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BUILDING AN OPEN SEISMIC HAZARD MODEL FOR SOUTH AMERICA: THE SARA-PSHA MODEL

J. Garcia(1), G. Weatherill(2), M. Pagani(3), L. Rodriguez(4), V. Poggi(5) and the SARA Hazard Working Group(6)

(1) *Senior Seismic Hazard Modeller, Global Earthquake Model (GEM) Foundation, Pavia, Italy, julio.garcia@globalquakemodel.org*
(2) *Senior Seismic Hazard Modeller, Global Earthquake Model (GEM) Foundation, Pavia, Italy, graeme.weatherill@globalquakemodel.org*
(3) *Hazard Coordinator Global Earthquake Model (GEM) Foundation, Pavia, Italy, marco.pagani@globalquakemodel.org*
(4) *PhD Student, Istituto Universitario di Studi Superiori, Pavia, Italy, luis.rodriguez@globalquakemodel.org*
(5) *Senior Seismic Hazard Modeller Global Earthquake Model (GEM) Foundation, Pavia, Italy, valerio.poggi@globalquakemodel.org*
(6) *Seismic Hazard Modellers, South American collaborators, e-mail address*

Abstract

The creation of a hazard model and the computation of seismic hazard for the territories covering the South American continent were two critical milestones of the South America Risk Assessment (SARA) project. This model is the first community-based assessment completed for this continent since the conclusion of the Global Seismic Hazard Assessment Program (GSHAP; [1]). It provides scientists, engineers and decision makers in the region with a complete and transparent assessment of seismic hazard - and its related uncertainties – based on common methods to collect and process input data.

The SARA seismic model was created using a compilation of updated and harmonised databases needed for PSHA (e.g. historical and instrumental catalogue, a compilation of active fault data) which were created following, to the greatest extent possible, common standards and transparent procedures. The construction of these databases was completed by a number of South American scientists and engineers.

The results computed with the SARA hazard model can support multiple objectives: i) input definition for national and/or regional scale seismic risk studies, ii) input definition for local or urban scale seismic risk studies and iii) seismic input definition consistent with the requirements of internationally recognised seismic design codes (e.g. International Building Code; [2]). Although these results do not intend to replace the existing national design regulations for seismic design and construction of buildings, they constitute a good reference for improving transparency, self-consistency and overall understanding of future revision of national hazard models.

Keywords: SARA, GEM, Probabilistic Seismic Hazard, South America

1. Introduction

The South America continent is bordered by several tectonic collision fronts, including that of the Nazca plate to the west, and, with an oblique subduction, with the Caribbean plate to the north. The tectonic processes associated to subduction dominate the occurrence of many large and destructive earthquakes along the western coast, producing significant damages to infrastructure and the loss of life. In addition, the presence of a complex system of shallow active faults capable to generate destructive events inland (e.g. western Argentina, Bolivia, Ecuador, Peru, Colombia and Venezuela) makes this region one of the most seismically active on the planet. Seismic hazard modelling in South America presents scientists and engineers with a diverse set of challenges because of the complexity of the tectonic setting, the inhomogeneous characterisation of seismicity between countries and the diverse properties of national active faulting and strong motion databases.

To address these challenges, a collaborative effort known as the South America Risk Assessment (SARA) gathered scientists and engineers from across South America to engage in, and contribute to, the development of a comprehensive model for seismic hazard and risk across the region. The earthquake hazard model created in the framework of the SARA project resulted from the collaboration between the GEM hazard team and scientists from the South American region. The main activities completed during this collaboration included the harmonisation of critical datasets (e.g. both historical and instrumental earthquake catalogues, seismically active crustal faults, and national databases of strong motion recordings), the development of common standards for data representation, the development of open tools for data collection, the construction of the earthquake source model and, the analysis and computation of hazard. In this paper, we describe the process adopted for the construction of the earthquake source model, with a special focus on the newest, innovative and controversial aspects, and on illustrating the impact of various modelling assumptions on the final results computed.

2. Seismotectonic framework

The forces driving the collision between the Nazca and the South America plates control most of the current tectonic evolution in South America. The Nazca plate subducts beneath the South America continent with different plunging angles, convergence rates and directions from a northeast direction in the Colombia-Ecuador sector to an almost east-west direction in Central Chile [3]. Ridge zones (e.g. Juan Fernandez, Iquique, Nazca and Carnegie) and fracture zones in the sea floor play a relevant role in the subduction mechanism, the interface coupling and the continental deformation [4]. This setting results in a complex system of crustal faults inland, with different style of faulting (e.g. right-lateral, left-lateral strike-slip, normal, reverse) across the region.

The spatial and temporal distribution of large earthquakes also varies along the western margin. As can be shown in Fig. 2, the strongest earthquakes are located in Chile, where $M_W \geq 8.0$ are frequent and the largest recorded earthquake in the instrumental era took place (i.e. 1960 M_W 9.5 Valdivia). In Peru thrusting focal mechanisms are predominant for moderate and large events associated with a flat subduction plate convergence, whilst along the coast of Ecuador an exceptional sequence of large thrust events associated with the subduction have occurred in the past century (1906, 1942, 1958 and 1979). In the northern part of the continent, the most active zones are associated with crustal seismicity along the border of mountain ranges in Colombia, and along the interaction zones between the South America and the Caribbean plates in Venezuela (e.g. Boconó Fault, San Sebastian Fault and Pilar Fault).

2.1 Database of crustal active faults

Within the SARA project, a team of South American geologists undertook the complex and challenging task of assimilating and homogenising active fault data across the region. Data came from many published sources including the International Lithosphere Program II-2 project [5], the Multinational Andean Project [6] and existing national neotectonic databases and fault data collections. Quaternary active structures known up to present in the region, particularly considering their possible seismogenic relevance, have been compiled under common criteria, building a harmonised database.

Due to the fact that data availability and accuracy is very heterogeneous across the region, harmonisation efforts on selecting priority faults were needed. The following alternative selection criteria were applied:

- Slip rates equal or larger than 0.1 mm/yr (this applies to rates already available or estimated by compilers using quantitative-semiquantitative criteria)
- Evidence of Late Pleistocene tectonic activity (confirmed and suspected)
- Confirmed or suspected sources of earthquakes with magnitudes greater than M_W 5.5.

The resulting database is shown in Fig. 1, together with the set of faults modelled as source faults. Around 30% of the overall faults collected have enough information to properly characterise their geometry and activity rate; only 486 of the suspected Quaternary faults satisfied the selection criteria. Clearly, additional investigations will be necessary in order to properly characterise the faults currently with insufficient data or missing in our compilation (e.g. faults associated to the frontal deformation Andean zone).

