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Selection of Subduction Ground Motion Prediction Equations for Seismic Hazard Assessment in Peru

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Abstract. The seismic hazard assessment is an essential tool for site seismic analysis and in general, for disaster mitigation. The selection of ground motion prediction equations (GMPEs) tends to exert a greater influence on the final results of seismic hazard calculations. Currently, in Peru, two GMPEs exists that are derived from local data; however, these models have important shortcomings due to few records used. This study investigates the applicability of foreign GMPEs derived from regional and global data to the Peruvian subduction-zone. To that end, it was compiled a database of subduction-zone strong-motion records, which consists of 484 ground motion records from 118 subduction-type events with moment magnitudes ranging from 5.0 to 8.4, recorded in Peru and northern Chile, between 1966 and 2015. The average log-likelihood method (LLH) of Scherbaum et al. [1] has been applied to assess the goodness of fit of different GMPEs to the data. Results show that for interface models Youngs et al. [2] and Zhao et al. [3] have the best performance; meanwhile, the Abrahamson et al. [4] model shows a good fit for periods greater than 1.0 s, but it would not be applicable to the northern Peruvian coast. For intraslab events, the Abrahamson et al. [4] model shows the best fit to the data followed by the Zhao et al. [5] model. Finally, weights for each selected GMPE were proposed for B and C site classes [6] in order to produce the best calculation of spectral acceleration.

Keywords. Seismic hazard, Peruvian subduction zone, ground motion prediction equations.

1. Introduction

Seismic activity in Peru is related to the subducting Nazca plate beneath the continental South American plate at a mean rate of 7 to 9 cm/year. The Peruvian subduction zone has experienced great destructive earthquakes, which has caused extensive damage in the past such as Chimbote 1970 (Mw 7.9), Atico 2001 (Mw 8.4) or Pisco 2007 (8.0 Mw). The seismic hazard assessment is an essential tool for site seismic analysis, and in general and for disaster mitigation, since through this analysis, the annual rate of exceeding of some level of the earthquake ground shaking at a site is estimated.

The selection of GMPEs has a significant influence on seismic hazard calculation [7] since the selected GMPE introduces variability to the results in seismic hazard studies,

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which is intrinsic to each one, moreover their contribution to the variability increase with increasing return periods. In Peru, due to the insufficient amount of ground motion records, only two GMPEs for subduction earthquakes exists that are derived from local data: Casaverde and Vargas [8] and Chávez [9]. The former model only uses 10 records which raises doubts about the adequate constraints of this equation, meanwhile Chávez et al. [9] ground motion model only gives results for site class C (IBC [6]) and the number of records used in their regression (about 300) is still little compared with modern GMPEs. These GMPEs would not be accepted according to the preselection criteria of Cotton et al. [10].

Because of the limited performance of local GMPEs, it has been common practice in Peru to adopt foreign GMPEs from other regions such as Chile, Japan, New Zealand, or GMPEs derived from global data. However, this practice suggests the following questions: Which GMPEs present in the literature is more appropriate for Peruvian subduction zone? If there is more than one GMPE, what weights must be assigned to each selected GMPE? Nowadays, in Peru, there is not clear support that answered these questions, so they are addressed with highly subjective criteria and only based on qualitative evaluation.

This study investigates the applicability of foreign GMPE to the Peruvian subduction zone, based on strong ground motion records from Peru and northern Chile. The goodness of fit of a GMPE to the dataset was quantified according to the log-likelihood method of Scherbaum et al. [1]. The log-likelihood approach was employed since it has been successfully applied in several recent studies to assess the applicability of a GMPE to a specific region (e.g., [11], [12]).

2. Ground motion database

Ground motion data recorded by network operators across Peru and northern Chile have been compiled and processed. In Peru, strong ground motion records from accelerograph networks deploy by Peru-Japan Centre of Seismic Research and Disaster Mitigation (CISMID) from the National University of Engineering (UNI) and Geophysical Institute of Peru (IGP) have been added to the database; however, the IGP network were used partially due to the limited availability of data. We also include records from three accelerographs from the South American Regional Seismological Centre (CERESIS) and one accelerograph from Pontifical Catholic University of Peru (PUCP). In Chile, strong ground motion data were obtained from networks operated by National Accelerographic Network of Chile (RENADIC), Chilean National Seismological Centre (CSN) and Integrated Plate Boundary Observatory Chile (IPOC).

