A seismic hazard assessment for a tailing dam site in Minas Gerais - Brazil

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Abstract

This paper presents a seismic hazard analysis for a tailing dam site located in the state of Minas Gerais, in the Southeast region of Brazil, near the city of Mariana, with UTM coordinates E=659343,205 and N=7764575,57. According to Berrocal *et al.* (1993) the seismicity in the Southeast region presents a diffuse distribution, thus not allowing the clear identification of faults and other tectonic features as active seismogenic sources, even though it may be admitted that the occurrence of earthquakes in the region are associated to reactivation of older faults or the emergence of new ones. In this study the hazard seismic evaluation was estimated considering a polygonal area encompassing 472 events with magnitude 3 or higher collected from the Brazilian seismic catalog (IAG/USP), excluded the eventual aftershocks in order to ensure statistically independent data. Additionally, due to seismotectonic characteristics of the region, the attenuation law proposed by Toro (1997, 2002) was adopted to any epicentral distance and earthquake magnitude. The maximum horizontal acceleration in the bedrock (PGA) was determined considering recurrence periods of 72 years, 475 and 975 years for a 50 year life-span of the tailing dam. The probabilistic analyses presented herein were carried out using the software CRISIS2007.

Introduction

Brazilian seismicity is low compared with the Andean coast of South America where strong earthquakes (magnitude > 6) occur more frequently, caused by subduction movement of the Nazca Plate under the South-American Plate. Most of the interplate earthquakes in Brazil present small magnitudes (<5) at small depths (< 30km), although more than ten earthquakes with magnitude > 5 have already occurred in the country since 1922.

A study of seismicity involves the knowledge of the distribution of seismic events within a specific area, expressed by relationships between location, magnitude and periodicity. Such study can be carried out through statistical or empirical approaches (Hu et al., 1996), requiring basic information from historical and instrumental earthquake catalogs as well as information about the regional seismogenic sources and their association with the previous seismic events.

The current tectonic conditions in the region of interest show a mild accommodation of the blocks moved during the Tertiary Period, thus characterizing probable seismogenic zones that could be identified according to the spatial distribution of the seismic epicenters and the existing structural features in the regional geology. These zones are areas of chronic weakness that showed seismic activity in the recent geological past which continues until the present days. However, the low level of seismic activity, the relatively recent use of instrumental apparatus for seismic recordings in Brazil (since 1968) and the lack of accuracy in estimating the epicentral locations do not allow the characterization of well-defined seismogenic sources yet.

Hence, due to the diffuse spatial distribution of seismic activity in Southeastern Brazil, this study used as a seismic zone the polygonal area shown in Figure 1, which contains 427 independent events (without aftershocks) collected from the IAG/USP earthquake catalog, covering the period from 1767 to 2011. The epicentral location of the older earthquakes occurred before 1970 are very inaccurate. According to Berrocal et al. (1996) few events in this period have reliable seismic data that allow location of the epicenters with errors of some kilometers (less than 10 km).

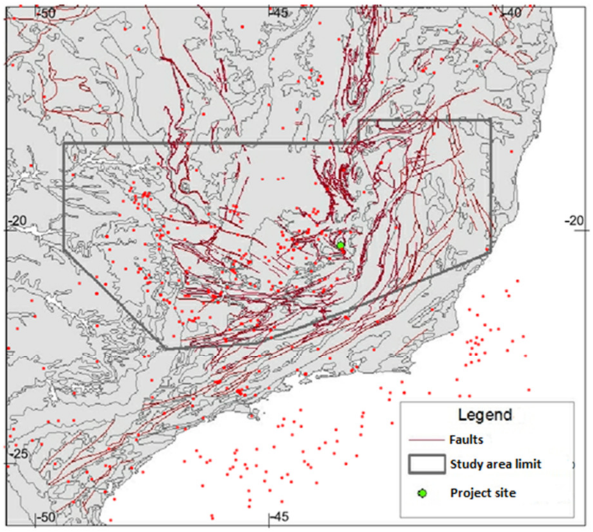

Figure 1: Area of interest showing the epicenters of the earthquakes recorded from 1767 to 2011. The green circle indicates the site of the tailing dam near the city of Mariana - MG.