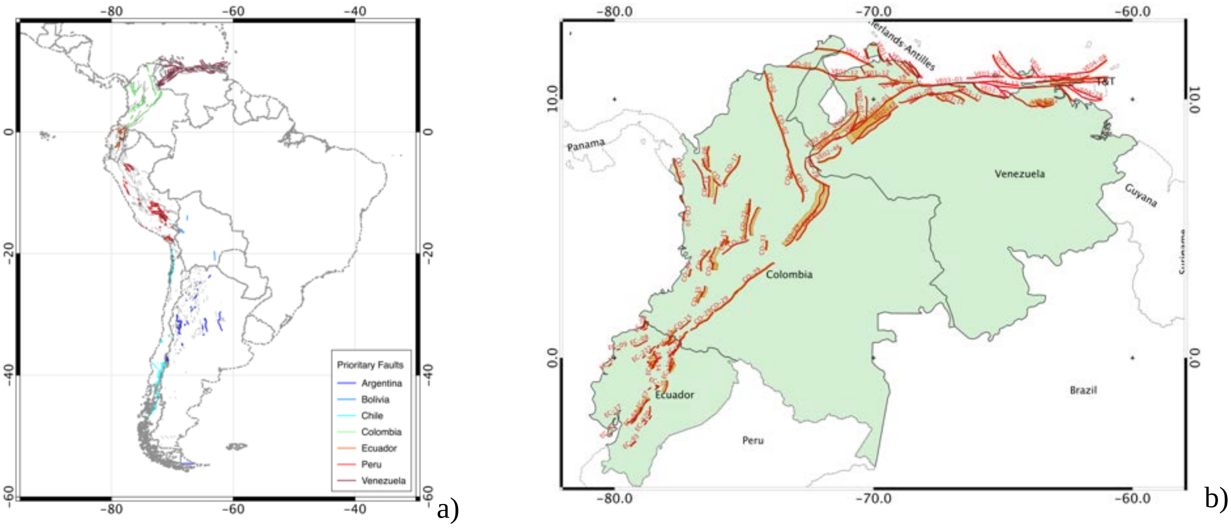

Fig. 1 – Database of crustal fault: a) fault traces of faults modelled as source faults with different colours, in black the faults discarded; b) Surface projection of fault sources in the north Andean block.

2.2 Subduction tectonic environment

Two research groups investigated the subduction process within the SARA project, focusing on collecting essential information for its characterization. The first research group, led by scientists from Colombia, prepared an extensive dataset of seismotectonic information related to subduction earthquakes including historical and instrumental seismicity and catalogues of focal mechanism solutions [7] and proposed a zonation of subduction-related sources affecting South America and surroundings (see details in [8]). The second research group focused on the characterisation of subduction zones for PSHA, which was built around the work of a PhD thesis focused on defining a complete characterisation of subduction along the western coast of South America. A more detailed description is provided in a following section of this paper.

3. The South America earthquake catalogue

The availability of a homogeneous earthquake catalogue is a fundamental requirement for any seismic hazard analysis. Two groups worked at compiling the SARA catalogue, each one focusing on different eras: i) the pre-1964 era, and ii) the post-1964 era.

Table 1 – Priority schema used to select a preferred location in the compilation of the pre-1964 catalogue.

Priority	Input Source
1	ISC-GEM catalogue
2	Centennial catalogue
3	Earthquake studies
4	National catalogues
5	CERESIS95 catalogue
6	CERESIS85 catalogue

Table 2 – Priority schema used to homogenize the magnitude to Mw in the compilation of the pre-1964 catalogue.

Priority	Earthquake size
1	Moment magnitude (Mw)
2	Surface magnitude (Ms)
3	Volumetric magnitude (mb)
4	Local magnitude (M_L)
5	Other magnitudes (M, UK)
6	Epicentral Intensity (Io)

The compilation of the pre-1964 catalogue was completed by an ad-hoc group of scientists. The activity consisted on collecting and on critically reviewing the information included in various sources such as the ISC-GEM catalogue [9], and the Global Historical Earthquake Archive [GHEA] and Catalogue [GHEC] [10] as well as local information (papers, national catalogues, reports). More than 2500 earthquakes reported in the pre-1964 era were critically assessed (e.g. assigned locations, origin times, and magnitudes), with magnitude estimates revised using globally and locally calibrated relations for different magnitude scales, as well as for macroseismic intensity and magnitude. The methodology used [10], relied on a hierarchical schema defining the preferential order for the selection of earthquake location and magnitude from the different solutions available for the same event in various catalogues (see Table 1 and 2).

The post-1964 catalogue was created using information from datasets such as the International Seismological Centre (ISC), the USGS/NEIC, the Global CMT catalogue and the CERESIS regional catalogue, in combination with the most updated versions of various national catalogues. Recently, GEM has developed a set of open-source tools to assist hazard modellers in the construction of a harmonised catalogue [12]. We used this tool to compile the database, to explore the relation between earthquake solutions provided by different sources (i.e. bulletins, catalogues), to build and apply empirical regression models for harmonising magnitude scales and, ultimately, to homogenise the earthquake catalogue.

Similarly to what already described for the compilation of the pre-1964 component of the catalogue, also in this case we defined two selection hierarchies, one for location and one for magnitude, which were differentiated on the basis of the time interval covered (see Table 3 and Table 4). The location and magnitude reported by the ISC-GEM catalogue were considered as the preferred solutions in both hierarchies before 1992, followed by solutions provided by global sources (e.g. EHB, ISC, CENT, NEIC) in a period where local solutions are missing or have a poor quality. The last period contains good solutions from local agencies/networks and then, as a general rule, wherever possible the preferred location solution is provided by a local agency.

Table 3 – Hierarchical schema used to set the preferred location solution in the post-1964 era.

