Probabilistic Assessment of Seismic Hazard in Southeastern Region of Brazil

Tatiana Romero, Edgar R. Rondán, Jesus Berrocal, Berrocal Inovações Geofísicas Ltda.

Abstract

An evaluation of seismic hazard for Southeastern region of Brazil was performed by using the probabilistic seismic hazard analysis (PSHA), which takes in consideration uncertainties in the dimension, location and time of occurrence of earthquakes. In this work were used seismic catalogs and attenuation relationships available for that region, in a systematic way of analysis. The level of seismicity in this region is low; however, it is significant in the seismicity context of the Brazilian territory, including earthquakes with magnitude up to 6.1 m_b. Most of Brazilian economical production is concentrated in the study region, and it is where the cities of this country with the largest human population, are located. These characteristics make essential in the Brazilian Southeastern region the development of important engineering works, such as hydroelectric dams, nuclear reactor power plants, chemical factories, etc., some of them presenting different level of potential risks to safety of the population provoked by natural disasters, among them, seismic phenomena are considered. The objective of this work is to execute the PSHA for some specific points of interest, such as the state capitals inside studied region, by determining the maximum horizontal acceleration that may be provoked by future earthquakes in those capitals.

Introduction

Major engineering works such as nuclear plants, hydroelectric plants, or beneficiation plants among others, can present risks to the safety of the population living nearby. These risks could be provoked by natural disasters such as seismic phenomena. Therefore, the construction of those important engineering works require the seismic risk assessment to enable the suitable construction of such works in order to resist the effects of probable large earthquakes that may occur during its lifetime, in that way preventing catastrophic damage to the population.

The Brazilian territory is located in an intraplate region, with a lower label of seismic activity comparing with the border regions of the South American tectonic plate, such as in the Andes or in the meso Atlantic ridge. However, the Southeastern region of Brazil and surrounding areas have a significant level of seismic activity, represented mainly by the occurrence of some historical earthquakes with magnitude up to 6.1 m_b and a significant number of earthquakes of magnitude smaller than 4.0 m_b, according to Assumpção et al. (1980) and Berrocal et al. (1984) and (1993).

Method for Assessment of Seismic Risk

The seismic risk assessment intends evaluate the level of seismic vibrations that could occur in a site of interest of an important engineering work, during a specific time interval, which will be provoked by a large magnitude earthquake, occurred in the seismogenic source closer to the site of interest.

For the execution of the probabilistic method to evaluate the seismic hazard curves of a certain site, it is necessary that the seismogenic sources used in this analysis could provide the following characteristics: i) Have a defined source format or be related to a tectonic feature or be regarded as a seismotectonic province , ii) have a complete and uniform seismic catalog that covers a reasonable time range to determine the recurrence curve of the source, iii) have a seismic attenuation function or assume this function from similar sources, and iv) to determine the maximum possible magnitude of earthquake that occurred in this source.

In the case of intraplate regions, where it is not possible to identify seismogenic sources clearly, or where the rate of seismic activity is low and does not allow determining the necessary parameters for performing a PSHA, the solution is join these diffuse seismic areas in a seismotectonic province. This enables to perform the PSHA. In this method, which Budnitz et al. (1997) recommends, one of the essential parameters is the seismic recurrence relation that specifies the average rate at which an earthquake of a given magnitude or large, could occur, characterizing the seismicity level of each seismogenic source.

Compiling the Catalog

The catalog used for this study, compiled from the Brazilian Seismic Bulletin (BSB) that is elaborated by the Institute of Astronomy, Geophysics and Atmospheric Sciences of the University of São Paulo (IAG-USP) was updated thoroughly the revision of some magnitudes and epicenter coordinates, and the exclusion of induced earthquakes and aftershocks. **Figure 1** shows the epicenters in the Brazilian territory of earthquakes of magnitudes 2.8 to 6.1, occurred from 1767 to 2010. **Figure 2** shows the epicenters map of earthquakes in the southeastern region of Brazil and neighboring areas, from

1767 to 2010, magnitudes range from 3.0 to 6.1.