Dependent events

In order to guarantee a statistically independent dataset, the Window Method (Van Stiphout et al., 2011) was applied to identify the main and the dependent (aftershocks) events in the earthquake catalog.

For each earthquake with magnitude M, the events are identified as dependent if they happened in a specific time interval t(M) or within a specific length d(M). The following equations define a space-time window used in processing the data file:

$$d = e^{1.77+(0.037+1.02M)^{1/2}} \left[km\right] \quad (1)$$

$$t = \begin{cases} 10^{2.8+0.024M}, M \geq 6.5 \\ e^{-3,95+(0.62+17.32M)^{1/2}}, M < 6.5 \end{cases} \left[days\right] \quad (2)$$

Probabilistic seismic hazard

The probabilistic seismic hazard analysis basically consists in defining an exceedance probability for a specific parameter related to the seismic movement, during a given period of time in the region of interest. The probabilistic approach used in this study is based on the general guidelines described by Budnitz et al. (1997), which involve the following steps:

- Finding potential areas of earthquake occurrence (seismogenic zones) and estimating the corresponding activities;
- Defining regional seismicity parameters;
- Selecting models for seismicity analysis;
- Adopting an attenuation law of seismic movements;
- Calculating exceedance probabilities for the requested movement parameter, using a seismic hazard curve.

Seismogenic source characterization

In areas such as the Southeast Brazilian region, where tere are no strong evidences associating seismogenic sources to tectonic features, it is usually recommended to consider as seismogenic source an entire area of interest.

In this study, this area of interest was defined by a polygonal line (Figure 1), whose geographical coordinates are list in Table 1 and the its main seismic parameters in Table 2.

Table 1. Geographical coordinates of the polygonal line encompassing the area of interest. .

Longitude (^{0}W)	Latitude (^{0}S)
-40.2	-20.3
-43.1	-21.5
-45.3	-22.3
-47.2	-22.4
-49.4	-20.3
-49.4	-18.0
-43.1	-18.0
-43.1	-17.5
-40.2	-17.5

The maximum known magnitude in the area of interest corresponds to the Pinhal earthquake ($m_b = 5.1$ or $M_w = 5.4$) happened in 1922. Using a rather conservative approach the upper limit of magnitude M_u was herein chosen as $M_u = 6.1$.

Table 2. Seismic parameters in the area of interest.

Average Depth (m)	M_u	$\nu_{(i=1)}$	β	M_0
5	6.1	1.327	2.4023	3

M_0: lower limit of magnitude
Mu: upper limit of magnitude
β = b.ln10 (see Equation 3 and Figure 2)
$\nu_{(i=1)}$ = annual average rate of seismic events with magnitude M ≥ M_0

Exceedance probability

Given the uncertainties associated to seismic events, they are usually treated as parts of a stationary stochastic process. It is assumed that there will be a constant accumulation of energy that will be randomly dissipated in time and that for a specific time interval, the rate of earthquakes of certain magnitude is constant (Oliveira, 1977, Hu et al., 1996).

The temporal model for the occurrence of seismic events is generally represented as a Poisson process where the exceedance probability F_T for a specific recurrence period T_R in determined time interval Δt is obtained by:

$$F_T(t) = 1 - exp(\Delta t / T_R) \quad (3)$$

Table 3 presents the exceedance probabilities F_T considering a time interval Δt = 50 years equivalent to the life-span of the tailing dam.

Exceedance probability	Δt = 50 years
	Recurrence period (years)
50%	72
10%	475
5%	975
2%	2475

Table 3. Exceedance probability F_T and recurrence period T_R considering a tailing dam with a life-span of 50 years.

