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BUILDING A GROUND-MOTION LOGIC TREE FOR SOUTH AMERICA WITHIN THE GEM-SARA PROJECT FRAMEWORK

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Abstract

Within the framework of the GEM-SARA project (http://www.globalquakemodel.org/what/regions/south-america/) aimed at estimating hazard and risk for South America, a working group on strong ground motion data and selection of Ground-Motion Prediction Equations (GMPEs) was created. The team includes researchers from South America (Bolivia, Brazil, Colombia, Chile, Ecuador, and Venezuela). In a first step, strong ground motion data was collected in each country. The same record processing and metadata collection schemes are used for the entire dataset in order to build a homogenized database. In a second step, tools were developed in order to benefit from the OpenQuake-engine and associated toolkits libraries to perform GMPEs comparisons. Based on expert judgment, the fit to the South American dataset, and the results of the comparisons, the group proposes a set of GMPEs to populate the Ground-Motion logic-tree for conducting PSHA analyses in South America.

Keywords: Ground Motion Records; South America; logic tree; OpenQuake-engine; GEM-SARA; GMPE

1. Introduction

Ground-Motion Prediction Equations are models, usually empirical, that relate the amplitude of ground-motion to a number of parameters such as the earthquake magnitude, the source-to-site distance, and the local site conditions for example. These models are essential in PSHA analysis since they allow us to compute the ground-motion generated by future earthquakes. In a PSHA calculation, one usually includes several alternative GMPEs to cover epistemic uncertainty.

The question is then how to select and rank the GMPEs. Nowadays, a lot of GMPEs have been developed for various contexts, the main ones being Active Shallow Crustal Regions (ASCR), Stable Continental Regions (SCR), and subduction regions with the distinction between inslab and interface events. In order to assess the applicability of GMPEs to a particular context, one can take benefit of the recorded data and analyze the residuals between observations and predictions.

The present paper summarizes the results obtained within the framework of the GEM-SARA project on the topic of Ground-Motion modelling. Our group created a database at the scale of South America, with recorded data and metadata gathered and processed in a homogenized manner, for the different tectonic contexts. These data sets are then used for comparison with a pre-selected set of GMPEs and allows us to identify the best-fitting GMPEs.

2. South American Strong-Ground Motion Data

Fig. 1 shows the spatial distribution of the events and stations collected in the South American strong-motion database. The magnitude range is quite large, going from about 2 to 9 because the database includes small events from Brazil as well as large megathrust interface events from the South American subduction zone (Maule, 2010). Most of the earthquakes occur at depths shallower than 50 km, but an important portion of them have hypocentral depths ranging from 50 to about 250 km. Most of the V_{s30} values are ranging from 250 to 1350 m/s, with a second peak at 2000 m/s. A large amount of V_{S30} values are estimated from different proxies. This is clearly a point of improvement for future versions of the database. The processing applied to the records includes: 1) Remove mean; 2) Pad with zeros; 3) Split the records into P-, S-, coda- wave and noise windows in order to evaluate SNR ratios; 4) Compute FFT for the different windows; 5) Identify minimum and maximum usable frequencies based on a SNR threshold (set at 3 in the present case); 6) Filter between minimum and maximum frequency using acausal, order>4 butterworth filter; and 7) Compute displacement, velocity, acceleration. Recorded PGAs are ranging from 0.0 to 0.7 g.

A lot of events are recorded by less than 5 stations (Fig. 1), but a non-negligible number of events are characterized by more than 5 records, reaching an upper bound of about 40 records per event. More than 75% of the database is made of data from subduction events, both interface and inslab (Fig. 1). Data from Active Shallow Crustal Regions (hereinafter called ASCR) and from Stable Continental regions (hereinafter called SCR) represent about 10% of the database each, while a couple of events are identified as crustal events occurring in oceanic crust (“Others”).

