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SEISMOLOGICAL BASIS OF THE BRAZILIAN STANDARD FOR SEISMIC DESIGN

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ABSTRACT

The Brazilian territory presents low seismicity, typical of a tectonic intra-plates region. Two regions are exceptions, with non-negligible seismicity: part of the Brazilian Northeast, due to its proximity with the South Atlantic Ridge and part of the Brazilian Northwest (Occidental Amazon), due to its proximity with the Pacific Plate border. Due to this low seismicity, up to 2006 Brazil was practically the only South-American country without a seismic design standard. In this year, the new Brazilian Standard for the Design of Seismic Resistant Structures, the NBR 15421, was issued. The available seismological data and the studies performed for defining the probabilistic distribution functions of seismic magnitudes, in several Brazilian regions, are reviewed herein. The considered probabilistic methodology and the analyses performed for the definition of the nominal values of horizontal accelerations are also presented. Equal probability design spectra are generated and compared with the ones defined in the Standard.

Introduction

The Brazilian territory presents low seismicity, typical of a tectonic intra-plates region. The study of the Brazilian seismicity, in a scientific basis, begun in the 70's, as a consequence of the very strict requirements defined for the design of the structures of Angra dos Reis Nuclear Power Plant. Since this decade, seismological data have been collected, from a seismological net that has been implemented and that is presently in continuous operation.

A complete study of the Brazilian seismicity has not, however, concluded up to now. A study of the seismic risk, in a global scale, was performed for the United Nations, by GFZ-Potsdam (1999), and its results were presented in its *Global Seismic Hazard Map*. This map confirms that the Brazilian territory possess a low seismicity, with nominal horizontal accelerations, for stiff ground and a return period of 475 years, generally inferior to 0.4 m/s^2.

Two Brazilian regions are exceptions to be noticed, with a non-negligible seismicity: part of the Brazilian Northeastern Region, due to its proximity with the South Atlantic Ridge and part of the Brazilian Northwest (Occidental Amazon), due to its proximity with the border of the Pacific Plate.

Due to this low seismicity in most of its territory, up to 2006 Brazil was practically the

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only South-American country without a specific Standard for the seismic design of structures. Only for the design of some special structures, pertaining to projects of particular social and economic importance, specific seismic requirements have been considered.

Nevertheless, from the data that have been collected since the 70's and from the theoretical studies that have been performed since then, it was progressively recognized by the Brazilian technical community that seismic effects could not be disregarded "a priori" in the structural design. In 2006, the new Brazilian Standard for the Design of Seismic Resistant Structures, the NBR 15421 (2006), was concluded and issued.

Considering the studies of GFZ-Potsdam and the additional ones described in this paper, the seismic zonation of Brazil established in NBR 15421 has been defined. This zonation is displayed in Figure 1, where the Seismic Zones and their respective values of the nominal horizontal accelerations a_g are shown.

