-BA), the NGA Chiou and Youngs (2008) model (NGA-CY), and the European Akkar and Bommer (2010) model (E-AB) will represent the former. The Eastern North America (ENA) stochastic Atkinson and Boore (2006) model (ENA-AB), the ENA Atkinson (2008) referenced-empirical model (ENA-A), and the ENA Campbell (2003) semi-empirical model (ENA-C) will represent the latter. The NGA-BA and ENA-AB models were updated according to Atkinson and Boore (2011), and the NGA-CY model was modified according to Chiou et al. (2010).

To evaluate the performance of GMPEs for the offshore earthquakes we use digital records from Mw4.8-6.0 events recorded within 100-400km from the source (see Table 1 for details). Although comparisons with active tectonic models should be restricted to the respective range of validity, we relaxed the distance upper distance limit to 250~km in order to increase the statistical significance of the results. The upper distance limit of validity for the NGA-BA model is 200km, and for the NGA-CY and E-AB models is 100 km only. Checking the validity of the extrapolation of GMPEs to larger distances is particularly relevant for the region since it is often implicit in seismic hazard studies.

The assessment of site effects through the parameter Vs30, which is the time-average shear wave velocity on the upper 30 m, was performed using two distinct methodologies. Method A is based on analogy to the geologically-geographically defined units of Wills and Claham (2006), while method B relies on the general classification of Vilanova et al. (2009) (very-soft-soil, soft-soil, intermediate-soil, stiff-soil, and rock) and the NEHRP site classification classes. The Vs30 estimates obtained from both methodologies are presented in Table 2.

We computed the 5% damping response spectra for each available record. Details on the data processing and noise analysis can be found in Vilanova et al. (2012). We also calculated the normalized residuals at several response spectra ordinates (PGA, and SA at 0.1 s, 0.2 s, 0.5 s, 1.0 s, and 2.0 s). The normalized residuals are computed by the following expression (e.g. Scherbaum et al., 2004)

$$Z_{ij} = \frac{ln(Y_{\mathrm{obs},ij}) - ln\ (Y_{\mathrm{pred},ij})}{\sigma}$$

where Y_{obs} is the observed response spectra amplitude for the j record of the i earthquake, Y_{pred} is the value predicted by the GMPE analysed, and σ is the standard deviation for the GMPE analysed.

To address the validity of results at larger magnitudes we used the analogue record from the M7.8 1969.02.28 earthquake (recorded 290 km away from the rupture) and intensity observations. In order to analyse macroseismic data we converted the predicted response spectra ordinate (at 0.01 s and 1.0 s) to intensity using the Atkinson and Kaka (2007) relationship, and then calculated the residuals between the observed and the predicted intensities for distances up to 500 km. Site effects were not considered in the macroseimic analysis and a fixed Vs30 value of 760m/s was used for all observations.

Table 1. Earthquakes used for the interplate-offshore region

Type of data	Date	Latitude (ºN)	Longitude (ºE)	M
Digital	2009.12.17	36.47	-09.89	5.6
Digital, macroseismic	2007.02.12	35.80	-10.31	6.0
Digital	2004.12.13	36.25	-09.98	4.8
Digital	2003.07.29	35.96	-10.56	5.3
Analog, macroseismic	1969.02.18	36.01	-10.57	7.8
Macroseismic	1964.03.15	36.13	-07.75	6.3

Table 2. Assessment of Vs30 based on different methodologies (see text for details).

Surface geology	Vs30 A (m/s^2)	Vs30 B (m/s^2)
Palaeozoic Rocks	1000	1077
Intrusive Magmatic rocks	1000	1077
Limestone and marbles	1000	1077
Carboniferous: Flysch turbidite	781±359	762
Marine Miocene	515±215	528
Pliocene sandstones, sandy-clayey complex	515±215	528
Pliocene clayey sands and clays	455±150	528
Pleistocene deposits	387±142	528
Holocene alluvium in major channels	515±215	528
Holocene alluvium in narrow valleys	349±89	183

2.1. Intraplate Earthquakes

For the intraplate region, given the scarcity of instrumental ground motions, we evaluated by visual inspection the performance of the GMPEs in predicting the motions for the M4.0 1999-04-30 earthquake (one should note that this magnitude is lower than the validity threshold of active tectonics models). The resulting response spectra comparison is presented in Figure 4.