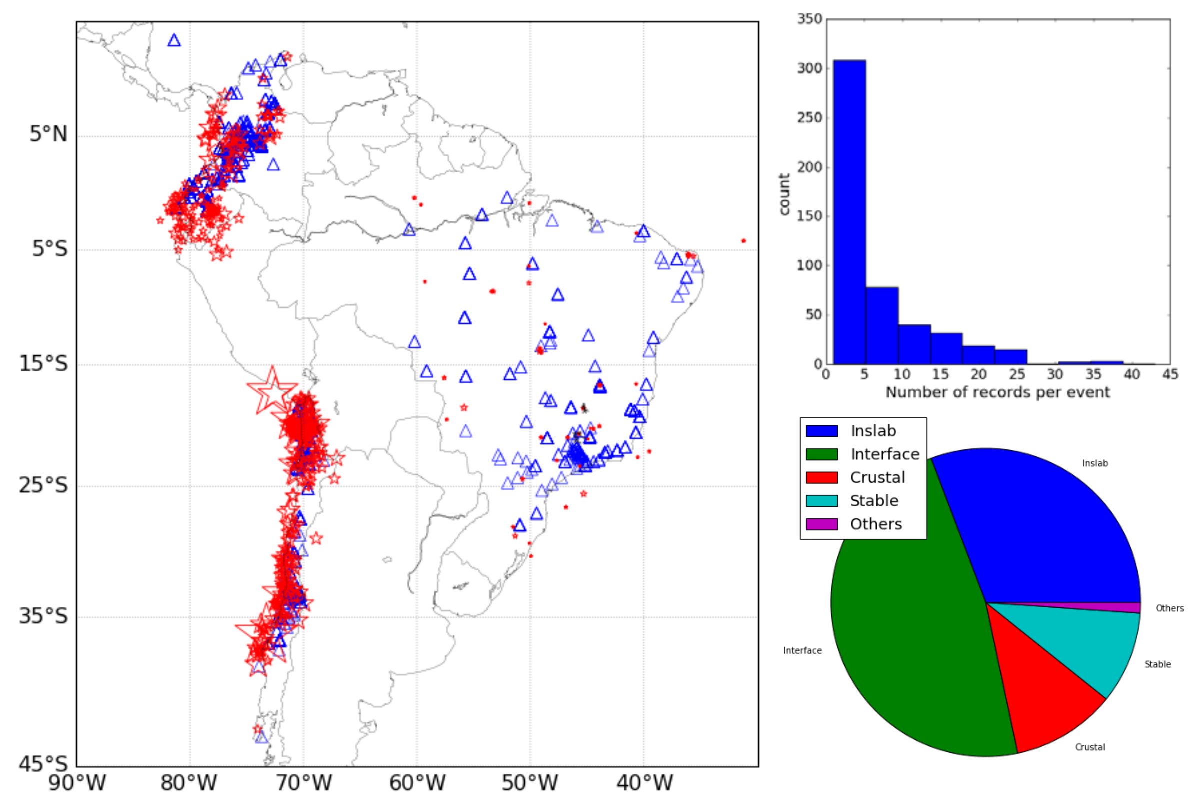

Fig. 1 – Left panel: Map of the events (red stars) and stations (blue triangles) included in the strong-motion database for South America. Upper right panel: Histogram of the number of records for each event. Lower right panel: the repartition of the database per tectonic enviroment.

The magnitude-distance scatter plot is shown in Fig. 2 for each tectonic environment. The figure shows that data for SCR is limited to events with Mw lower than 4 and relatively large distances, mainly in the range

200-1000 km. Data for ASCR are dominated by events with magnitudes between 4 and 5 at distances lower than 300 km. The data for subduction events covers a wider range of magnitudes from 4 to about 9 for distances lower than 500 km. In the following analyzes only events recorded by more than 3 stations are kept.

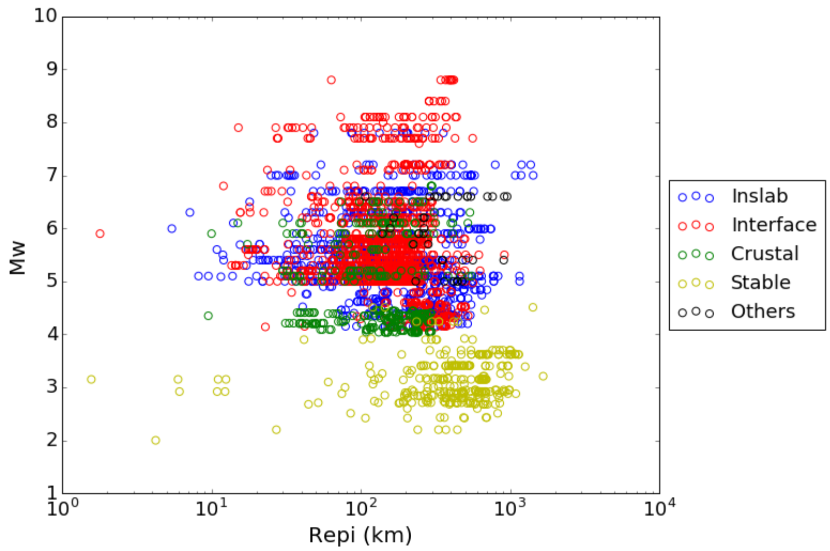

Fig. 2 - Magnitude distance scatter plot by tectonic environment

3. Selection of GMPEs

The number of GMPEs available in the literature has increased very much in the recent years, especially for shallow active crustal environment [1] (http://www.gmpe.org.uk, last accessed May 2016) and the process of selecting the most appropriate ones for PSHA analysis is now a complex problem.

A standard approach nowadays consists in the following steps: 1) pre-select appropriate GMPEs using exclusion criteria [2,3] 2) rank and weight GMPEs according to expert judgment and to results of comparison with recorded data in the region of interest [4].

In the present study, the pre-selection of GMPEs used in analysis were models implemented in OpenQuake [5] which includes a large-selection of GMPEs for each tectonic context (ASCR, SCR, subduction inslab and interface events). In addition, we limited the number of GMPEs based on expert judgment. During a group meeting, we reviewed the implemented GMPEs and removed those that for example where superseded by most recent models.