The database includes 484 ground motion records from 118 subduction type events with moment magnitudes ranging between 5.0 and 8.4, recorded in Peru and northern Chile, between 1966 and 2015. Large earthquakes in the database includes among others the occurred in Lima 1966 (Mw 8.1), Chimbote 1970 (Mw 7.9), Atico 2001 (Mw 8.4), Tarapacá 2005 (Mw 7.8), Pisco 2007 (Mw 8.0) and Iquique 2014 (Mw 8.1). The information compiled includes earthquake-related parameters (e.g., moment magnitude, epicentral location, and focal depth), classification of subduction type event (i.e., interface or intraslab), source to site distance measures (i.e., epicentral, hypocentral and closest distance to fault plane) and site characterization of each recording station. Site condition characteristics of 87 recording stations were compiled; the information reviewed include geological and geotechnical characteristics of the ground, geophysical surveys, and seismic microzonation studies. Additionally, as a guide in the assignment of the site classes, we identified predominant period from average H/V spectral ratios of the 5% damped response spectra at each site. In the case of Peruvian stations, geophysical surveys performed in stations located in Lima city [13], [14], Tacna city [15] and closest stations to Pisco 2007 [16] and Atico 2001 [17] earthquakes epicenters were used to assign Vs30. For stations located in Northern Chile, geophysical surveys of Chilean stations presented by Leyton [18] were used to assign site class to each station. For stations without Vs profile, but with site conditions described as rock, Vs30 = 760 m/s was assumed; for other cases, Vs30 value was not defined but the site class followed by the candidates GMPEs were derived using seismic microzonation studies and H/V spectral ratios. Charca [19] discuss details about the compiled strong ground motion database and site characterization assign to each recording station. The distribution of moment magnitude, rupture distance, focal depth, and site class are shown in Figure 1.

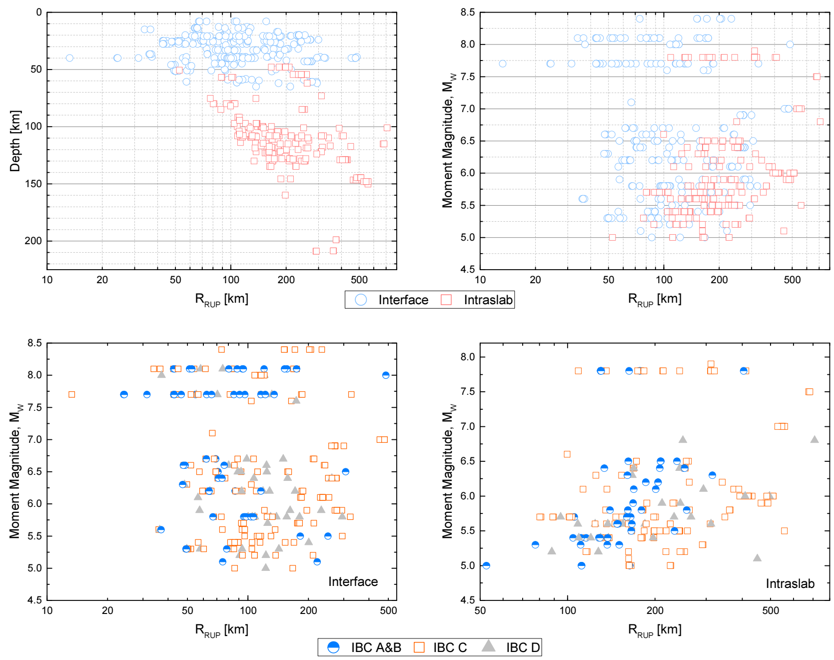

Figure 1. Dataset distribution regarding moment magnitude, focal depth, the closest distance to fault plane, and site class.