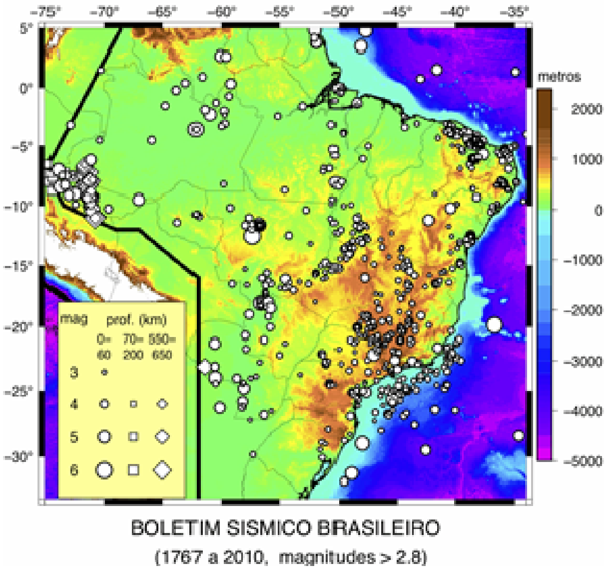

Figure 1. Brazilian seismic activity. White circles are epicenters from the BSB, elaborated by the IAG-USP, magnitudes range from 2.8 to a maximum of 6.1 and period from 1767 to 2010.

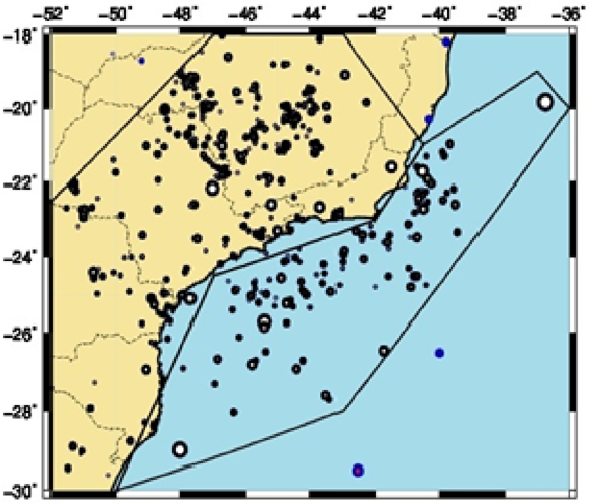

Figure 2. Regional seismicity in SE Brazil. White circles are epicenters, magnitudes range from 3.0 to 6.1 and period from 1767 to 2012.

Seismogenic Sources

According to Almeida *et. al.*, 2013, the inversion of striae from Paleogene-Neogene faults indicated that the stress regimes in the region varied during the Cenozoic (Riccomini et al., 2004), **Figure 3**. Rifting processes, including faulting, sedimentation and magmatism in the continent occurred during the Eocene-Oligocene, firstly as a result of reactivation of NE to E-W-oriented shear zones as normal faults under NNW-SSE-oriented extension. After its installation the rift system was subjected to four phases of deformation, which has initiated in the early Miocene with left-lateral strike-slip and minor thrust reactivation of NE to E-W shear zones, under a general strike-slip regime with NW-SE extension and local NE-SW compression. The second phase of deformation, during the Late Pleistocene to Holocene, is recorded by right-lateral strike-slip and thrust reactivation of NE to E-W-oriented Neoproterozoic shear zones, resulting from a NW-SE compression and NE-SW extension. During the Holocene the region has experienced a rapid change of the stress regime, initially an E-W to WNW-ESE extension responsible for the development of N-S-oriented grabens, and finally an E-W compression, which affects colluvial and alluvial deposits younger than 3,410 years BP (Riccomini and Assumpção, 1999; Modenesi-Gauttieri et al., 2002; Almeida *et al.*, 2013).