After this pre-selection, we were still dealing with a large amount of GMPEs, 45 for ASCR, 13 for subduction interface events, 10 for subduction inslab events and 15 for SCR context.

4. GMPEs Evaluation

To assess the evaluation of the different GMPEs to the strong ground motion data from South America the normalized residual distributions were computed. We use two different approaches; on the one hand an approach based on mean, median, standard deviation and likelihood of distribution ([6]), and the other hand, a metric based on average sample log-likelihood (LLH) values ([7]).

In [6] methodology the goodness-of-fit of each GMPE was characterized through four parameters mentioned above. If the data is unbiased, the normalized residuals would be distributed with zero mean and unit variance. The classes which define the goodness-of-fit of each GMPE to the observed data are defined in [6]. Moreover, we computed the average sample LLH values according the methodology proposed by Scherbaum et al. (2009) [7]. This approach has the advantage of not needing subjective judgments to decide the thresholds that define the classes and allows the calculation of weights associated to each GMPE for used on logic trees under PSHA framework [4].

In order to reduce the number of GMPEs, in a rapid and efficient way, we excluded from the list of pre-selected GMPEs those leading to an LLH value greater than 3 for all the periods and those leading to LLH values greater than 4 for at least 1 spectral period for the ASCR context. The levels were slightly higher for the other contexts between 4 and 5. The selected GMPEs after this process are given in Table 1 per tectonic environment.

In next subsections, we show the classes, LLH values and weights for PGA and pseudo-spectral accelerations of 0.2 and 2 seconds for each tectonic environment on South America.

Table 1 – Ground Motion Prediction Equations selected

Active Shallow Crustal Regions	**Stable Crustal Regions**
AbrahamsonEtAl2014 [8] AkkarCagnan2010 [9] AkkarEtAlRepi2014 [10] BindiEtAl2014Rhyp [11] BooreEtAl2014 [12] CampbellBozorgnia2014 [13] CauzziEtAl2014FixedVs30 [14] ChiouYoungs2014 [15] FaccioliEtAl2010 [16]	AtkinsonBoore2006Modified2011[17] DrouetBrazil2016 [18] DrouetBrazil2016withDepth [18] SilvaEtAl2002MwNSHMP2008 [19] TavakoliPezeshk2005 [20]
Subduction Inslab Regions	**Subduction Interface Regions**
AbrahamsonEtAl2015SSlab [21] AbrahamsonEtAl2015SSlabHigh [21] AbrahamsonEtAl2015SSlabLow [21] MontalvaEtAl2016SSlab [22] YoungsEtAl1997SSlab [23]	AbrahamsonEtAl2015SInter [21] AbrahamsonEtAl2015SInterHigh [21] AbrahamsonEtAl2015SInterLow [21] MontalvaEtAl2016SInter [22] YoungsEtAl1997SInter [23] ZhaoEtAl2006SInter [24]

4.1 Active Shallow Crustal Regions

The database for Active Shallow Crustal Regions (ASCR) includes 326 records from 37 earthquakes recorded at 102 stations. Fig. 3 shows the magnitude-distance distribution for ASCR including magnitudes from 4.0 to about 6.5 and distances from 10 to 300 km with a few more distant recordings. The figure also shows a clear separation of the datasets from the different countries in terms of magnitude and distance ranges. The Ecuadorian dataset includes only small events with magnitudes between 4.0 and 4.5, while data from Colombia and Chile cover the higher magnitude range (M>=5).

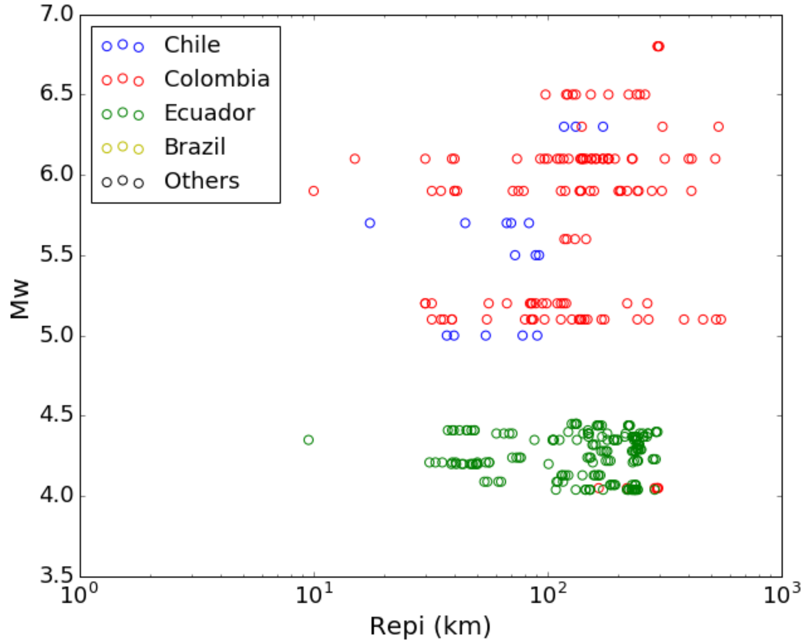

Fig. 3 - Magnitude distance scatter plot for the database for Active Shallow Crustal Regions