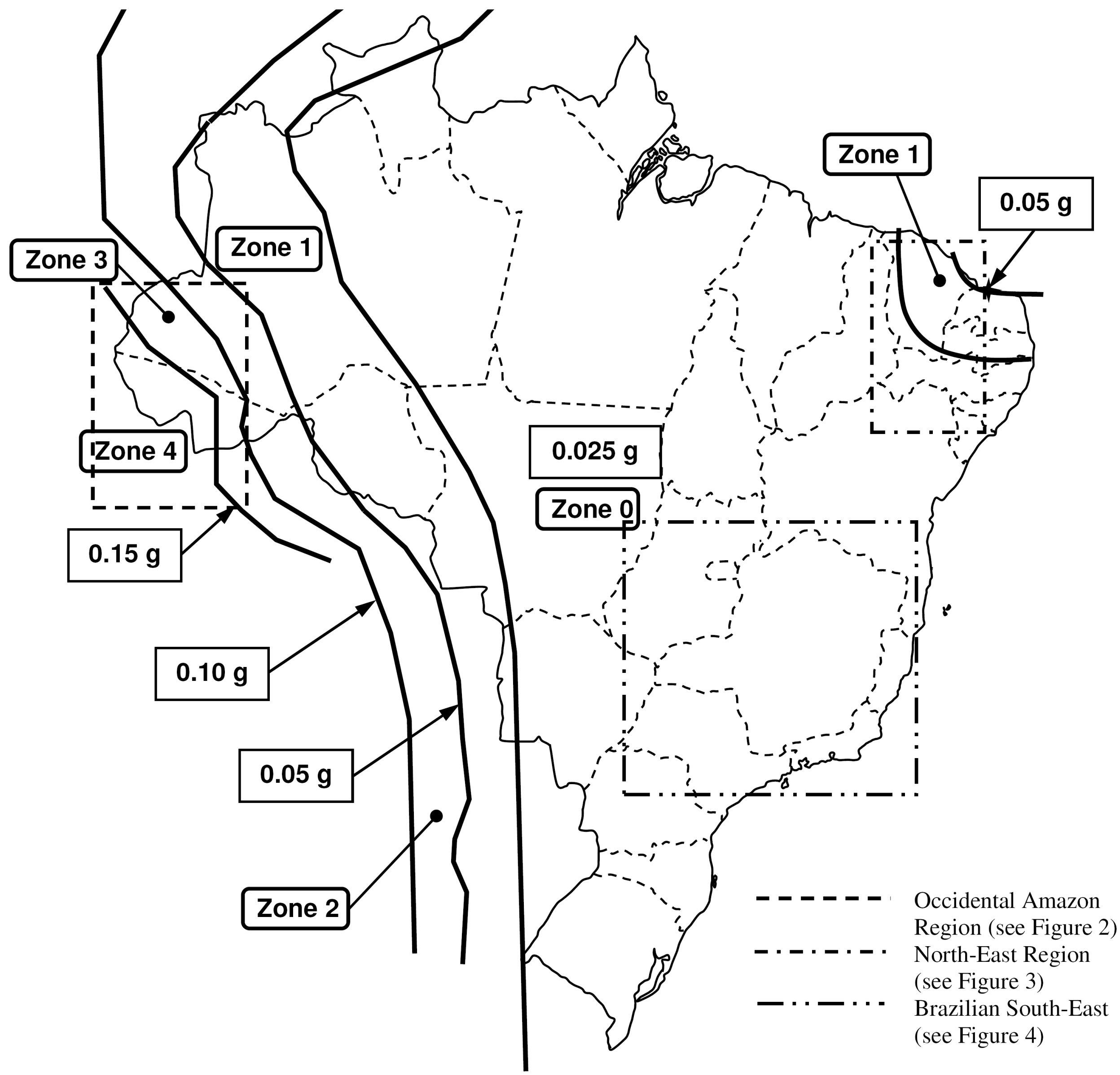

Figure 1. Seismic zonation of Brazil (Nominal horizontal accelerations a_g in g's)

It is to be noticed that this zonation reflects the higher seismicity present in the two Brazilian regions already described. The three rectangular areas displayed in the map correspond to the regions where specific seismological analyses have been made in this paper. The accelerations a_g defined in Fig. 1 correspond to a nominal probability of 90% of non-exceedance in 50 years, i.e., to a return period of 475 years, in rock subsoil conditions.

Analysis of the Seismological Data in Brazil

The description of the main aspects of NBR 15421 and the performed analyses for the definition of the Brazilian seismic zonation have been presented by Santos and Souza Lima (2008). These analyses are redone herein using a more precise methodology.

The Brazilian Standard NBR 15421 considers that most of the Brazilian territory presents low seismicity, but that in the two Brazilian regions, as already described, a non negligible seismic potential is found. In this way, for the considerations presented in this paper, the Brazilian territory is divided in three regions:

- Western part of Brazilian Northern and Center-Western Regions (Occidental Amazon);
- North-Eastern Brazilian States of Ceará, Rio Grande do Norte and Paraíba;
- Remaining of the Brazilian territory.

Analysis of Occidental Amazon Region

The seismic zonation defined by NBR 15421 for this area was based on the *Global Seismic Hazard Map* of the GFZ-Potsdam. Recently, Monroy et al. (2005) presented a comprehensive study of the seismicity of Peru. In this study, the seismicity of the Brazilian Amazon Region contiguous to Peru is also defined, as show in Figure 2 (reference period of 475 years, zero period acceleration).

From the comparison between Figures 1 and 2 it is apparent that the accelerations defined by NBR 15421 are conservative enough for this region.

Analysis of North-Eastern Region

This Brazilian States of the North-Eastern Region considered as the most seismically active ones are the States of Ceará, Rio Grande do Norte and Paraíba. The seismicity defined by Marza et al. (2004) for the state of Ceará is considered as representative for these States.

The seismicity of Ceará is graphically illustrated in Figure 3, where the circles represent the earthquakes registered in the region. In the figure, an area of 78,729 km^2 is also defined, in which it is conservatively considered that all the seismicity of Ceará is concentrated. The 351 sub-regions, with typically 225 km^2, to be considered in the analyses of seismic attenuation, are also shown. In these sub-regions, the Ceará seismicity is considered as uniformly distributed.