Additionally we compared the analysed GMPEs with intensity observations using the intensity-ground motion conversion described above. The earthquakes used in the analysis are summarized in Table 3.

Table 3. Earthquakes used for the intraplate region

Type of data	Date	Latitude (ºN)	Longitude (ºE)	M
Digital	1999.04.30	39.72	-08.96	4.0
Macroseismic	1909.04.23	38.95	-08.82	6.0
Macroseismic	1858.11.11	41.20	-07.00	7.1
Macroseismic	1722.12.27	37.17	-07.58	6.9
Macroseismic	1531.01.26	38.95	-09.00	6.9

3. RESULTS

3.1. Offshore Interplate Earthquakes

Figure 1 shows an example of the comparison between the response-spectra amplitudes predicted by the GMPEs analysed and those computed for the M6.0 2007.02.12 earthquake, at station PFVI, located 199 km away from the epicentre. The results for other earthquakes and other stations show a similar pattern, and are corroborated by the analysis of the instrumental record from M7.8 1969.02.28 earthquake. This general behaviour is clearly illustrated in the residual analysis presented in Figure 2: active tectonics models evidence a strong tendency towards lower-that predicted ground motion, particularly at high frequencies, while ENA GMPEs (ENA-AB, ENA-A, ENA-C) adequately represent the motions. The misfit of active tectonic models decreases with increasing spectral period, and at 1.0 s and 2.0 s both the active tectonics and ENA GMPEs predict the ground motion amplitudes adequately.

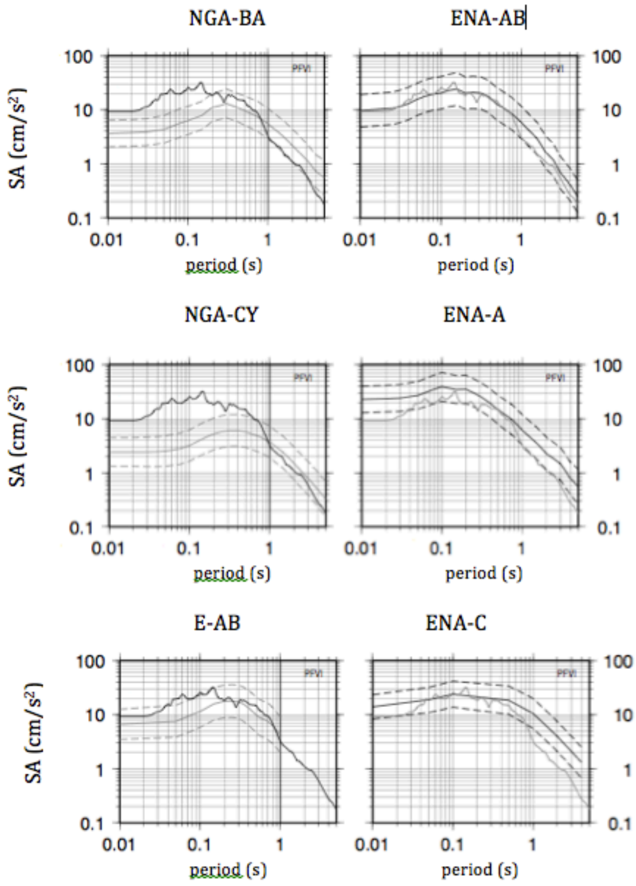

Figure 1. Comparison of the 5% damped response spectra for the M6.0 2007.02.12 earthquake recorded at PFVI station (199 km away from the epicentre) with the GMPEs analysed.