Table 2 gives the classes according to the ranking defined in [6], the average sample LLH values and associated weights as defined in [7], for the ASCR GMPEs for three spectral periods: PGA, and spectral acceleration at 0.2 and 1.0 sec. Fig. 4 shows the variation of LLH with period. The obtained ranks are bad especially for high frequencies, and the results show that the standard deviation of the residuals is high (higher than predicted by the GMPEs).

Table 2 – Classes (as defined in [6]), average sample LLH values and associated weight of GMPEs resulting from the analysis for ASCR database

	PGA			**Sa @ 0.2 sec**			**Sa @ 1 sec**		
GMPE	**Class**	**LLH[1]**	**w_i[2]**	**Class**	**LLH[1]**	**w_i[2]**	**Class**	**LLH[1]**	**w_i[2]**
AbrahamsonEtAl2014	D	3.32	0.11	D	3.62	0.09	C	2.65	0.1
AkkarCagnan2010	C	2.915	0.15	C	2.856	0.15	A	2.258	0.13
AkkarEtAlRepi2014	D	3.402	0.11	D	3.352	0.11	C	2.6	0.1
BindiEtAl2014Rhyp	D	3.259	0.12	D	3.338	0.11	B	2.241	0.13
BooreEtAl2014	D	3.649	0.09	D	3.754	0.08	C	2.808	0.09
CampbellBozorgnia2014	D	3.63	0.09	D	3.74	0.08	C	2.996	0.08
CauzziEtAl2014FixedVs30	D	3.291	0.11	D	3.244	0.12	B	2.269	0.13
ChiouYoungs2014	D	3.615	0.09	D	3.445	0.1	C	2.857	0.09
FaccioliEtAl2010	D	3.113	0.13	C	2.844	0.15	B	2.22	0.14
[1]LLH = average sample Log-Likelihood									
[2]w_i = weigth of GMPEs									

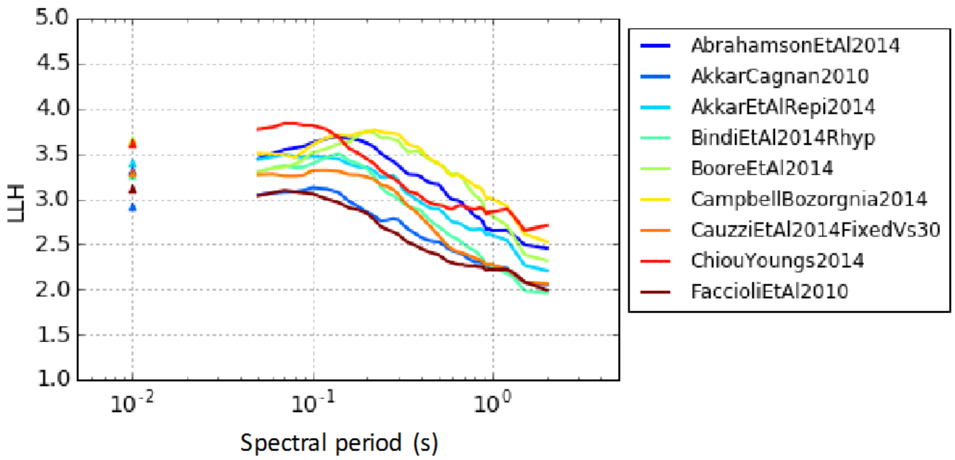

Fig. 4 – Average sample LLH value versus period for the ASCR GMPEs

4.2 Stable Crustal Regions

The data set for SCR is more homogeneous since all the data are coming from Brazil. It includes 279 records of 37 earthquakes at 96 stations. Fig. 5 shows the magnitude-distance distribution for the SCR dataset which is dominated by small events (M<=4) and long distances in the range 100-1000 km.

Table 3 gives the classes according to the ranking defined in [6], the average sample LLH values and associated weights as defined in [7] for the SCR GMPEs for three spectral periods: PGA, and spectral acceleration at 0.2 and 1.0 sec. Fig. 6 shows the variation of LLH with period. As for ASCR, the ranks obstained and LLH values are relatively low. For the SCR data, the limitation comes from the limited magnitude-distance range which implies data of low amplitude that can be affected by noise which may explain the tendency of increasing LLH with increasing period (Fig. 6).