Time period	**Priority [from higher to lower]**
1930/01/01 - 1964/12/31	ISC-GEM, EHB, ISC, ISS, GUTE, CER
1965/01/01 - 1991/12/31	ISC-GEM, EHB, CENT, ISC, NEIC, GCMT, CER
1992/01/01 - 2013/12/31	BSB, GUC, SGCN, FUNV, IGEPN, FONT, IGQ, SJA, SCB, CASC, UPA, ISC-GEM, EHB, CENT, ISC, NEIC, GCMT, IDC

ISC-GEM: ISC-GEM catalogue
EHB: Engdahl-van der Hilst catalogue
ISC:ISC revised bulletin
ISS: ISS bulletin
GUTE: Gutenberg-Richter catalogue
CENT: Centennial catalogue
NEIC: USGS/NEIC catalogue
GCMT: Global CMT bulletin
IDC: International Data Centre bulletin
CER: CERESIS catalogue

BSB: Brazil catalogue
GUC: Chile catalogue
IGEPN, FONT: Ecuador catalogue
SGCN: Colombia catalogue
FUNV: Venezuela catalogue
IGQ: Peru catalogue
SJA: Argentina catalogue
SCB: Bolivia catalogue
CASC, UPA: Central America catalogues

An exhaustive analysis was performed in order to define empirical magnitude conversion equations for the region. We obtained several conversion equations between the preferred magnitude scale [M_W] and other magnitude scales [e.g. M_W versus M_S, mb, md, M_L, UK]. Finally, the harmonised post-1964 catalogue with more than 93000 individual events was created automatically using the Catalogue-Toolkit and the hierarchical schema defined.

Table 4 – Hierarchical schema defining the priority followed to homogenise the magnitude in the post-1964 era.

Order	Magnitude	Priority [from higher to lower]
1	Mw	ISC-GEM, GCMT, CENT, NEIC, Others
2	Ms	ISC, NEIC, IDC, [BRK, SYK, PSA, SCB]
3	mb	ISC, NEIC, ABE, [SCB, CAR, GUC, IGQ, IGP, PSA]
4	md	IGEPN, [TRN, UCV, CASC, PSA, SJA]
5	M_L	SGCN, FUNV, CASC, GUC, SJA
6	M, UK	PAS

PAS: California Institute of Technology
BRK: Berkeley Seismological Laboratory
SYK: Sykes and Edwing (1965) catalogue
PSA: Instituto Nacional de Prevención Sísmica (INPRES), Argentina
ABE: Abe studies [Abe (1981, 1984 and Abe & Noguchi (1983)]

The SARA catalogue contains 100,530 earthquakes occurred between 1500 and 2013 in an area defined within longitude 90°W to 35°W and latitude 60°S to 16°N. It was created by a simple aggregation of the two catalogues described before (pre and post 1964).

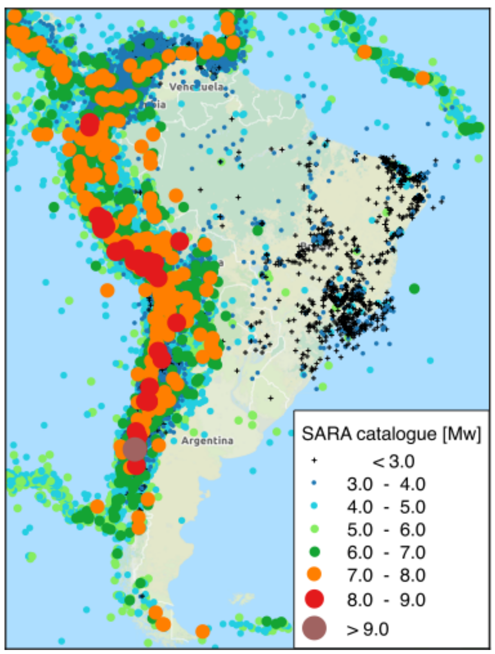

Fig. 2 – SARA catalogue: distribution of earthquakes with $M_W > 3.0$ from 1500 – 2013.

3.1 The catalogue pre-processing

Two crucial analyses must be performed on the catalogue prior it being used in PSHA: the declustering and the completeness analyses. During the declustering analysis we attempted to identify and to remove earthquakes, which occurred in clusters such as foreshocks/aftershocks sequences and swarms, whilst the main goal of the completeness analysis was to obtain an estimate of the earliest time at which all events for different magnitudes classes are included in the catalogue. In this study, we used the Gardner and Knopoff method [13] for declustering purposes. In order to decluster the catalogue, taking into account the tectonic context and related seismicity present in the region (active shallow, stable and interface/inslab subduction) we tested the performance of the method using different time-windows (Grünthal, Gardner and Knopoff and Uhrhammer, see [16]). In the active shallow and subduction regions, the best results were obtained using a Gardner and Knopoff window, whilst for the stable continental area using an Uhrhammer window was considered as more effective.

The completeness can be analysed using different statistical techniques (e.g. [17], [18] and [19]). For this purpose, we used the Stepp method [16]. The region was divided into several large-scales zones in order to identify regional variations on completeness and possible common b-value areas. For each zone, the temporal variation in catalogue completeness was explored. The Stepp algorithm was run with a one-year time interval and two different magnitude intervals (0.25 and 0.5). A "preferred" solution was selected after a detailed inspection and revision of the initial results. The magnitude-time completeness table computed for each large-scale zone was used as default in the computation of the activity rates. Further minor modifications were made when variations of the completeness were found within each region during the calculation of the activity rates.

4. Building the SARA Seismic Hazard model and hazard calculations

To manage the basic information for the construction of the Earthquake Source Model, the HMTK [16] was used, but new functionalities were introduced to support specific components of the model (e.g. subduction and active fault modelling). In the following sections, we discuss the process followed for the construction of the various components of the seismic hazard model, with special focus on key aspects, on illustrating the impact of various modelling assumption on the final results computed.

3.1 Building the distributed seismicity sources in Active and Stable Shallow Crust

The model for distributed seismicity sources in Active and Stable Shallow Crust was defined using a number of polygons (or volumes) delineating regions with homogeneous temporal and spatial characteristics of seismicity, tectonic and geodynamic setting. The definition of polygons' geometry and their characterisation was based mainly on information contained in the earthquake catalogue, on tectonic/geophysical information from literature (e.g. [22], [23]), on focal mechanism solutions, on the database of crustal faults described before and the strain model (GEM GSRM v2.1 [24]). This approach was based on criteria proposed by [25], where an objective schema for the source zone boundary delineation is suggested.

The area source model for active shallow and the stable continental regions contains 72 sources zones (see Fig.5a). For each source zone, the parameters used to describe seismicity occurrence are: a) the maximum magnitude: derived by adding an increment of 0.5 to the largest observed magnitude, b) the seismogenic thickness: constrained also using the Moho depth, c) the focal depth distribution of earthquakes and its probability which is assessed using histograms of hypocentral depth distribution obtained from past seismicity, d) the orientation and faulting styles of ruptures: obtained using the faults located within the source boundaries and the focal mechanism solutions and - ultimately- e) the activity rate: represented by a truncated Gutenberg-Richter distribution assuming a magnitude binning of 0.1, a minimum magnitude of 4.5, and *b* and *a* values computed using the maximum likelihood estimator proposed by Weichert [26].