3. Testing GMPEs against observations

3.1. Candidate Ground-Motion Prediction Equations

As a part of the Global Earthquake Model project, for global application Stewart et al. [20] recommended three subduction zone models, namely Atkinson and Boore [21] (hereafter, AB2003), Zhao et al. [22] and Abrahamson et al. [4] (hereafter, BC2016); these models were included in the list of candidate GMPEs. Nonetheless, we replaced Zhao et al. [22] model by the updated equations presented by Zhao et al. [3], [5] (hereafter, Z2016). For evaluation purpose, we also include Youngs et al. [2] (hereafter, Y1997) and McVerry et al. [23] (hereafter, Mc2006) since the Y1997 and Mc2006 models are widely used for seismic hazard evaluation in Peru (e.g., Gamarra [24], SENCICO [25]). Table 1 shows a summary of the candidate models assessed in this research.

Table 1. Summary of candidate GMPEs for subduction zone earthquakes.

GMPE	Region	$T_{MÁX}$ [a]	R [b]	M [c]	$H_{MÁX}$ [d]	Site Class [e]
Y1997	Worldwide	Rock=3.0 s Soil=4.0 s	10-500 km	$M_W > 5.0$	-	2 site classes (rock and soil)
AB2003	Worldwide	3.0 s	e=R < 300 km a=R < 200 km	e=$M_W > 5.5$ a=$M_W > 6.0$	100 km	B,C,D and E [6]
Mc2006	New Zealand	3.0 s	30-400 km	5.2 - 7.5	150 km	3 site classes
BC2016	Worldwide	10.0 s	0-300 km	e=$M_W > 6.0$ a=$M_W > 5.0$	120 km	V_{S30}
Z2016	Japan	5.0 s	0-300 km	$M_W > 5.0$	-	4 site classes

[a] Longest period response

[b] Range of distances in the dataset, e = interface, a = intraslab

[c] Range of magnitudes in the dataset. e = interface, a = intraslab

[d] Maximum depth recommended by authors for intraslab events when applying the model

[e] Site classes in the model

After this study was finished, Montalva et al. [26] published a GMPEs for subduction zone earthquakes using data recorded by Chilean strong ground motion network. Further studies could evaluate the goodness of fit of this model to the Peruvian strong ground motion database.

3.2. Goodness of fit of GMPEs to the database

The subduction models Y1997, AB2003, Mc2006, Z2016, and BC2016 were tested against a homogeneous dataset described previously. The goodness of fit of the candidate GMPEs to the observed data was assessed using the information-theoretic approach proposed by Scherbaum et al. [1]. The method provides one value, the negative average log-likelihood LLH, which reflect the goodness of fit between the model and the data. Lower LLH values indicate better agreement between observations and predictions, lower than 1.9 can be considered acceptable, according to Bastías et al. [1].

Additionally, mean of the normalized residuals (Z) across spectral periods of each GMPE were also implemented, where the normalized residual (Z) is defined as the subtraction between the logarithmic of the accelerations observed and logarithmic model prediction divided by the total standard of the model. Positive values indicate underprediction and negative values overprediction of the observed spectral accelerations. Based on residual distribution, a GMPE presents a good fit to the dataset when the normalized residual distribution agrees well with normal standard distribution (i.e., with mean 0 and standard deviation 1).

The performance of each model according to the type of event (i.e., interface or intraslab) and the period response was segregated. Mean of normalized residuals (Z) is shown in Figure 2. In order to quantify the goodness of fit between the database and the candidates GMPEs, Figure 3 shows the LLH values obtained for each response period.

3.2.1. Performance of the candidate GMPEs

According to the results, it is apparent from Figure 3a that BC2016 interface model shows good performance for periods greater than 1.0 s, where LLH values are less than 1.9. However, the segregated results for magnitudes (Figures 3b,c) reveals that the bias for periods less than 1.0 s appears to be controlled by magnitudes between 5.0 and 6.0 Mw. The mean residuals shown in Figure 2a,b,c indicate an underestimation of the observed spectral accelerations for magnitudes between 5.0 and 6.0 Mw; nevertheless when the magnitude increase, the mean values tends to zero. These results agree with restrictions of the model (Table 1) since the BC2016 model was developed only with interface events with magnitudes higher than 6.0 Mw. Other studies such as Arango et al. [27] and Bastías et al. [11] also found a bias for magnitudes for periods less than 1.0 s. For intraslab events, according to the computed LLH values (Figures 3d,e), the BC2016 model appears to match the data best across all periods considered. The mean residuals (Figure 2d,e) also indicate a good performance of the model showing values near zero (mean Z <0.25) for most of the periods.