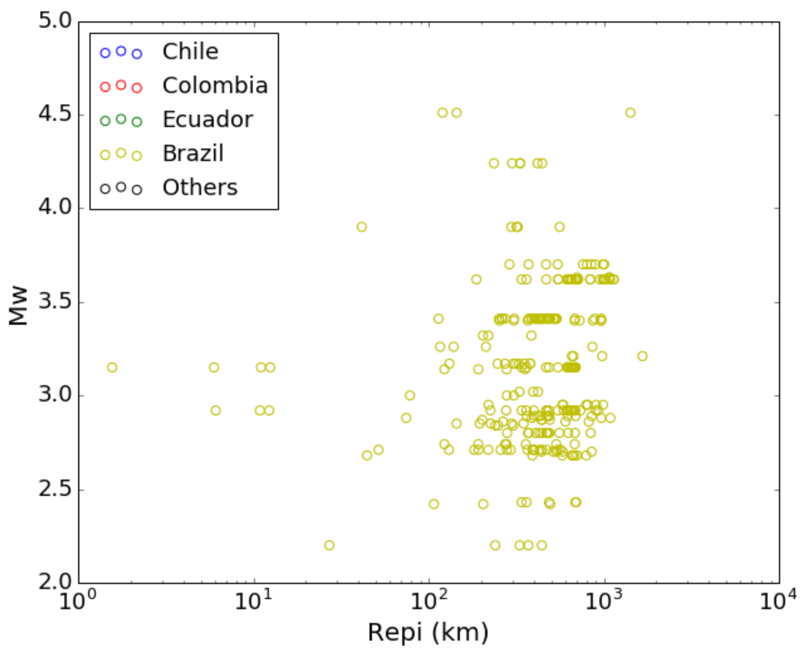

Fig. 5 - Magnitude distance scatter plot for the database for Stable Crustal Regions

Table 3 - Classes (as defined in [6]), average sample LLH values and associated weight of GMPEs resulting from the analysis for SCR database

	PGA			Sa @ 0.2 sec			Sa @ 1 sec		
GMPE	**Class**	**LLH[1]**	**w_i[2]**	**Class**	**LLH[1]**	**w_i[2]**	**Class**	**LLH[1]**	**w_i[2]**
AtkinsonBoore2006Modified2011	D	3.067	0.17	D	2.948	0.18	D	3.504	0.12
DrouetBrazil2016	D	3.876	0.10	D	3.253	0.14	D	4.536	0.06
DrouetBrazil2016withDepth	B	2.340	0.28	B	2.084	0.32	D	2.565	0.23
SilvaEtAl2002MwNSHMP2008	D	2.730	0.22	C	2.499	0.24	D	3.494	0.12
TavakoliPezeshk2005	C	2.607	0.23	D	3.482	0.12	A	1.625	0.42
[1]LLH = average sample Log-Likelihood									
[2]w_i = weigth of GMPEs									

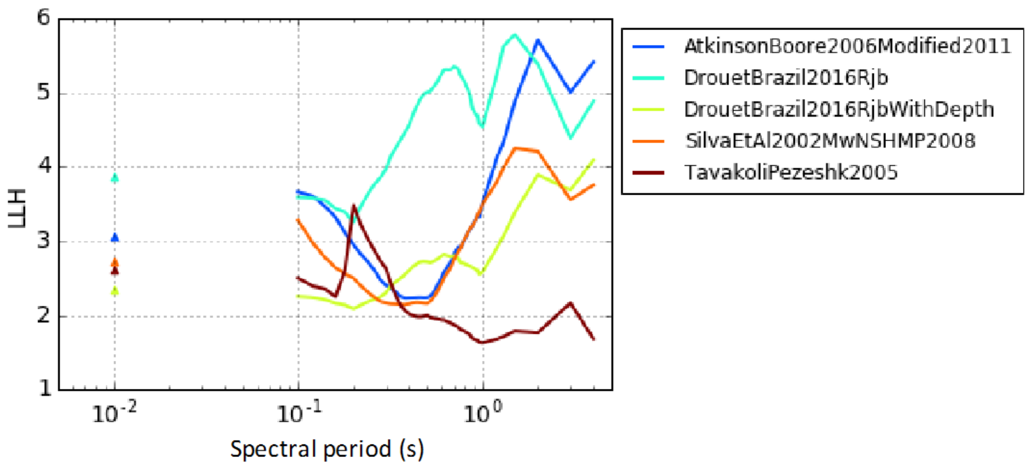

Fig. 6 - Average sample LLH value versus period for the SCR GMPEs

4.2 Subduction Inslab Regions

The number of records for the subduction inslab dataset is 890 for 89 events recorded at 208 stations. Fig. 7 presents the magnitude-distance distribution showing a good coverage of magnitude and distance with relative overlap for each country, even though the data from Ecuador includes smaller magnitude events than the other two regions.