3.2 Building the fault based crustal model

Occurrence rates on faults are generally modelled either following a characteristic, a truncated Gutenberg Richter model or of a combination of the two. In developing the current model, we opted for the use of a truncated Gutenberg-Richter model (e.g. [27], [28], [29]). To model a fault source, a generalised 3D representation of the fault plane and its mean activity rate was necessary. The following additional assumptions were used in building the fault model: a) the occurrence of the events on the fault follows a GR, and the total seismic moment rate from the magnitude frequency distribution equals the geological moment rate derived from the fault dimension and slip rate, b) The b-value on the fault is the same as the b-value of the area source within which the fault is located, and, c) for each fault a lower and upper-bound magnitudes are assigned. The lower bound assigned is ≥ M6 since the small magnitude earthquakes are modelled using distributed seismicity sources, whilst the upper-bound magnitude is constrained by the fault dimension and the scaling relation used to compute this value.

Figure 5b shows the 486 crustal faults modelled as source faults, that we assumed had generated surface-faulting earthquakes in the geologically recent past (with Mw>6.0) and that may be capable of producing future, potentially damaging earthquakes across the South American region.

3.3 Combining the distributed seismicity model with the fault based model

Due to the fact that the spatial distribution of faults across the region cannot be considered complete, we adopted a methodology to integrate the activity rates from the distributed seismicity with those obtained by the faults within each area source. This methodology consisted on first creating a discrete representation of area sources by converting them to a set of OpenQuake-engine point sources distributed on a regular grid covering the area source; earthquake occurrence rate for each point source corresponds to the one defined for the area source divided by the number of points sources. In order to avoid overlapping contributions from the faults and background sources within the magnitude range covered by the MFD (Magnitude Frequency Distribution) assigned to the encompassing area source and the MFDs of the shallow faults included, the MFD of the point sources within a buffer around the surficial projection of each fault source is truncated at a magnitude value, which corresponds to the minimum magnitude of the double truncated magnitude frequency distribution computed for the fault source (see Fig. 3). In addition, the point sources within the buffer take the same orientation and faulting styles of the corresponding fault.

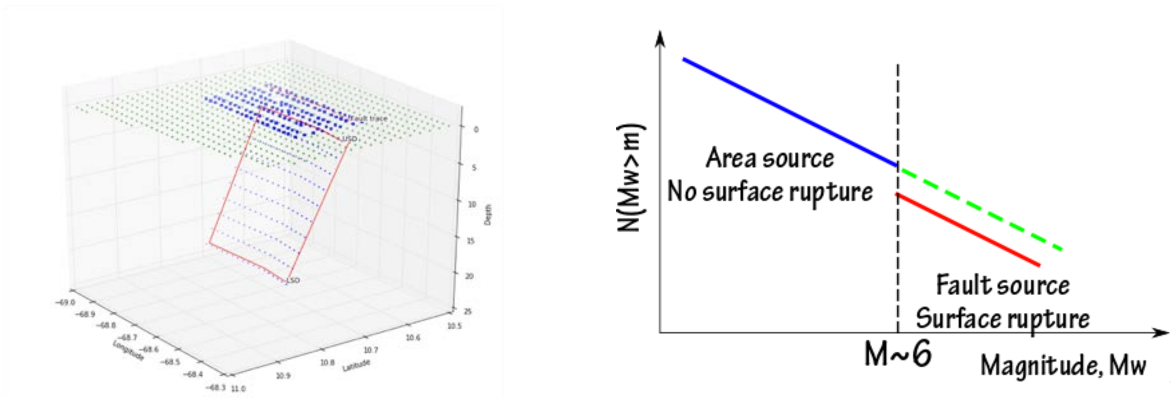

Fig. 3 – Example of distributed seismicity and fault MFD integration: left panel) in green: distributed seismicity associated to the area source, in red: 3D representation of the fault, in blue: distributed seismicity modified by the fault contribution; right panel) related MFDs.

3.4 Modelling of subduction and deep seismicity sources

The modelling of the subduction and of the deep seismicity earthquakes involved three main stages: a) definition of the slab geometry and the typology of the sources, b) characterization of source in terms of long term recurrence and maximum magnitude; and c) segmentation. In this regard we tried to accomplish three main goals: a) to create a geometry using the most simple and generalized methodology to represent the seismogenic areas, b) that such areas agree with the complexity of the region and tectonic environment, and, c) the source must be suitable to be used for hazard analysis.

In this study we defined the geometry of the source zones using mainly the hypocentral distribution of the earthquakes (as in [30]), and their respective focal mechanisms, but using additional information available (i.e. finite ruptures for large events, thickness of the crust, thermodynamic models, topography), which serves as a complementary constraint in the geometry definition. The whole area was divided into four regions (Pacific west coast, Bucaramanga nest, Southern section of the Lesser Antilles and the Panama block).

The method proposed by [31] was applied to define the geometry of interface source zones, but using as constraints the information cited before (see details in [33]). Then, the sources are represented using a three-dimensional surface (complex fault in the OQ-engine definition) that captures the complex geometry of the slab. In a similar way it was defined the geometry of the in-slab and deep seismicity sources.

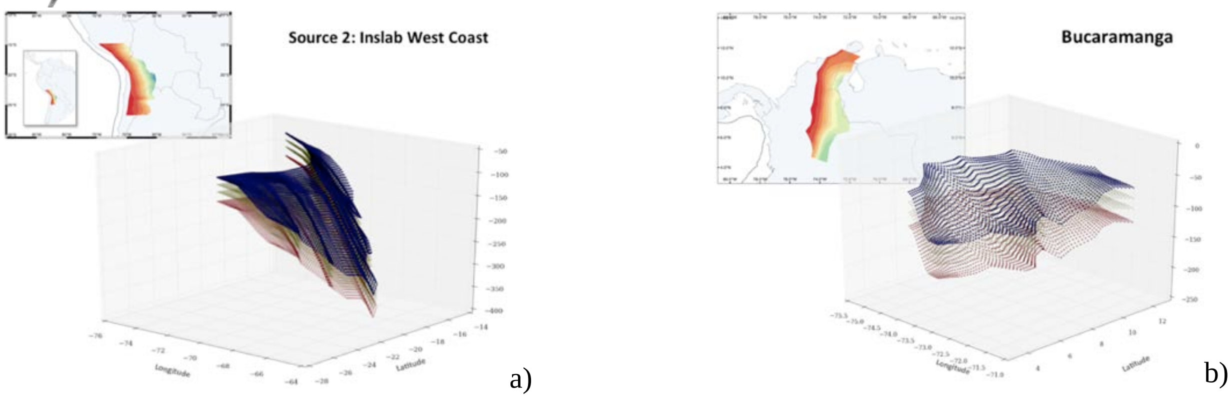

Fig. 4 – Three- dimensional definition of in-slab and deep sources represented as a volume of point sources at different depths: a) in-slab source in the west coast, b) Bucaramanga deep source.