Figure 3. Tectonic setting of the study area: 1) Precambrian basement rocks; 2) Paleozoic sedimentary rocks of the Paraná Basin; 3) Early Cretaceous tholeiitic volcanic rocks of the Serra Geral Formation; 4) Mesozoic to Cenozoic alkaline rocks; 5) Cenozoic rift basins and 6) Precambrian shear zones, in part reactivated during the Mesozoic and Cenozoic. The Cenozoic rift basins are: 1-Itaboraí Basin, 2- Barra de São João Graben, 3- Macacu Basin, 4- Volta Redonda Basin, 5- Resende Basin, 6-Taubaté Basin, 7- São Paulo Basin, 8- Sete Barras Graben, 9- Pariqüera-Açu Formation, 10- Alexandra Formation and Guaraqueçaba Graben, 11- Curitiba Basin, and 12- Cananéia Graben). The red star indicates the site of the Angra dos Reis Nuclear Power Plants. After Riccomini et al. (2004).

The different pulses of uplift and changes in the stress field played a major role in the development of the drainage network of this region. The major rivers in the Serra do Mar region are controlled by E-W to NE-SW-oriented basement structures, but the pulses of tectonic activity along NW-SE-oriented faults, mainly during Neogene and Quaternary, have promoted numerous river captures (Riccomini et al., 2010).

Figure 2 shows the regional seismicity in SE Brazil where the maximum observed magnitude was a 6.1 m_b in the continental shelf in 1955 (epicenter near 20°S). Earthquakes offshore tend to have reverse faulting mechanisms and occur mainly along the continental slope with magnitudes 5 and above once every 15-20 years on average (Assumpção et al., 2011). In the continent, the maximum known earthquake was a magnitude 5.1 m_b in 1922 near the NE border of the Paraná basin. Earthquakes near the southern border of the São Francisco craton indicate stresses characterized by E-W compression and N-S extension, suggesting a different seismic source zone compared to the offshore seismicity.

An interesting aspect of the seismicity in SE Brazil is its present low level in the Serra do Mar coastal ranges (as seen in **Figure 2**) despite the presence of several neo-tectonic faults mapped in the area (Assumpção and Riccomini, 2010). The seismic source characterization (SSC) model that is to be developed for this PSHA will need to take account of the fact that the earthquake catalog alone is unlikely to be a sufficient basis for defining the spatial distribution of future earthquakes. An important aspect of assessing epistemic uncertainty in the seismic source model will be degree to which the long-term earthquake potential in the Serra do Mar coastal ranges is consistent with the seismicity data (Almeida *et al.*, 2013).

For developing the seismic hazard curve, it was used the recurrence curve equations presented bellow and an attenuation function of seismic energy used in the tectonic province of central-eastern United States (Toro et al., 1997), which has some similarity to the studied area. The seismic hazard curve relates the parameter of ground motion, represented by the peak horizontal acceleration, with the probability of this acceleration value be exceeded.

Seismic Source 1 (Oceanic Portion)

Table 1. Number of historical and recent earthquakes used for defining a corrected annual frequency and the recurrence intervals for some levels of cumulative magnitude up to the maximum credible earthquake.

Magnitude levels	Number of events ∑N	Interval in years	Annual frequency	Recurrence Interval in years
m_b ≥3,0	22	22	1.0000	1.00
m_b ≥3,5	20	32	0.6250	1.60
m_b ≥4,0	3	32	0.0938	10.67
m_b ≥4,5	1	44	0.0227	44
m_b ≥5,0	1	50	0.0200	50
m_b ≥5,5	1	92	0.0109	92
m_b ≥6,0	1	92	0.0109	92
m_b ≥6,5	0	92	-	-
m_b ≥7,0	0	92	-	-

The frequency/magnitude relation of cumulative magnitudes for Source 1 is:

$$\mathrm{Log}\sum N = 1.9414\ (\pm 0.223) - 0.8432\ (\pm 0.097)\ m_b \qquad (1)$$

Seismic Source 2 (Continental Portion)

Table 2. Number of historical and recent earthquakes used for defining a corrected annual frequency and the recurrence intervals for some levels of cumulative magnitude up to the maximum credible earthquake.