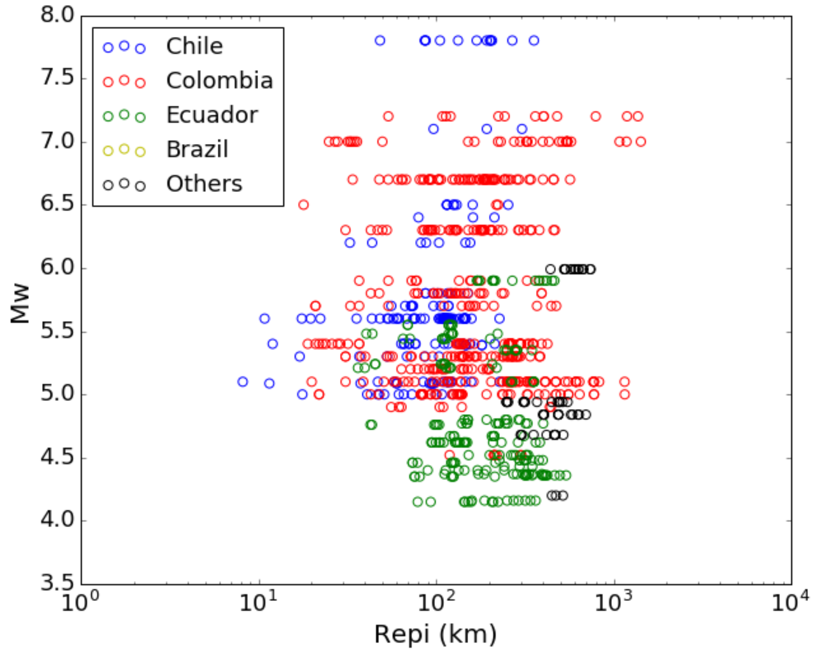

Fig. 7 - Magnitude distance scatter plot for the database for Subduction Inslab Regions

Table 4 gives the classes according to the ranking defined in [6], the average sample LLH values and associated weights as defined in [7] for the subduction inslab events GMPEs for three spectral periods: PGA, and spectral acceleration at 0.2 and 1.0 sec. Fig. 8 shows the variation of LLH with period.

Table 4 - Classes (as defined in [6]), average sample LLH values and associated weight of GMPEs resulting from the analysis for subduction inslab events database

	PGA			**Sa @ 0.2 sec**			**Sa @ 1 sec**		
GMPE	**Class**	**LLH[1]**	**w_i[2]**	**Class**	**LLH[1]**	**w_i[2]**	**Class**	**LLH[1]**	**w_i[2]**
AbrahamsonEtAl2015SSlab	D	4.865	0.20	D	4.662	0.18	D	3.168	0.27
MontalvaEtAl2016SSlab	D	3.763	0.43	D	3.374	0.44	C	2.81	0.34
YoungsEtAl1997SSlab	D	4.848	0.20	D	4.689	0.18	D	3.892	0.16
ZhaoEtAl2006SSlab	D	5.057	0.17	D	4.512	0.20	D	3.399	0.23
[1]LLH = average sample Log-Likelihood									
[2]w_i = weigth of GMPEs									

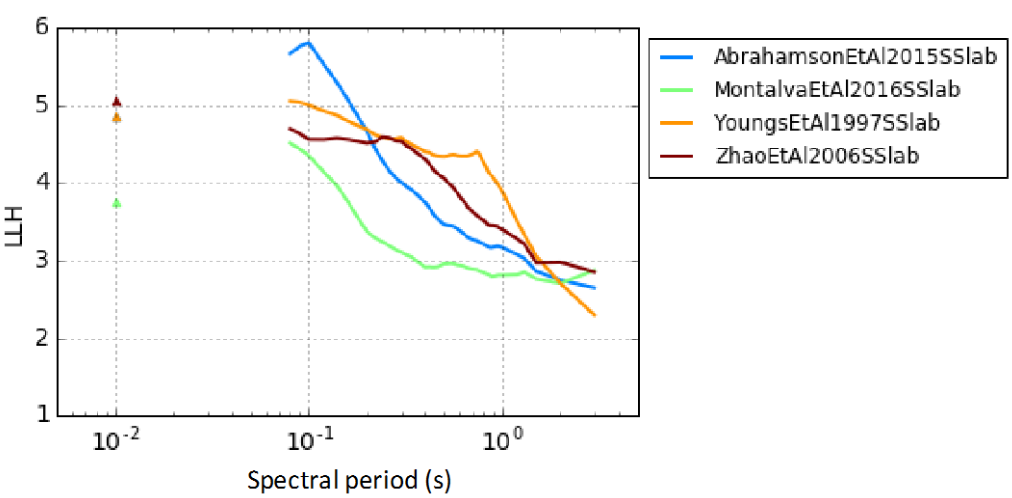

Fig. 8 - Average sample LLH value versus period for the subduction inslab GMPEs

4.2 Subduction Interface Regions

The largest dataset corresponds to subduction interface events, with a number of records reaching 1365 for 126 events recorded at 189 stations. This dataset is dominated by data from Chile as shown in the magnitude-distance distribution plot (Fig. 9). Again Ecuadorian data are from smaller magnitude events.