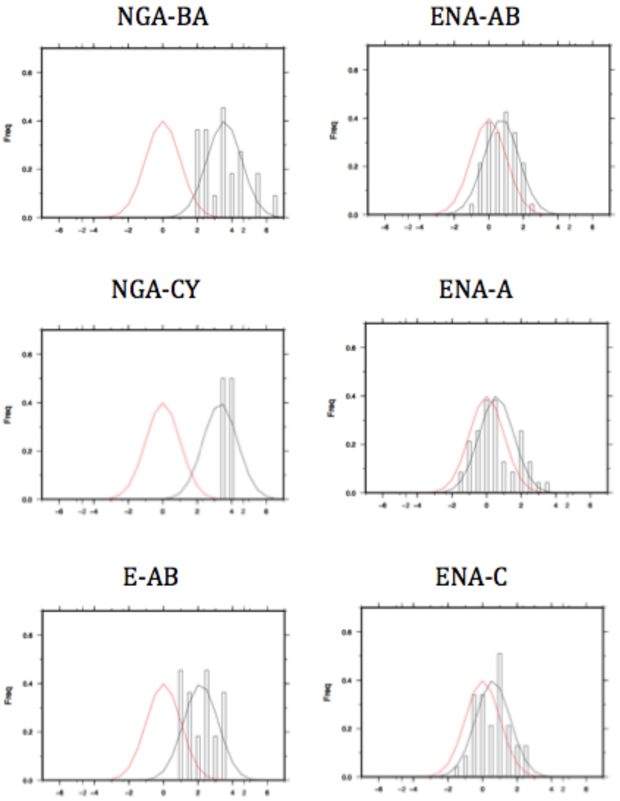

Figure 2. Residual analysis for response spectra ordinate at 0.1 s, using instrumental data from interplate earthquakes.

The analysis of intensity observations from the M6.0 2007.02.12 and the M6.2 1964.03.15 earthquakes show a similar pattern indicating that, although less accurate (E-AB data displays a better fit for intensity observations than from instrumental records for 2007.02.12 earthquake), macroseismic data can be useful in such analysis. However, residual analysis using intensity observations for the M7.8 1969.02.28 earthquake, presented in Figure 3, shows strongly positive residuals for all models. Since ENA GMPEs predicts reasonably the response spectra amplitudes for the instrumental record, the large observed misfit suggests that for strong distant earthquakes intensities may not correlate with ground motion amplitudes, depending on factors such as ground-motion duration.

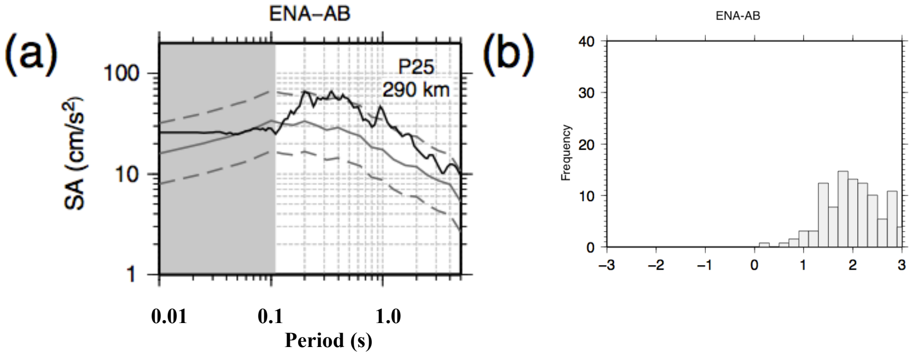

Figure 3. (a) Comparison of the 5% damped response spectra for the M7.8 1969.02.28 earthquake recorded at P25 station (290 km away from the fault rupture) with the ENA-BA GMPE; (b) Residual analysis using observations for the M7.8 1969.02.28 earthquake and ENA-BA GMPE.

3.2. Intraplate Earthquakes.

To address the issue of ground-motion attenuation from offshore versus onshore earthquakes we visually compared the response spectra for the Mw4.0 1999.04.30 onshore earthquake with the ENA and active tectonics models. Figure 4 shows that ENA models can adequately predicts the recorded motions for the M4.0 1999.04.30 intraplate earthquake while NGA and European models underestimate it, likewise what was observed for interplate earthquakes. Therefore, the data analysed support the use of the same GMPEs for both regions.

The intensity analysis performed is in general in agreement with the above-described trends (see Vilanova et al., 2012, for details). However, the ENA GMPEs show very dissimilar performances amongst themselves in the prediction of motions for moderate earthquakes at short distances, thus highlighting the degree of epistemic uncertainty inherent to those models.