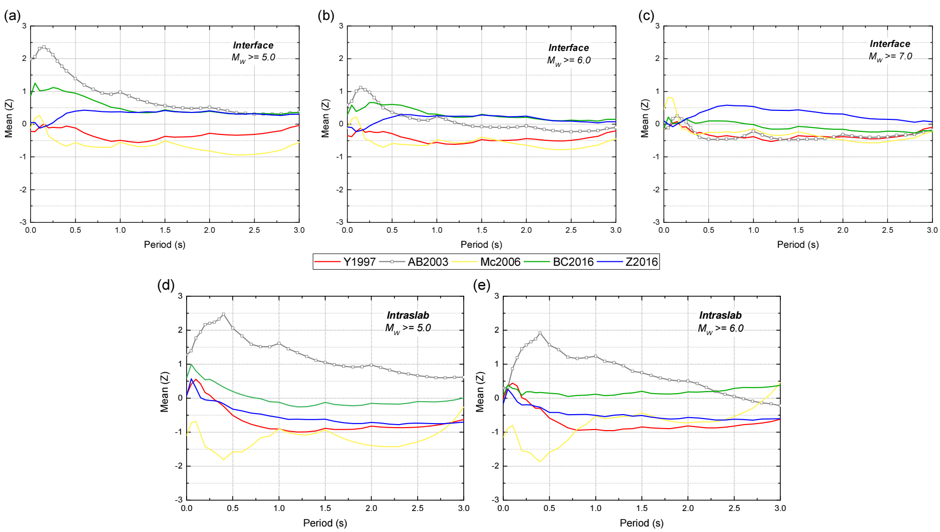

Figure 2. Mean of normalized residual distribution versus period response, according to moment magnitude and type of event. (a,b,c) interface events and (d,e) intraslab events.

Regarding the interface model Z2016, Figures 3a,b,c shows a good performance across all periods and magnitudes with LLH values lower than 1.9. The residual analysis (Figures 2a,b,c) indicate that the Z2016 model shows a slight tendency to underpredict the data for periods greater than 0.5 s. For intraslab events, the LLH values lower than 1.9 (Figures 3d,e) suggest a good match between observations and predictions, improving the performance of the model when increasing magnitudes. The mean residuals (Figures 2d,e) show a small bias towards overprediction for periods longer than 0.5 s.

As seen in Figures 3a,b,c, the LLH values computed for the Y1997 interface model are lower than 1.9, but unlike the Z2016 model, the mean residuals indicate that the Y1997 tends to overpredict the data between 0 to 0.5 units for periods higher than 0.5s. In the case of intraslab events, the Y1997 model is strongly biased for periods higher than 0.5s, with LLH values greater than 1.9 (Figures 3d,e). Moreover, the mean residual values also indicate a large overprediction of the observed values for periods higher than 0.5s (Figures 2d,e).

The LLH values computed for the interface model Mc2006 indicate values close or greater than 1.9 across most of the periods. The mean residuals indicate a biased towards underprediction for long periods in small magnitude events (Figure 2a) and underprediction for short periods for significant magnitude events (Figure 2c). For intraslab events, the LLH values indicate that the Mc2006 model is strongly biased (Figure 3d,e), according to the mean residual values (Figure 2d,e), this bias would be due to a strong tendency towards overprediction for periods lower than 1.0 s (Figure 3e).

The interface model AB2003 shows poorly fit to the data (Figure 4a). The mean residual values also indicate a bias towards underprediction for magnitudes lower than 6.0 Mw (Figure 2a,b); however, this behavior changes towards a significant overprediction for periods greater than 0.35 s. For intraslab events, the AB2003 model is predominantly biased towards underprediction (Figure 2d,e) across most of the periods.