However, the definition depends on whether the sources represent the down-going continuation of the slab below the interface (e.g. Pacific west coast), or the seismicity is related to intermediate/deep subduction sources. In the second case a polynomial regression was used to determine the in-slab source geometry, resulting in a continuous definition of the slab, which was constrained by: a) transition between the interface and in-slab obtained in the previous stage and b) forcing the definition to follow the down-going trend of the slab. The sources were modelled as a collection of point sources distributed in a volume, that follows the shape and extension of the slab at depths, and where finite ruptures are modelled at each point (see details in [33]). The volume is built from the three-dimensional definition of the slab and the slab thickness, which is assumed constant in our case (see Fig. 4).

The occurrence rates were computed using a doubled truncated Gutenberg-Richter distribution similar to the distributed seismicity case and the maximum magnitude was assigned according to the largest observed magnitude, but constrained by the rupture-area predicted by the scaling relationship proposed by Strasser et al. [38].

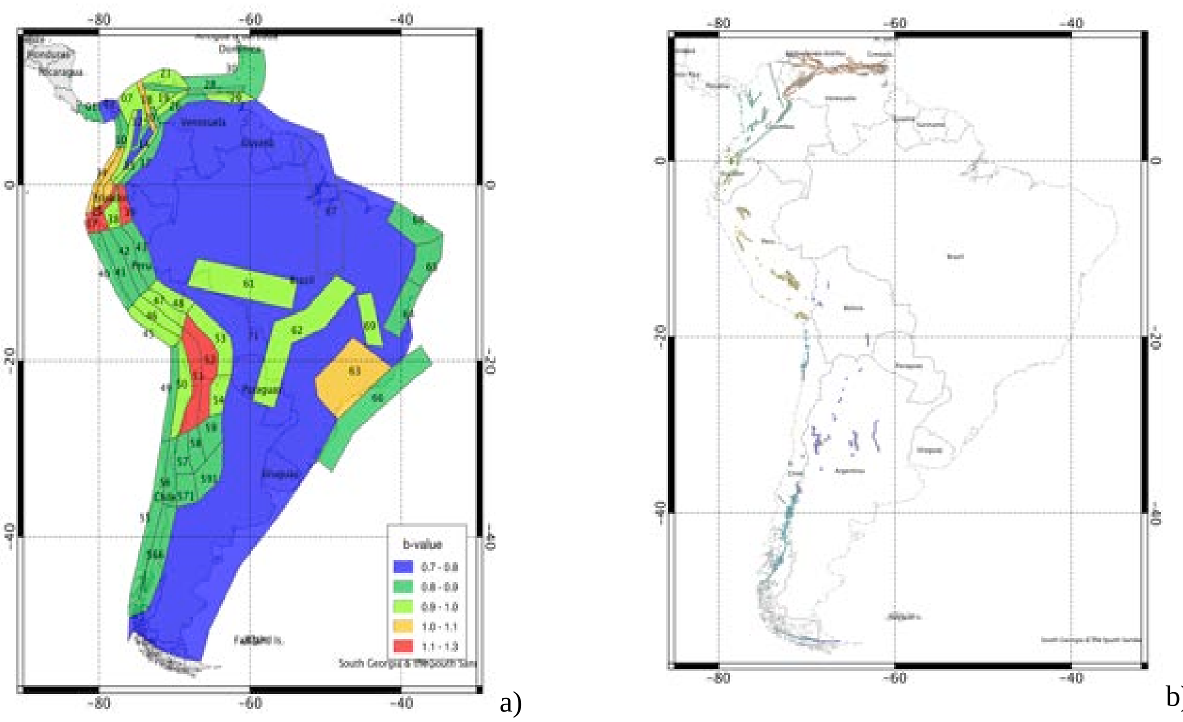

Fig. 5 – Components of the earthquake hazard model: a) distributed seismicity model, b) fault model

3.5 Ground motion modelling and ground motion logic tree

Strong motion networks are in operation across South America, and the data they record can provide fundamental insight into the earthquake process and the associated attenuation of strong shaking. A consortium of scientists from Brazil, Bolivia, Chile, Colombia, Ecuador and Venezuela constructed a continental-scale South American strong motion database and provided suggestions on the selection and creation of the ground-motion logic-tree for hazard analysis in South America. About 2100 horizontal and vertical component records were collected and processed. The attributes describing the characteristics of each strong motion record (earthquake, site and record itself) were collected and organised following the data model proposed in [35]. The adopted processing scheme follows the procedure proposed in [36].