The Gutenberg and Richter (1944) expression, applied by Marza et al. to Ceará, is reproduced in Eq, 1, correlating magnitude (M) with annual cumulate frequency ($\sum N$), for the total considered area of 78,729 km^2:

$$\log_{10}(\sum N) = a - b.M = 2.92 - 1.01M \qquad (1)$$

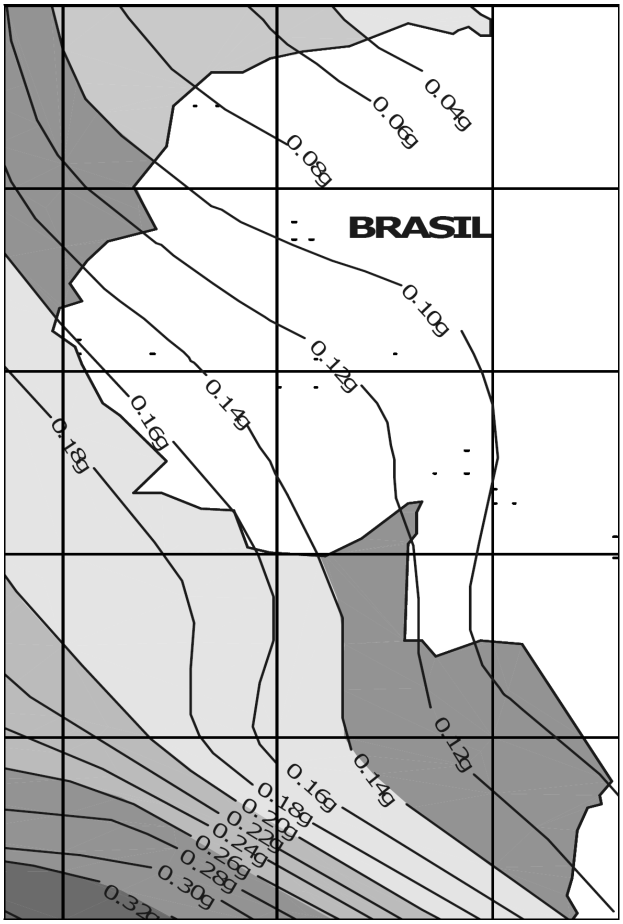

Figure 2. Seismicity in the Occidental Amazon

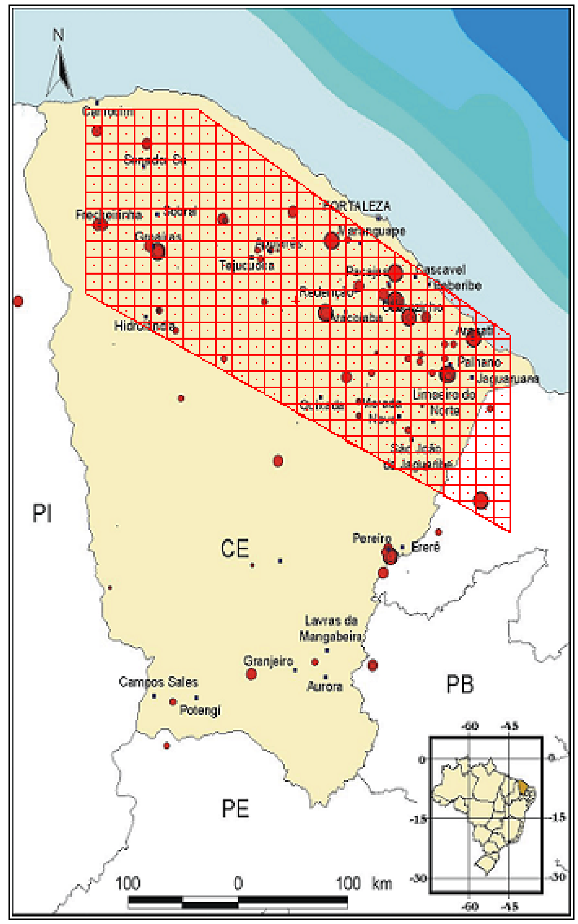

Figure 3. Seismicity in Ceará.

In Eq. 1, *a* e *b* are the coefficients of the Gutenberg-Richter expression, which depend on the local seismicity. The expression can, alternatively, be put in the form:

$$\sum N = \frac{1}{T_M} = c\,.\exp(-d\,.M) \tag{2}$$

In Eq. 2, $c = 10^a = 831.8$ and $d = b.\log_e 10 = 2.326$; $\sum N$ is the total number of earthquakes with magnitude equal or superior to M, in a one year period.

$T_M(M)$ is the recurrence period of an earthquake with magnitude at least equal to M, defined as $T_M(M) = 1/\sum N(M)$. In this paper, M means the body wave magnitude m_b associated with each seismic event.

It should be pointed out that adopting this formula for the seismic characterization implies in considering the seismic sources as “area sources”, as defined by McGuire (2004). This means that in this type of non-active intra-plate region, future seismicity is assumed to have distributions of sources properties and locations of energy release that do not vary in time and space. The seismic risk is not evaluated from actual fault sources with a given seismic potential, but from sources diffusely distributed on the considered Tectonic Province.