Gutenberg – Richter distribution

A relationship between frequency and magnitude was proposed by Gutenberg and Richter (1944)as

$$\log N = a - b \cdot M \quad (4)$$

where N is the number of earthquakes with magnitude M or higher in the interval [M, M_t+ΔM], where the subscript t indicates the number of subintervals (ΔM), provided that ΔM is large enough to result in a well-fitted curve to Equation 4. The parameter *a* (seismic activity) is related to the total number of earthquakes and the parameter *b* to the magnitude distribution.

Considering

$$\alpha = a \cdot \ln 10 \text{ and } \beta = b \cdot \ln 10 \qquad (5)$$

results

$$\ln N = \alpha - \beta \cdot M \text{ or } N = e^{\alpha - \beta \cdot M} \qquad (6)$$

If the lower magnitude limit is M_o, then the total number of earthquakes is

$$N_T = e^{\alpha - \beta \cdot M_0} \qquad (7)$$

and the probability of occurrence of an earthquake with magnitude not less than M given by

$$1 - F(M) = \frac{N}{N_T} = \frac{e^{\alpha - \beta \cdot M}}{e^{\alpha - \beta \cdot M_0}} = e^{-\beta(M - M_0)} \qquad (8)$$

or the probability of occurrence of an earthquake with magnitude not higher than M expressed as

$$F(M) = 1 - e^{-\beta(M - M_0)} \qquad (9)$$

with a probability density function

$$f(M) = \beta \cdot e^{-\beta(M - M_0)} \qquad (10)$$

Although the Gutenberg – Richter law provides satisfactory results to moderate earthquakes, it underestimates the number of small magnitude earthquakes and does not limit the occurrence of large earthquakes.

Cornell and Van Marke (1969) suggested to include a upper magnitude limit M_u by rewriting Equation (9) as

$$F(M) = \frac{1 - e^{-\beta(M - M_0)}}{1 - e^{-\beta(M_u - M_0)}} \qquad (11)$$

with corresponding probability density function defined by

$$f(M) = \frac{\beta \cdot e^{-\beta(M - M_0)}}{1 - e^{-\beta(M_u - M_0)}} \qquad (12)$$

with $M_0 \leq M \leq M_U$.

In this study a magnitude interval ΔM = 0.1 was considered in Equation 4, resulting in a linear least-square fit (Figure 2) with correlation coefficient r^2 = 0.9646.

Attenuation law

The Southeastern region of Brazil shows similar characteristics to the East coast of the United States and Canada. Therefore, in this study was used the attenuation law proposed by Toro (1997, 2002) to those north american regions, which can be applied to any epicentral distance and earthquake magnitude.

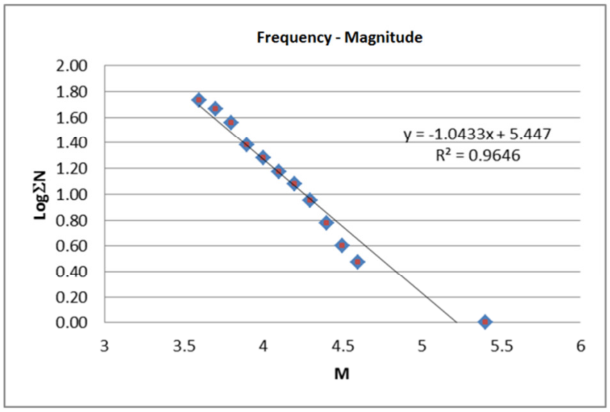

Figure 2: Least-squares linear regression and the Gutenberg-Richer frequency - magnitude relationship.

The maximum horizontal acceleration in the bedrock, expressed in g unit, is given by:

$$lnY = C_1 + C_2(M-6) + C_3(M-6)^2 - C_4 lnR_M - (C_5 - C_4) max\left[ln\left(\frac{R_M}{100}\right), 0\right] - C_6 R_M + \varepsilon_e + \varepsilon_a \qquad (12)$$

$$R_M = \sqrt{R^2 + C_7^2\left[\exp\left(-1.25 + 0.227M\right)\right]^2} \qquad (13)$$

where

Y is the maximum acceleration (g),

C_1 to C_7 are constants with values listed in Table 4 for magnitudes M_w,

M is the moment magnitude M_w,

ε_a is the random uncertainty,

ε_e is the epistemic uncertainty.