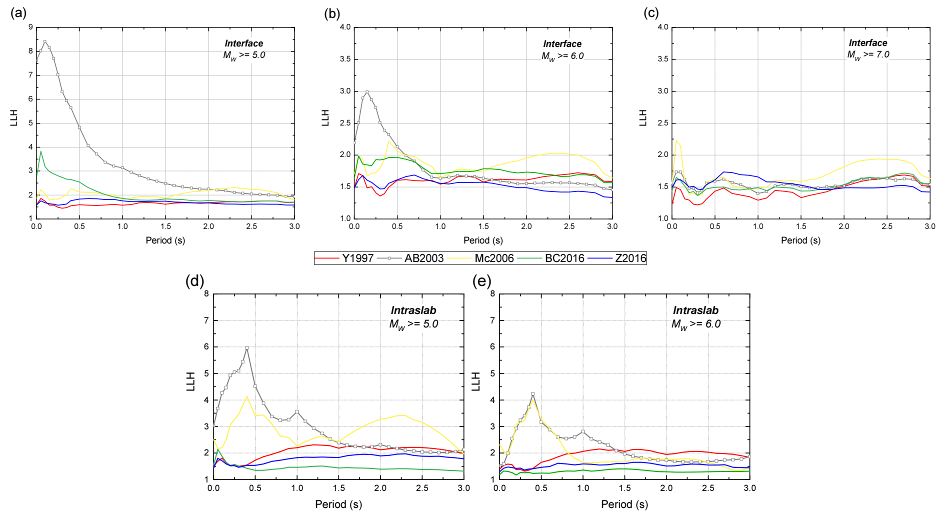

Figure 3. LLH values for different GMPEs assessed against observations, versus period response, according to magnitude and type of event. (a,b,c) interface events and (d,e) intraslab events.

On the other hand, since the seismic hazard assessment analysis is carried out considering all scenarios magnitudes and distances, then the GMPE selected must show a good performance across all range of magnitudes and periods. According to these criteria, we selected the following GMPEs:

- Regarding the interface models, the results indicate that the Y1997, Z2016, and BC2016 models can be used to calculate the ground motions caused by interface earthquakes. We include the BC2016 model since the results only indicate a bias for periods lower than 1.0 s. Furthermore, the model is biased due to events with a magnitude between 5.0 and 6.0 Mw, which are not necessarily scenarios that contribute most in the evaluation of the seismic hazard in Peru. However, the use of the BC2016 model may present limitations (underprediction of observed accelerations) in regions where the seismic hazard is strongly influenced by interface events with magnitudes lower than 6.0 Mw. This case can be found in Northwestern coast of Peru (Piura and Tumbes), where the seismicity is strongly influenced by lower magnitudes events regarding than large earthquakes, which could be because of a short window of time of the seismic catalog.

- For intraslab models, the results indicate that the Z2016 and BC2016 models could be used to estimate spectral accelerations due to intraslab earthquakes. The Y1997 model could also be used for periods lower than 0.5 s; however, for longer periods, significant bias towards overprediction should be expected.

4. Weighting the GMPEs using the Information-Theory Method

For a set of GMPE with corresponding LLH values, the weighting of each model could also be assigned through the method of Scherbaum et al. [1]. The weights obtained were segregated according to the type of event and site class B and C [6] (Figure 4a,b,c,d). The results show a variation of the weights according to the response period and type of event. To the best of our knowledge, for some PSHA software (e.g., CRISIS2015, widely used in Peru) it is not possible to take into account different weights for each GMPE depending on the response period. In order to obtain practical results, it has been possible homogenize the weights for the entire range of periods, due to the variations found in the final results are not significant for the study. The homogenized weights are shown in Figure 4e,f,g,h and Table 2 (Weighting "P1"),