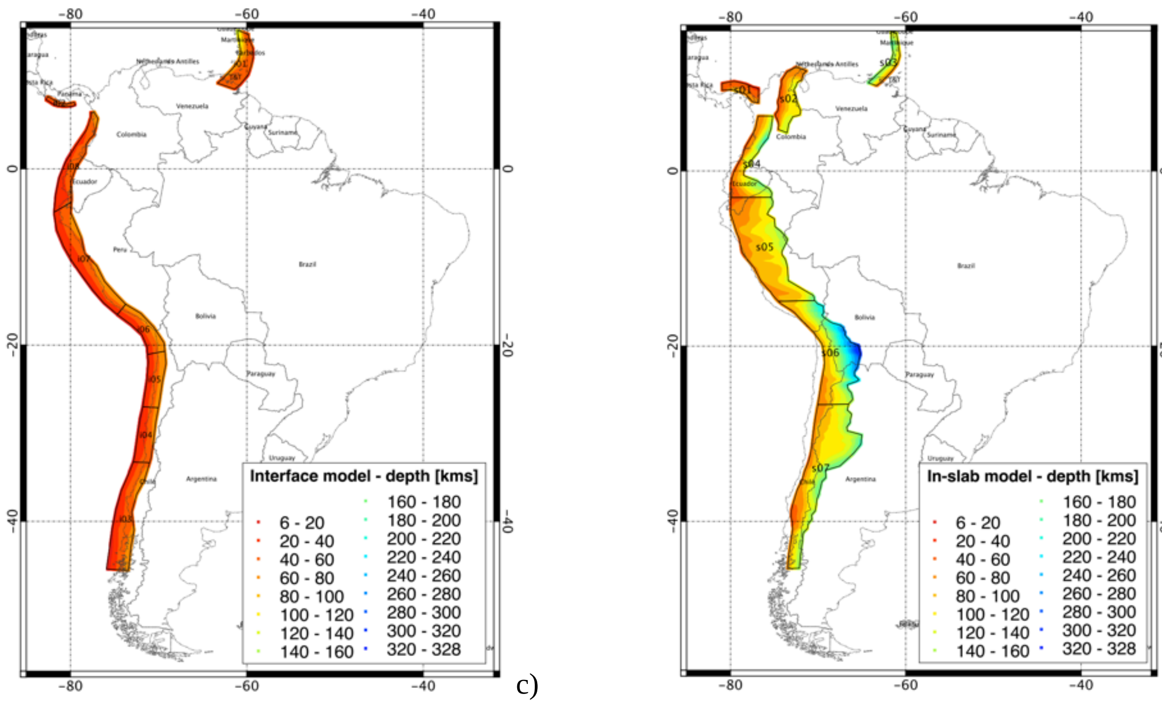

Fig. 5 – Components of the earthquake hazard model: c) subduction interface model and d) in-slab and deep model.

A new open-source tool was created to manage the data and facilitate the model comparisons (OpenQuake Ground Motion Toolkit- GMPE-SMTK). Different approaches implemented in the GMPE_SMTK ([36], [37], [38]) were used. The resulting GMPE selection (by tectonic region type) together with their relative weights for each GMPE is presented below.

Table 6 - Ground Motion Prediction Equations included within version 1.0 of SARA hazard model

GMPE	OQ-engine Acronym	Weight
Active Shallow Crust		
Akkar et al. (2014)	AkkarEtAlRjb2014	0.3333
Bindi et al. (2014)	BindiEtAl2014Rjb	0.3333
Boore et al. (2014)	BooreEtAl2014	0.3334
Stable Shallow Crust		
Atkinson and Boore (2006)	AtkinsonBoore2006Modified2011	0.25
Tavakoli and Pezeshk (2005)	TavakoliPezeshk2005	0.50
Drouet (2015) - Brazil with depth version	DrouetBrazil2015withDepth	0.25

GMPE	OQ-engine Acronym	Weight
Subduction interface		
Zhao et al. (2006)	ZhaoEtAl2006SInter	0.3333
Abrahamson et al. (2015)	AbrahamsonEtAl2015SInterHigh	0.3333
Montalva et al. (2016)	MontalvaEtAl2016SInter	0.3334
Subduction in-slab		
Abrahamson et al. (2015)	AbrahamsonEtAl2015SSlab	0.5
Montalva et al. (2016)	MontalvaEtAl2016SSlab	0.5

3.6 Hazard calculation and main results

The hazard calculation was completed using the hazard component of the OpenQuake-engine (OQ-engine version 1.9). The study region was divided in a mesh of 205,750 sites at a 10 km resolution covering the South America continent. Rock conditions with a fixed V_{S30} reference value of 800 m/s were assumed. The ground motion intensity types used for calculation are PGA and 5% damped response spectral acceleration (in g), estimated for probabilities of exceedance of 10% and 2% in 50 years, which are considered a standard reference in seismic design.

The aggregated seismic hazard maps for peak ground acceleration (PGA) having a 2% and 10% probability of exceedance in 50 years are shown in Fig. 6 (for the calculation of these maps we truncated at 3 standard deviations the ground motion probability distribution). The highest ground motions values are observed near the subduction slabs along the western coastlines of Peru and Chile mainly. The influence of in-slab sources seems to be crucial, in particular in areas were the slab presents steep angles(e.g. northern part of Chile). Large acceleration values are reached inland across the entire region, around the major faults.

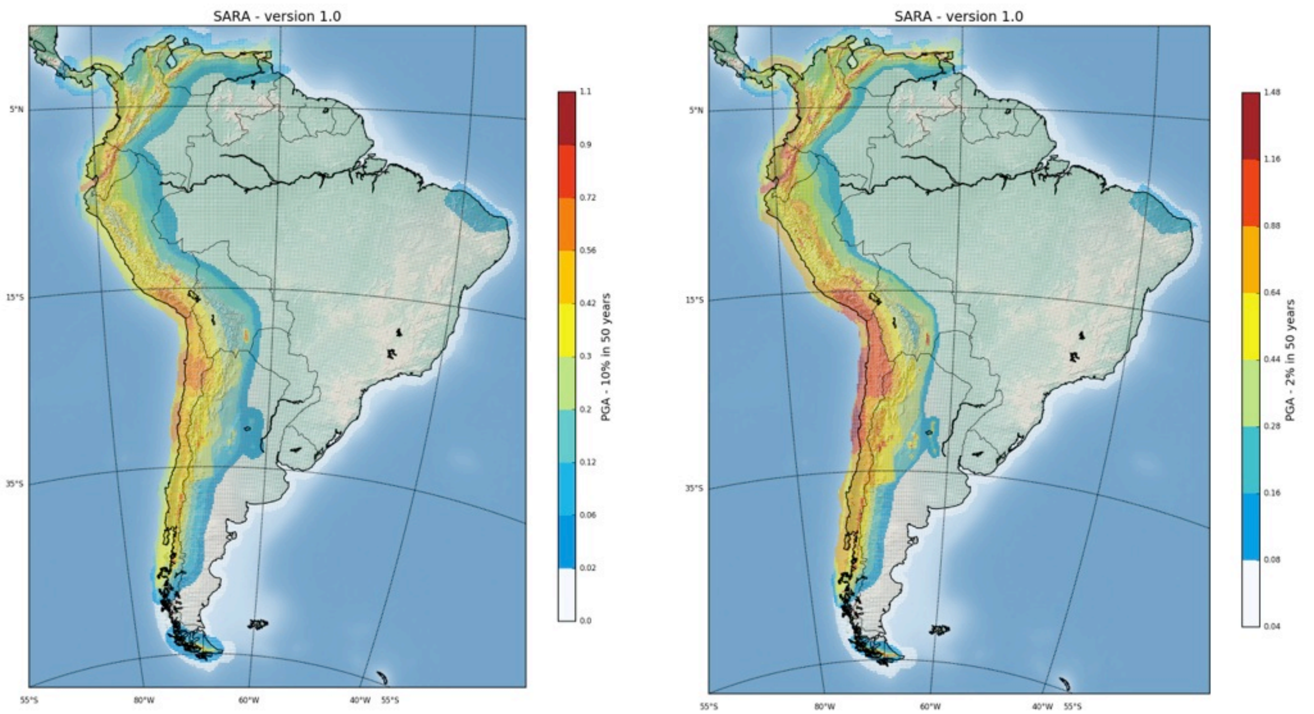

Fig. 6 - Aggregated seismic hazard maps for peak ground acceleration (PGA) having a 10% and 2% probability of exceedance in 50 years.