Table 5 gives the classes according to the ranking defined in [6], the average sample LLH values and associated weights as defined in [7] for the subduction inslab events GMPEs for three spectral periods: PGA, and spectral acceleration at 0.2 and 1.0 sec. Fig. 10 shows the variation of LLH with period.

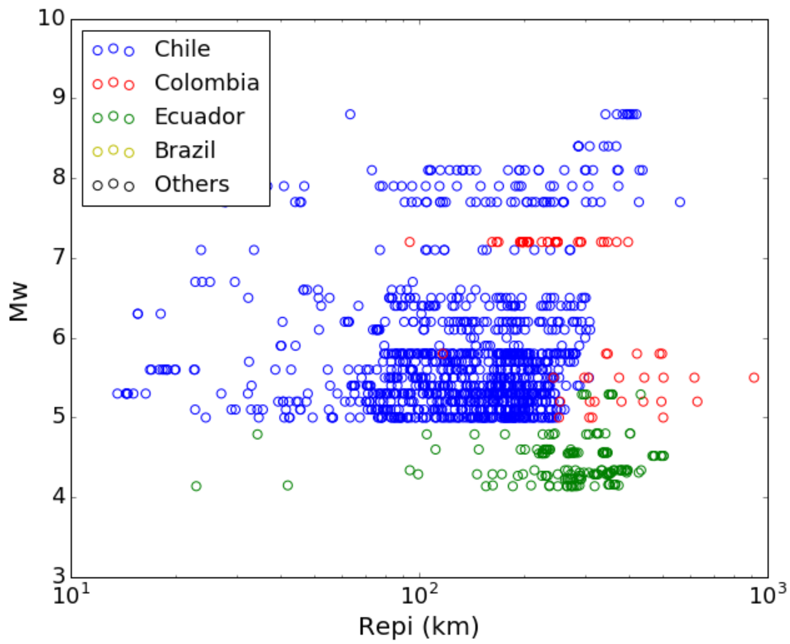

Fig. 9 - Magnitude distance scatter plot for the database for Subduction Interface Regions

Table 5 - Classes (as defined in [6]), average sample LLH values and associated weight of GMPEs resulting from the analysis for subduction interface events database

	PGA			**Sa @ 0.2 sec**			**Sa @ 1 sec**		
GMPE	**Class**	**LLH[1]**	**w_i[2]**	**Class**	**LLH[1]**	**w_i[2]**	**Class**	**LLH[1]**	**w_i[2]**
AbrahamsonEtAl2015SInterHigh	C	2.8	0.22	D	3.149	0.17	C	2.535	0.20
MontalvaEtAl2016SInter	B	2.293	0.32	A	2.196	0.32	A	2.165	0.26
YoungsEtAl1997SInter	D	2.611	0.25	C	2.6	0.24	C	2.104	0.28
ZhaoEtAl2006SInter	C	2.89	0.21	B	2.457	0.27	A	2.206	0.26
[1]LLH = average sample Log-Likelihood									
[2]w_i = weigth of GMPEs									

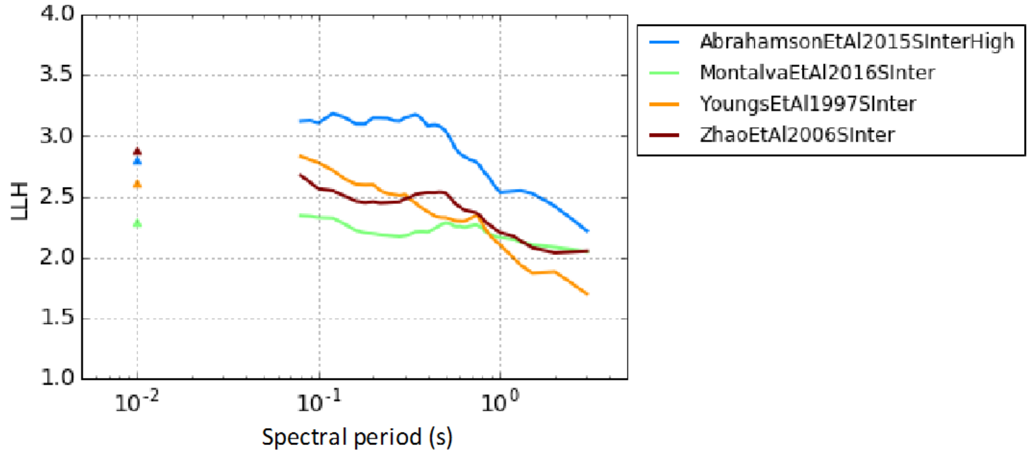

Fig. 10 - Average sample LLH value versus period for the subduction interface GMPEs

5. Conclusions

In this paper we presented the results of the group working on GMPEs within the framework of the GEM-SARA project. We created a homogeneous database of strong-motion recordings at the scale of South America. This database was then used for comparison with GMPEs using tools developed around the OpenQuake program developed by the GEM Foundation.