In general the standard deviation of the uncertainties depends on magnitude and distance, and the total random uncertainty is calculated as

$$\sigma_a(M,R) = \sqrt{\sigma^2_{a,modeling+\Delta\sigma}(M) + \sigma^2_{a,depth+Q+k}(R_{jb})} \qquad (14)$$

The values for $\sigma^2_{\mathrm{a,modeling+\Delta\sigma}}$ are presented in Table 5 and for $\sigma^2_{\mathrm{a,depth+Q+k}}$ in Table 6. For distances between 5km and 20km these values can be determined by linear interpolation.

In order to apply the attenuation law it was necessary to convert the magnitudes of the Brazilian seismic catalog (IAG/USP) from m_b magnitude into M_w magnitude through the correlation proposed by Scordilis (2006).

Construction of a seismic hazard curve

The objective is to obtain the seismic hazard curve, in other words, a function that represents the exceedance probability of the peak ground acceleration (PGA). The procedure follows the methodology proposed by Cornell (1969).

Table 4. C_1 to C_7 constants for the attenuation law with magnitude M_w.

Freq. (Hz)	C_1	C_2	C_3	C_4	C_5	C_6	C_7
0.5	-	1.86	-	0.92	0.46	0.0017	6.9
1	0.09	1.42	-0.2	0.9	0.49	0.0023	6.8
2.5	1.07	1.05	-0.1	0.93	0.56	0.0033	7.1
5	1.73	0.84	0	0.98	0.66	0.0042	7.5
10	2.37	0.81	0	1.1	1.02	0.004	8.3
25	3.68	0.8	0	1.46	1.77	0.0013	10.5
35	4	0.79	0	1.57	1.83	0.0008	11.1
PGA	2.2	0.81	0	1.27	1.16	0.0021	9.3

Table 5. Values for $\sigma^2_{\mathrm{a,modeling}+\Delta\sigma}$

Freq. (Hz)	M5	M5.5	M8
0.5	0.61	0.62	0.66
1	0.63	0.64	0.67
2.5	0.63	0.68	0.64
5	0.6	0.64	0.56
10	0.59	0.61	0.5
25	0.62	0.63	0.5
35	0.62	0.63	0.5
PGA	0.55	0.59	0.5

Table 6. Values for $\sigma^2_{a,depth+Q+k}$

Freq. (Hz)	<5 km	>20 km
0.5	0.45	0.12
1	0.45	0.12
2.5	0.45	0.12
5	0.45	0.12
10	0.5	0.17
25	0.57	0.29
35	0.62	0.35
PGA	0.54	0.2

It is assumed that for each earthquake epicenter, r_l kilometers distant from the site of interest (tailing dam site near Mariana city - MG), an earthquake of magnitude m_k may occurs with probability $P_{MR}[r_l,m_k]$. The contribution of this event to the exceedance probability of the peak ground acceleration y^* is given by

$$P[Y \geq y^* | M = m_k, R = r_l] \qquad (15)$$

As there are many possible combinations of magnitudes and distances within the area of interest, single results are determined for each given combination which is finally superimposed to obtain the total exceedance probability.

$$P[Y \geq y^*] = \sum_{k=1}^{M_M} \sum_{l=1}^{N_R} P[Y > y^* | M, R] \cdot p_M\,[m_K] \cdot p_R[r_l] (16)$$

where N_M is the number of different magnitudes, N_R is the number of epicentral distances, $p_M\,[m_k]$ is the probability of the random variable M has the value m_k and $p_R\,[r_l]$ is the probability of the random variable R has the value r_l.