5. Conclusions

The hazard model [v.1.0] here proposed can be considered innovative in many respects, since it is a model developed within a community-based effort, which promoted advanced and original methods for earthquake modelling, such as: a) the shallow seismicity modelled using an integrated model of distributed seismicity (area-source for both, active shallow crust and stable continental regions) and crustal fault sources, b) the subduction interface seismicity, modelled as large fault sources with a 3D geometry, c) the subduction in-slab seismicity, modelled as 3D volumes of ruptures describing the spatial distribution of events within this area.

The different assumptions underlying the SARA-PSHA model have a specific impact on the results obtained. The area source model integrated with the faults displays relatively smooth transitions across the full range of hazard values in areas where the faults are not present and higher values near the faults. However, the model reflects the heterogeneity of the national models still present, despite the effort made.

The compilation of active faults represents a milestone of the SARA project and an important contribution for the next generation of hazard models in South America. However, those located in the stable shallow region are poorly known (e.g. Brazil faults are not included in the model), with the exception of Argentina. The mapping and characterisation of seismogenic faults is a big challenge in the region (Costa et al., 2016), but a task that will definitely improve future hazard models. A systematic update of the faults database will contribute to reduce the uncertainties related to geometry of the faults (e.g. fault-sites distances applying on GEMPEs), slip rates values and seismic coupling.

The results achieved within the hazard component of the SARA project represent an important milestone for the whole seismological community of the region. The hazard model produced within SARA constitutes a solid basis for the construction of new national and local hazard and risk models; in this regard, preliminary contacts with some national organisation are already on-going and will be intensified in the future. The datasets, results and the PSHA model are freely accessible online in the SARA WIKI at http://sara.open quake.org/start and in the GEM-OPENQUAKE platform at http://platform.openquake.org/.

6. References

[1] Giardini, D., G. Grünthal, K.M. Shedlock and P. Zhang (1999). The GSHAP Global Seismic Hazard Map, Annali di Geofisica, 42 (6), 1225-1230; doi:10.4401/ ag-3784.

[2] International Building Code (IBC) (2009). International Building Code. Country Club Hills, IL: International Code Council, Inc.

[3] Yeats, R. Active Faults of the World. Cambridge University Press, 2012. ISBN 9781139035644. Cambridge Books Online.

[4] Carena, S. (2011) Subducting-plate topography and nucleation of great and giant earthquakes along the South American trench. Seismological Research Letters, 82(5): 629–637, 2011.

[5] Costa, C., H. Cisneros, M. M. Machette, R. L. Dart, (2003). A new database of Quaternary faults and folds in South America. ILP Task Group II-2 (western Hemisphere). Proceedings of the A. G. U., Fall Meeting 2003,

[6] Getsinger, J. S., C. J. Hickson (2000). Multinational Andean Project (MAP). Geological co-operation across borders. Journal of the Geological Association of Canada, 27(3): 121-129

[7] Salcedo-Hurtado, E. J., Vargas, C. A., and Triviño, M. (2015a). Report of the focal mechanism database, Topic 3: Modeling the subduction process along the western coast and creation of a source model to be used for hazard calculations. Technical report, Fundacion Universidad del Valle, SARA Internal Report, 2015.

[8] Salcedo-Hurtado, E., Elkin, J., Vargas, C. A., and Triviño, M. (2015b). Modelling the subduction process along the western coast and creation of a source model to be used for hazard calculations. Topic 3: Modeling the subduction process along the western coast and creation of a source model to be used for hazard calculations. Technical report, Fundacion Universidad del Valle, 2015a. SARA Internal Report, 2015.

[9] Albini, P., Musson R.M.W., Rovida A., Locati M., Gómez-Capera A.A., Viganó D. (2014). The Global Earthquake History. Earthquake Spectra, 30:2:607-627, Earthquake Engineering Research Institute.

[10] Storchak, D.A., Di Giacomo D., Bondár I., Engdahl E.R., Harris J., Lee W.H.K., Villaseñor A. and Bormann P. (2013). Public Release of the ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009), Seism. Res. Lett., 84, 5, 810-815, doi: 10.1785/0220130034.

[11] Beauval, C., Yepes, H., Palacios, P., Segovia, M., Alvarado, A., Font, Y., Aguilar, J., Troncoso, L., and Vaca, S. (2013). An earthquake catalog for seismic hazard assessment in Ecuador. Bulletin of the Seismological Society of America, 103(2A) : 773–786.

[12] Weatherill, G., Pagani, M. and Garcia, J., (2016). "Exploring Earthquake Databases for the Creation of Magnitude-Homogeneous Catalogues: Tools for Application on a Regional and Global Scale, Geophysical Journal International, in press

[13] Gardner, J. K. and L. Knopoff (1974). "Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian?" In: Bulletin of the Seismological Society of America 64.5, pages 1363–1367 (cited on page 20).

[14] Stiphout, T. van, J. Zhuang, and D. Marsan (2012). Theme V -Models and Techniques for Analysing Seismicity. Technical report. Community Online Resource for Statistical Seismicity Analysis. URL: http://www.corssa.org.

[15] Uhrhammer, R. (1986). Characteristics of Northern and Central California Seismicity. In: Earthquake Notes 57.1, page 21.

[16] Weatherill, G. A. (2014). Openquake Hazard Modellers Toolkit - User guide.

[17] Stepp, J. C. (1971). An investigation of earthquake risk in the Puget Sound area by the use of the type I distribution of largest extreme. PhD thesis, Pennsylvania State University

[18] Albarello, D., R. Camassi, and A. Rebez (2001). Detection of space and time heterogeneity in the completeness level of a seismic catalogue by a statistical approach: An application to the Italian area, Bull. Seismol. Soc. Am. 91, no. 6, 1694–1703.

[19] Woessner, J., and S. Wiemer (2005). Assessing the quality of earthquake catalogues: Estimating the magnitude of completeness and its uncertainty, Bull. Seismol. Soc. Am. 95, no. 2, 684–698.