The testing between recorded data and GMPEs has be performed for the four tectonic contexts of interest for South America: ASCR, SCR, and subduction including inslab and interface events. The analysis of the residuals following the methods proposed by [6,7] allowed us to narrow the set of pre-selected GMPEs and identify those that are most adapted for PSHA.

Our analysis reveals that the observed variability is greater than that predicted by the GMPEs (Fig. 11). This may suggest that further efforts are needed to homogenize the database. More specifically, the vs30 values included in the datasets are mostly coming from different proxies and may not correctly reflect actual site effects. This is clearly a point of improvement for future developments of the database.

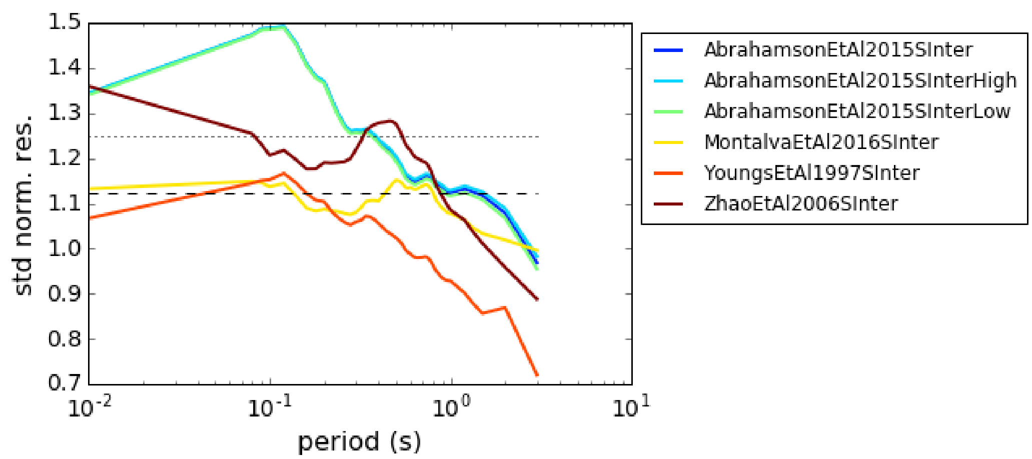

Fig. 11 – Standard deviation of the normalized residulas for the subduction interface dataset.

We also started to analyze the standard deviations of the residuals trying to break-down variability into its different elements. As a first result, regional variation clearly appears on the between-event residuals for PGA (Fig. 12). With the Ecuadorian events showing negative between-event residuals while Chilean events are leading to residuals more centered on zero, and events from Colombia show an intermediate trend. Further tests will be performed at smaller regional scale in order to better constrain regional variations of ground-motion. Also for future work, we hope to succeed to gather more people to contribute to the database, for example data from Peru would be very useful to test regional variations as would be data for Argentina.

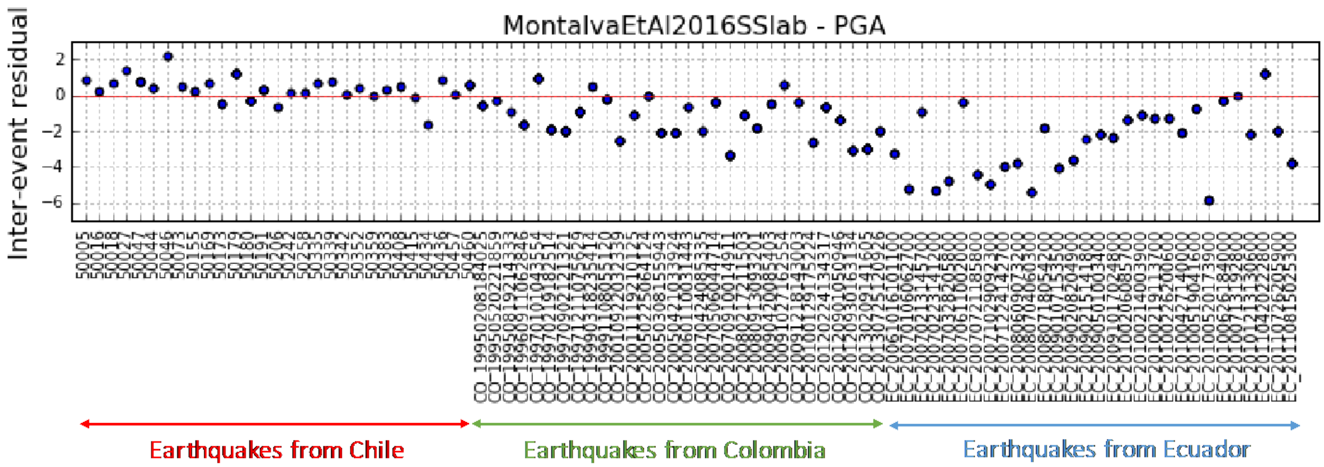

Fig. 12 – Between-event residulas for the subduction inslab dataset using the Montalva et al. (2016) GMPE at PGA (from left to right events from Chile, Colombia and Ecuador are represented).

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