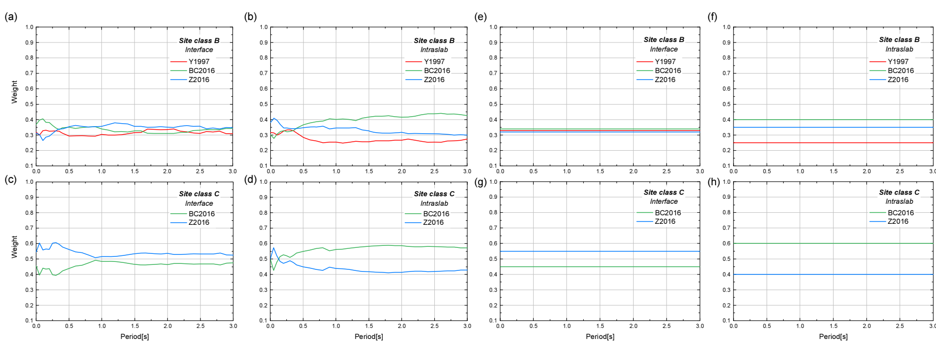

Figure 4. Weights assign to each GMPEs according to the type of the event and site class B and C. a,b,c,d). Weights computed according to LLH values. e,f,g,h) Homogenized weights for all response periods.

Table 2. Weighting considering the type of event ("P1") and replacing the weights of interface events with the weights used for intraslab events ("P2").

Type of event	GMPE	Weighting "P1"		Weighting "P2"	
		Site Class B	Site Class C	Site Class B	Site Class C
Interface	BC2016	0.33	0.45	0.40	0.60
	Z2016	0.33	0.55	0.35	0.40
	Y1997	0.33	-	0.25	-
Intraslab	BC2016	0.40	0.60	0.40	0.60
	Z2016	0.35	0.40	0.35	0.40
	Y1997	0.25	-	0.25	-

On the other hand, according to the seismic hazard maps published by Charca [19], the intraslab events present greater influence than interface events on the seismic hazard across most of the Peruvian territory, thus, in order to obtain practical results we replace the weights used for interface events with the weights used for intraslab events, obtaining the weighting "P2". It must be highlighted that this change performed in the weights "P1" was done only for practical purposes, in order to obtain the same weight for interface and intraslab events. Uniform hazard spectrums using both weighting schemes indicate that there is no significant difference (Figure 5). Similar conclusions were obtained in other cities and return periods. Therefore, the weighting scheme "P2" is recommended in order to get practical results for seismic hazard assessment in Peru. Similar conclusions were obtained for site class C.

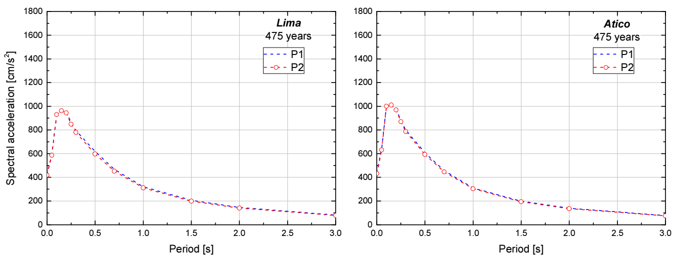

Figure 5. Uniform hazard spectrums for rock sites (site class B) and 475 years return period in Lima and Atico cities considering the weighting schemes "P1" and "P2".

5. Conclusions and Recommendations

Three parameters that significantly influenced the capability of a GMPE to predict the observations were found: response period, magnitude range, and type of the event (i.e., interface or intraslab).

The results presented suggest that BC2016, Z2016, and Y1997 models can be used in Peru for the estimation of the spectral accelerations observed during interface events. BC2016 model was included since presents a good performance for magnitudes higher than 6.0 Mw. Nonetheless, the use of BC2016 model could present limitations for regions where the seismic hazard is strongly influenced by events between 5.0 and 6.0 Mw (e.g., northwestern coast of Peru). For intraslab events, the BC2016 and Z2016 models match very well the data; nonetheless, the Y1997 model is also considered for their good match to the data for response periods less than 0.50 s.

The weighting scheme "P2" is recommended for the seismic hazard analysis in Peru. The proposed weights were derived from a limited number of ground motion records. These weights should be updated and refined as the Peruvian records increase.

Among the selected models, the BC2016 model shows the best performance predicting the observations, so the functional form of this model could be used for the development of a new GMPE derived from Peruvian subduction earthquakes.

At the time this study was finished, Mak et al. [28] proposed an evaluation method based on the multivariate logarithmic score, an extension of the log-likelihood score. Further studies could address the implementation of this score.

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