[20] Cornell, C. A. (1968). Engineering Seismic Risk Analysis. Bulletin of the Seismological Society of America, 58(5), 1583-1606.

[21] McGuire, R. K., (2004). Seismic Hazard and Risk Analysis: Earthquake Engineering Research Institute Report MNO-10, 240 p.

[22] van der Meijde, M., Juli, J., and Assumpcao, M. (2013). Gravity derived Moho for South America. Tectonophysics, 609:456 – 467. ISSN 0040-1951. doi: http://dx.doi.org/10.1016/ j.tecto.2013.03.023

[23] Lloyd, S., van der Lee, S., Franc ̧a, G. S., Assumpcao, M., and Feng, M. (2010). Moho map of South America from receiver functions and surface waves. Journal of Geophysical Research: Solid Earth, 115(B11)

[24] Kreemer, C., Blewitt, G., and Klein, E. C. (2014). A geodetic plate motion and global strain rate model. Geochemistry, Geophysics, Geosystems. 15(10): 3,849-3,889.

[25] Vilanova SP, Nemser ES, Besana-Ostman GM et al (2014) Incorporating descriptive metadata into seismic source zone models for seismic-hazard assessment: a case study of the Azores-West Iberian region. Bull Seismol Soc Am 104:1212–1229. doi:10.1785/0120130210

[26] Weichert, D. H. (1980). Estimation of the Earthquake Recurrance Parameters for Unequal Observation Periods for Different Magnitudes. In: Bulletin of the Seismological Society of America 70.4, pages 1337 –1346

[27] Petersen, M., Harmsen, S., Haller, K., Mueller, C., Luco, N., Hayes, G., and Rukstales, K. (2010). Preliminary Seismic Hazard Model for South America. In Proceedings of Confer- encia Internacional. Homenaje a Alberto Giesecke Matto.

[28] Petersen, M. D., Frankel, A. D., Harmsen, S. C., Mueller, C. S., Haller, K. M., Wheeler, R. L., Wesson, R. L., Zeng, Y., Boyd, O. S., Perkins, D. M., Luco, N., Field, E. H., Wills, C. J., and Rukstales, K. S. (2008). Documentation for the 2008 Update of the United States National Seismic Hazard Maps. Unites States Geological Survey Open File Report, 2008-1128 (version 1.1), page 128.

[29] Youngs, R. R. and K. J. Coppersmith (1985). "Implications of fault slip rates and eaarthquake recurrence models to probabilistic seismic hazard estimates". In: Bull. Seism. Soc. Am. 75.4, pages 939–964

[30] Hayes, G. P., Wald, D. J., and Johnson, R. L. Slab1.0: A three-dimensional model of global subduction zone geometries. Journal of Geophysical Research: Solid Earth, 117(B1):n/a–n/a, 2012. ISSN 2156-2202.

[31] Heuret, A., Lallemand, S., Funiciello, F., Piromallo, C., and Faccenna, C. (2011). Physical characteristics of subduction interface type seismogenic zones revisited. Geochemistry, Geophysics, Geosystems, 12

[32] Weatherill, G., Pagani, M. and Garcia, J. (2017). Modelling In-slab Subduction earthquakes in PSHA: Current practice and challenges for the future. 16th World Conference on Earthquake, 16WCEE, 2007

[33] Rodriguez-Abreu L.E. (2016). Characterization of subduction source models for probabilistic seismic hazard analysis (PSHA). Thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in Engineering Seismology. IUSS, Pavia, Italy, April 2016.

[34] Martin, C., Combes, P., Secanell, R., Lignon, G., Carbon, D., Fioravanti, A., and Grellet, B. R ́evision du zonage sismique de la France France: Etude probabiliste. Technical report, GEOTER, 2002. Rapport GEO-TER nGTR/MATE/07/01-150.

[35] Weatherill, G. A. (2014). OpenQuake Ground Motion Toolkit - User Guide. Global EarthquakeModel (GEM). Technical Report

[36] Boore, D.M., Azari Sisi, A. and Akkar, S. (2012). Using Pad-Stripped Acausally Filtered Strong-Motion Data, BSSA 102(2), 751-760.

[37] Atkinson Gail M. and David M. Boore (2006). Earthquake Ground-Motion Prediction Equations for Eastern North America; Bulletin of the Seismological Society of America, Volume 96, No. 6, pages 2181-2205

[38] Strasser, F. O., Arango, M. C., and Bommer, J. J. Scaling of the source dimensions of interface and intraslab subduction-zone earthquakes with moment magnitude. Seis- mological Research Letters, 81(6):941–950, 2010b.

[39] Bindi D., M. Massa, L.Luzi, G. Ameri, F. Pacor, R.Puglia and P. Augliera (2014). Pan-European ground motion prediction equations for the average horizontal component of PGA, PGV and 5 %-damped PSA at spectral periods of up to 3.0 s using the RESORCE dataset, Bulletin of Earthquake Engineering, 12(1), 391 - 340

[40] Boore David M., Jonathan P. Stewart, Emel Seyhan and Gail Atkinson (2014). NGA-West2 Equations for Predicting PGA, PGV, nd 5 % Damped PGA for Shallow Crustal Earthquakes; Earthquake Spectra, Volume 30, No. 3, pages 1057 - 1085.

[41] Tavakoli B. and S. Pezeshk in 2005 and published as "Empirical-Stochastic Ground-Motion Prediction for Eastern North America" (2005, Bull. Seism. Soc. Am., Volume 95, No. 6, pages 2283-2296).

[42] Abrahamson N., N. Gregor and K. Addo (2015). BC Hydro Ground Motion Prediction Equations For Subduction Earthquakes Earthquake Spectra, in press.

[43] Drouet S. (2015). Unpublished for Brazil based on the method described in Drouet & Cotton (2015)

[44] Drouet, S., Cotton, F. (2015): Regional Stochastic GMPEs in Low-Seismicity Areas: Scaling and Aleatory Variability Analysis—Application to the French Alps. – Bull. Seism. Soc. America, 105, 4, pp. 1883—1902.

[45] Montalva G. A., Bastias N. and Rodriguez-Marek A. (2016). Ground Motion Prediction Equation for the Chilean Subduction Zone, Seismological Research Letters, in press.

[46] Zhao, J. X., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., Ogawa, H., Irikura, K., Thio, H. K., Somerville, P. G., Fukushima, Y., & Fukushima, Y. (2006). Attenuation relations of strong ground motion in Japan using site classification based on predominant period. Bulletin of the Seismological Society of America, 96(3), 898–913.