However, Equation 16 is not sufficient in order to determinate the seismic hazard curve because is inherently time independent. Budnitz et al. (1997) and Kramer (1996) admitted the additional assumption that a temporal earthquake distribution follows a Poisson process,

$$P[Y \geq y^* \text{ in } t \text{ years}] = 1 - \exp(-\lambda\,(y^*) \cdot t) \qquad (17)$$

with $\lambda(y^*)$ the average annual frequency of events with peak horizontal acceleration,

$$\lambda\,(y^*) = \sum_{i=1}^{n_i} v_i \cdot P[Y > y^*] \qquad (18)$$

where $n_s(y^*)$ represents the number of seismic sources with magnitude $M \geq M_0$ and ν_l the annual average frequency of events at every seismic source.

In this study the value of ν_1 was determined according to Figure 3, considering Toro's attenuation law (1997, 2002) for spectral accelerations in the bedrock and recurrence periods as listed in Table 3.

Combining Equations 15, 16 and 18 the final expression for the seismic hazard curve is written as:

$$P_H(y^*) = P\left[Y > y^* in\_years\right] = 1 - \exp$$

$$\left(\sum_{i=1}^{n_l} \sum_{k=1}^{N_M} \sum_{l=1}^{N_R} -t.v_i.P\left[Y > y^* \middle| m_k, r_l\right] p_R(r_l) P_M(m_K) \right) \qquad (19)$$

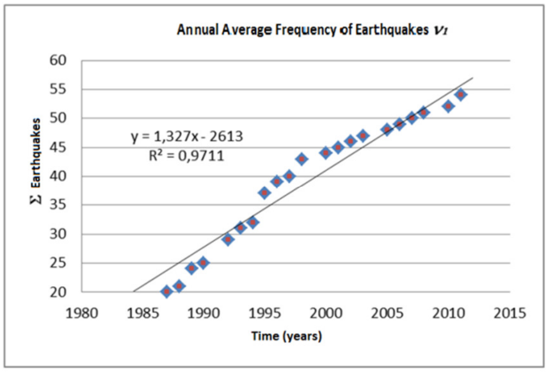

Figure 3: Annual average frequency of earthquakes in the area of interest.

The seismic hazard curve is the usual form to show results of probabilistic analyses, giving for a specific time interval (the predicted life-span of the tailing dam) the exceedance probability for different values of peak ground acceleration.

Results

Seismic hazard curve for the tailing dam site

The results of the seismic hazard analysis for the tailing dam site (UTM coordinates E = 659343. 205, N = 7 764 575.57), near the city of Mariana – MG, are now presented.

In Figure 4 is showed the seismic hazard curve, in function of the exceedance probabilities of acceleration for period T=0 in basement rock.

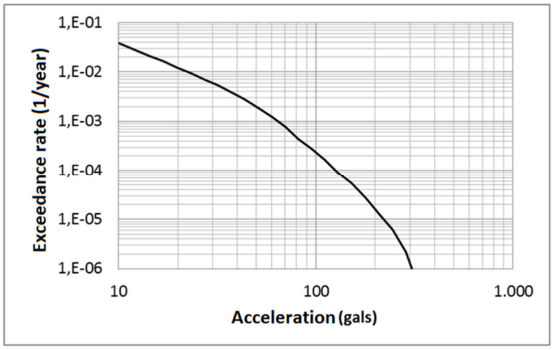

Figure 4: Seismic hazard curve for bedrock horizontal acceleration in the tailing dam site at period T=0. Acceleration expressed in gal = 10^{-2}g.

Uniformly probable design response spectra

Design spectra were determined by probabilistic methods using the CRISIS2007 computational program. The generation of the design spectrum was made for the following cases:

a) Operating Basis Earthquake (OBE)

The operating basis earthquake (OBE) was determined as the response spectrum considering a material damping ratio of 5%, exceedance probability of 50% and 50 years of seismic exposition (life-span of the tailing dam), which corresponds to a recurrence period T_R = 72 years. Thus, the peak ground acceleration (PGA) can be obtained from the seismic hazard curve (Figure 4) as PGA = 0.0187g (Table 6).