Magnitude levels	Number of events ∑N	Interval in years	Annual frequency	Recurrence Interval in years
m_b ≥3,0	60	38	1.5789	0.6333
m_b ≥3,5	25	53	0.4717	2.12
m_b ≥4,0	7	113	0.0619	16.1429
m_b ≥4,5	2	173	0.0116	86.5
m_b ≥5,0	1	213	0.0047	213
m_b ≥5,5	0	213	-	-
m_b ≥6,0	0	213	-	-
m_b ≥6,5	0	213	-	-
m_b ≥7,0	0	213	-	-

The frequency/magnitude relation of cumulative magnitudes for Source 2:

$$\mathrm{Log}\sum N = 3.0797\ (\pm 0.236) - 1.3375\ (\pm 0.102)\ m_b \qquad (2)$$

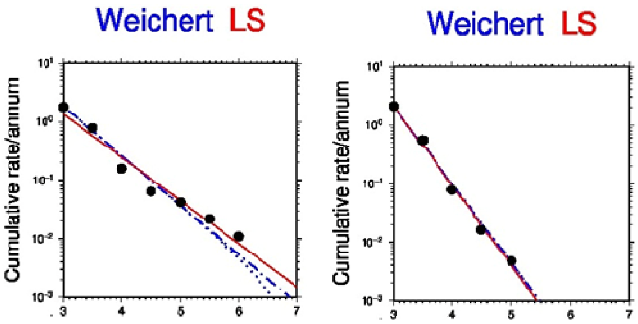

Figure 4. Cumulative frequency/magnitude distribution curves for adopted seismic sources. In the left, is the curve for Source 1 (Oceanic Portion) and in the right, for the Source 2 (Continental Portion).The red line corresponds to the linear regression by applying least squares (LS) method; the blue line corresponds to the linear regression by applying the Weichert method. Equations (1) and (2) are the results from LS method.

Results

PSHA Curves for Specific Points of Study Area

Considering the tectonic characteristics and the seismicity parameters defined for the study region, PSHA has been executed for some capital cities located in Southeastern region of Brazil: *Belo Horizonte* (BH), *Rio de Janeiro* (RJ) *and São Paulo* (SP).See **Figure 5** and **Table 3**.

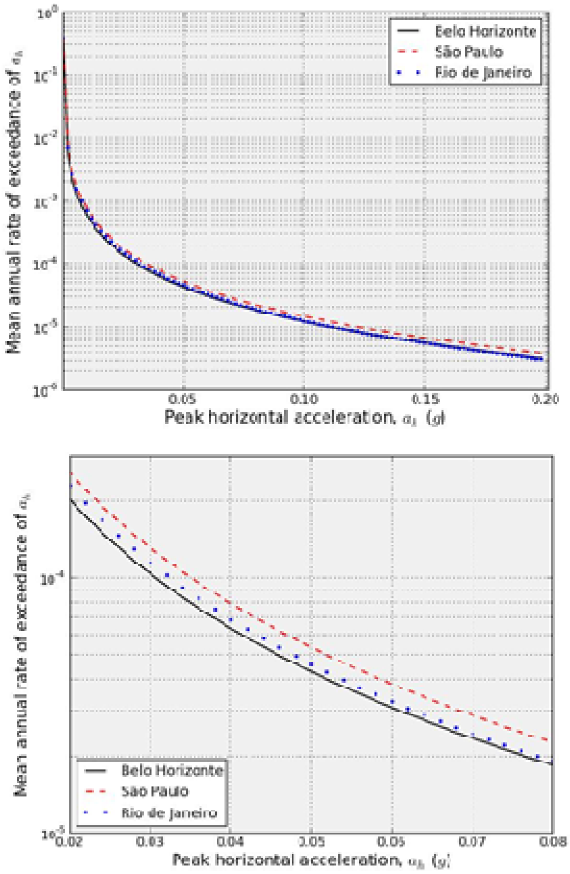

Figure 5. Seismic hazard curves for three capital cities in Southeastern region of Brazil. The curves between 0 and 0.2 are presented in the upper part and a blow up of those curves, between 0.002 and 0.08 g, is presented in lower part.

Table 3. Seismic Hazard results for the selected sites considering the influence of both sources 1 and 2.