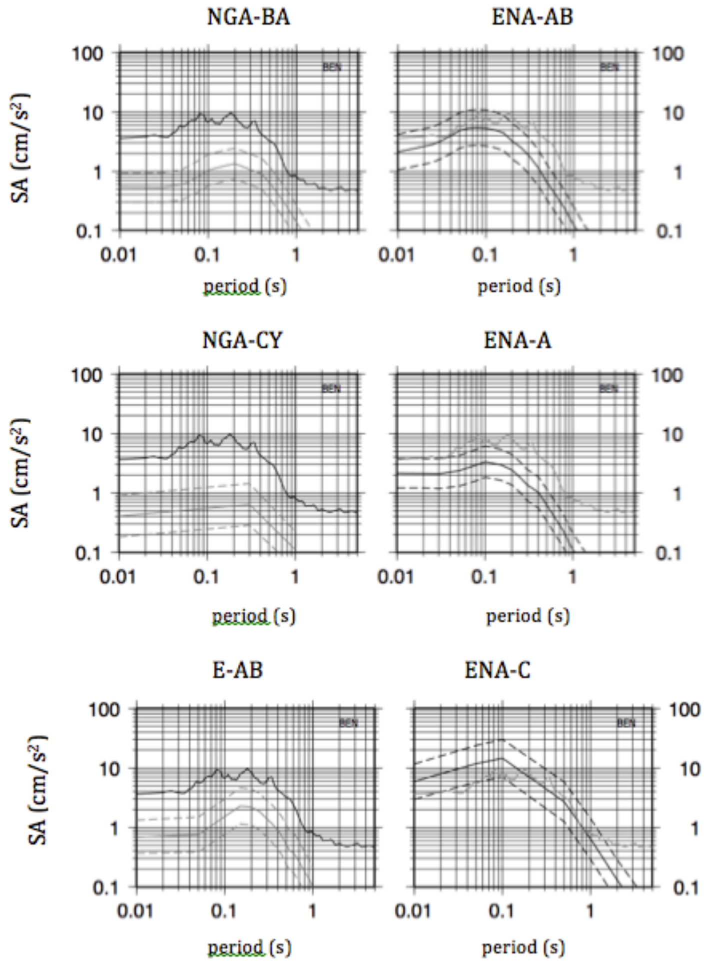

Figure 4. Comparison of the 5% damped response spectra for the 1999.04.30 earthquake recorded at BEN station (95 km away from the epicentre) with the GMPEs analysed. Spectral periods above 0.7 s were excluded at this station by noise analysis.

4. DISCUSSION AND CONCLUSIONS

Lopez Casado et al. (2000) studied the ground motion attenuation in Iberia using macroseimic data, ranking both offshore and onshore regions of Western Iberia in the lowest-attenuation group. The comparison performed by Vilanova and Fonseca (2007) between PGA-converted macroseismic intensities and GMPEs developed for eastern North America and for active Europe and the Middle East favoured the former with respect to the latter. No onshore versus offshore significant differences were evidenced by the macroseismic intensity data analysed by Vilanova and Fonseca (2007).

The results from the instrumental and macroseismic data used in the present study are consistent with those of Casado et al. (2000) and Vilanova and Fonseca (2007). The GMPEs developed for active tectonic regions strongly underestimate the high-frequency ground-motion amplitudes for regional earthquakes, while GMPEs developed for stable regions display good performances over the range of response spectra ordinates analysed. The ground-motion attenuation from offshore plate-boundary related earthquakes is not abnormally low, as implied by Sousa and Campos Costa (2009), since GMPEs developed for stable continental regions can adequately predict it.

Additionally, no striking differences were observed between the ground motion attenuation characteristics produced by offshore-plate boundary earthquakes and by intraplate earthquakes. Therefore we conclude that GMPEs developed for stable regions should be attributed a larger weight relatively to GMPEs developed for active tectonic regions in the PSHA studies for western Iberia. Also, the same GMPEs logic tree should be used for PSHA studies in both tectonic domains of western Iberia.

ACKNOWLEDGEMENT

This work was supported by the Portuguese Foundation for Science and Technology (FCT), through Project SCENE (PTDC/CTE-GIX/103032/2008). We also wish to acknowledge Instituto de Meteorologia, Lisbon, Portugal, and Instituto Geografico Nacional, Madrid, Spain, for supplying seismic data and metadata used in this study.

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