b) Design Basis Earthquake (DBE) for T_R = 475 years

The design basis earthquake (OBE) was determined as the response spectrum considering a material damping ratio of 5%, exceedance probability of 10% and 50 years of seismic exposition (life-span of the tailing dam), which corresponds to a recurrence period T_R = 475 years. The peak ground acceleration (PGA) can be obtained from the seismic hazard curve (Figure 4) as PGA = 0.0491g (Table 6).

c) Design Basis Earthquake (DBE) for T_R = 975 years

This design basis earthquake (OBE) was determined as the response spectrum considering a material damping ratio of 5%, exceedance probability of 5% and 50 years of seismic exposition (life-span of the tailing dam), which corresponds to a recurrence period T_R = 975 years. The peak ground acceleration (PGA) can be obtained from the seismic hazard curve (Figure 4) as PGA = 0.0639g (Table 6).

d) Maximum Considered Earthquake (MCE)

The maximum considered earthquake (OBE) was determined as the response spectrum considering a material damping ratio of 5%, exceedance probability of 5% and 50 years of seismic exposition (life-span of the tailing dam), which corresponds to a recurrence period T_R = 2475 years. The peak ground acceleration (PGA) can be obtained from the seismic hazard curve (Figure 4) as PGA = 0.0842g (Table 6).

The uniformly probable design response spectra described above are all represented in Figure 6 and Table 7.

Table 6 – Peak ground acceleration (PGA) at the bedrock for several design response spectra.

Attenuation law	Maximum horizontal acceleration (g) to a return period (years) of			
	72	475	975	2475
Toro (1997, 2002) for rock	0.0187	0.0491	0.0639	0.0842

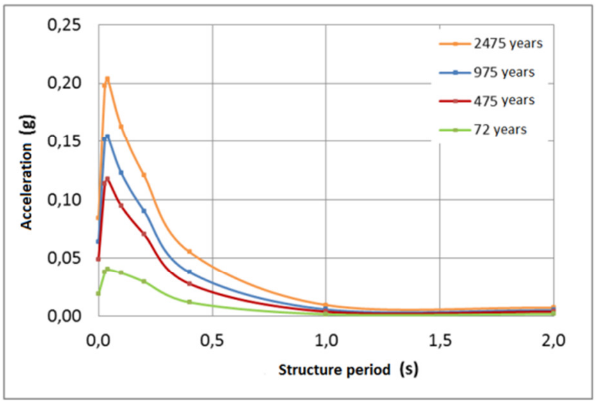

Figure 5: Design response spectra for recurrence period T_R = 72, 475, 975 and 2475 years.

Table 7 Spectral accelerations determined at the bedrock for different recurrence periods.

T_R (yr.)	Spectral accelerations (g) for several periods of the tailing dam (s)					
	0 (PGA)	0,1	0,2	0,4	1,0	2,0
72	0,0187	0,0372	0,0295	0,0117	0,0015	0,0017
475	0,0491	0,0946	0,0706	0,0276	0,0037	0,0037
975	0,0639	0,1229	0,0904	0,0377	0,0057	0,0049
2475	0,0842	0,1628	0,1628	0,0553	0,0094	0,0071

Conclusions

The Brazilian Southeast region shows a diffuse seismic activity which does not enable to define specific seismogenic zones. In this work, the whole area of interest, encompassed by the polygonal line shown in Figure 1, was considered has a diffuse seismic source.

From the Brazilian seismic catalog (IAG/USP) 472 earthquakes with magnitude equal or superior to 3, occurred from 1767 to 2011, were used as our basic dataset, after a preliminary processing in order to eliminate the eventual dependent events.

From a regional probabilistic seismic hazard assessment the maximum horizontal acceleration in the bedrock

(PGA) for the site of the tailing dam was determined considering recurrence periods of 72 years corresponding to the Operating Basis Earthquake (OBE), 475 and 975 years for the Design Basis Earthquake (DBE) and exceedance probability of 10% and 5%, respectively.

It is important to emphasize that these values are applied only to horizontal accelerations in the outcrop rock. For a complete dynamic behavior analysis of the tailing dam, the soil layers present in the geotechnical profile must be taken into account.

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