Site	Probability	Peak Horizontal Acceleration
Belo Horizonte	10^{-3}	0.007 g
	10^{-4}	0.031 g
Rio de Janeiro	10^{-3}	0.008 g
	10^{-4}	0.032 g
São Paulo	10^{-3}	0.008 g
	10^{-4}	0.035 g

Conclusions

It can be noticed from the results that those curves are similar among them, and present relatively low expected horizontal pick acceleration values (just above 0.03 g) for a 10^{-4} annual probability. It may be concluded any site of interest located within the states of São Paulo, Rio de Janeiro e Minas Gerais should present a seismic hazard curve close to curves shown in **Figure 5**, and a peak of horizontal acceleration just around 0.03 g for that annual probability. For an annual probability of 10^{-3}, the corresponding acceleration is around 0.009 g.

The capital site (São Paulo) located near the highest seismicity level of Source 1 (Oceanic Portion) has the largest peak of horizontal ground acceleration. In compensation, Belo Horizonte that is far away from Source 1, has the smallest peak of horizontal ground acceleration.

References

Almeida, A.; Assumpção, M.; Berrocal, J.; Bommer, J.; Drouet, S.; Ferrari, L.; Prates,L.C.; Riccomini, C. and Riera, J. (2013). “Developing a logic-tree for updating the probabilistic seismic hazard assessment for the Angra dos Reis Nuclear Power Plant Site in Brazil. IASMiRT – 22 San Francisco California, USA.

Assumpção, M., Dourado, J.C., Ribotta, L.C., Mohriak, W.U., Dias, F.L., Barbosa, J.R. (2011).” The São Vicente earthquake of April 2008 and seismicity in the continental shelf off SE Brazil: Further evidence for flexural stresses”, Geophysical J. Int., doi: 10.1111/j.1365-246X.2011.05198.x

Assumpção, M. and Riccomini, C. (2011). “Seismicity and Neotectonics in the coastal ranges of SE Brazil (Serra do Mar): A case of activity migration?” Abstract, 2011 Meeting of the Seismological Society of America, Memphis, USA.

Berrocal, J., Assumpção, M., Antezana, R. Dias Neto, C.M., Ortega, R., França, H. Adbd Veloso, J.A.V. (1984). Sismicidade do Brasil. Instituto Astronômico e Geofísico da Universidade de São Paulo e Comissão Nacional de Energia Nuclear, Brazil, 320 pp.

Berrocal, J., Fernandes, C., Bueno, A., Seixas, N. and Bassini, A. (1993). “Seismic activity in Monsuaba (state of Rio de Janeiro), Brazil, between 1988 December and 1989 February”, Geophysical Journal International, 113, 73-82.

Modenesi-Gauttieri, M.C., Hiruma, S.T. and Riccomini, C. (2002). “Morphotectonics of a high plateau on the northwest flank of the Continental rift of Southeastern Brazil”, Geomorphology, 43, 257-271.

Riccomini, C., Sant'Anna, L.G. and Ferrari, A.L. (2004). "Evolução geológica do Rift Continental do Sudeste do Brasil" In: Mantesso Neto, V., Bartorelli, A., Carneiro, C.D.R. and Brito Neves, B.B.. (Eds.). Geologia do Continente Sul-Americano: Evolução da Obra de Fernando Flávio Marques de Almeida, São Paulo, Beca, p.383-405. Riccomini, C. and Assumpção, M. (1999). "Quaternary tectonics in Brazil", Episodes, 22(3), 221-225.

Riccomini, C., Grohmann, C.H., Sant'Anna, L.G. and Hiruma, S.T. (2010). "A captura das cabeceiras do Rio Tietê pelo Rio Paraíba do Sul", In: Modenesi-Gauttieri, M.C., Bartorelli, A., Mantesso-Neto, V., Carneiro, C.D.R. and Lisboa, M.B.A.L. (Eds.). A Obra de Aziz Nacib Ab'Sáber. São Paulo, Becca, p.157-169.

Toro, G.R., Abrahamson, N.A. and Schneider, J.F. (1997). "Model of strong ground motions from earthquakes in Central and Eastern North America: Best estimates and uncertainties", Seismological Research Letters, 68(1), 41-57.