For the application in a reliability analysis, the Eq. (2) is transformed in an approximated Gumbel function, defining a "probability of failure" $p_f(M)$ as the probability of occurrence of an earthquake with a magnitude at least equal to M, in a reference time period equal to one year:

$$p_f(M) = \exp[-\alpha(M-u)] = c\,.\exp(-d\,.M) \tag{3}$$

$$\alpha = d = 2.326; u = \frac{\log_e c}{d} = 2.891; \mu = u + \frac{0,577}{\alpha} = 3.139; \sigma = \frac{\pi}{\sqrt{6}.\alpha} = 0.551 \tag{4}$$

Analysis of South-Eastern Region

The South-Eastern Region is considered as representative of the remaining of the Brazilian low-seismicity regions, i.e., the ones not analyzed in the two previous items.

The Brazilian South-Eastern Region comprises four states: São Paulo, Rio de Janeiro, Minas Gerais and Espírito Santo. A complete study of the seismicity of the Region was presented by Berrocal et al. (1996); this study was later refined by Almeida (2002), considering a more complete set of data.

Figure 4. Area for the seismicity analysis of Southeast Region.

In the Fig. 4, an area of 998,263 km^2 is defined, in which it is considered that all the seismicity of South-East Region is distributed. The 313 sub-regions, with typically 3,136 km^2, to be considered in the analyses of seismic attenuation, are also shown.

It is considered that all the seismicity of the South-Eastern Region is concentrated and is uniformly distributed in these sub-regions. The following Gutenberg-Richter expression is defined, for the total considered area of 998,263 km^2, from Almeida:

$$\log_{10}(\sum N) = 4.44 - 1.28M \quad (5)$$

In this relationship, $\sum N$ and M have the same meaning defined for expression (1). For the same reasons given for North-Eastern Region, in South-Eastern Region the seismic sources are considered as "area sources". The parameters c and d are now c = 27542 and d = 2.947. The parameters of the approximate Gumbel function, for the South-Eastern Region, are equal to:

$$\alpha = 2.947; u = 3.469; \mu = 3.665; \sigma = 0.435 \quad (6)$$

Definition of the Probabilistic Distributions of Accelerations

Attenuation Functions

Specific studies defining seismic attenuation functions for the Brazilian territory have not been concluded up to now. It has been considered herein that the attenuation functions, proposed by Toro et al. (1997) for the Central and East United States (CEUS), can be also applied in the similar Brazilian low seismicity conditions.

The considered Toro's function is the following:

$$\ln(a_g) = C_1 + C_2.(M - 6) + C_3.(M - 6)^2 - C_4.(\ln R_M) - (C_5 - C_4) \max[\ln(R_M/100),0] - C_6.R_M \quad (7)$$

In this expression, a_g is the spectral acceleration (for a given period T), r is the epicentral distance, M is the magnitude and R_M is given by:

$$R_M = (r^2 + C_7^2)^{1/2} \quad (8)$$

The parameters C_1, C_2, C_3, C_4, C_5, C_6 e C_7 are given in the table below, as a function of the spectral frequencies to be obtained.

Table 1. Coefficients of the attenuation functions

Freq.(Hz)	C_1	C_2	C_3	C_4	C_5	C_6	C_7
0.5	-0.97	2.52	-0.47	0.93	0.60	0.0012	7.0
1.0	-0.12	2.05	-0.34	0.90	0.59	0.0019	6.8
2.5	0.9	1.70	-0.26	0.94	0.65	0.0030	7.2
5	1.60	1.24	0	0.98	0.74	0.0039	7.5
10	2.36	1.23	0	1.12	1.05	0.0043	8.5
25	3.54	1.19	0	1.46	1.84	0.0010	10.5
35	3.87	1.19	0	1.58	1.90	0.0005	11.1
PGA	2.07	1.20	0	1.28	1.23	0.0018	9.3

Probabilistic Analyses

The probabilistic analyses are done considering the seismicity as uniformly distributed in the several sub-regions defined in Figs. 3 and 4. Then, several magnitude levels are defined; the accelerations induced for each of the magnitude levels by each of the several sub-regions in a reference point defined in the center of the main regions are evaluated. The probabilistic distributions of the accelerations are then obtained through a simple summation process.

The main results of the analyses are shown in Fig. 5: relationships between maximum horizontal accelerations ("PGA - Peak Ground Accelerations", rock conditions), and return periods T_M (inverse of the annual exceedance probability), for the South-Eastern and North-Eastern Regions. The reference periods of 475 and 2475 years, are also depicted in the figure.

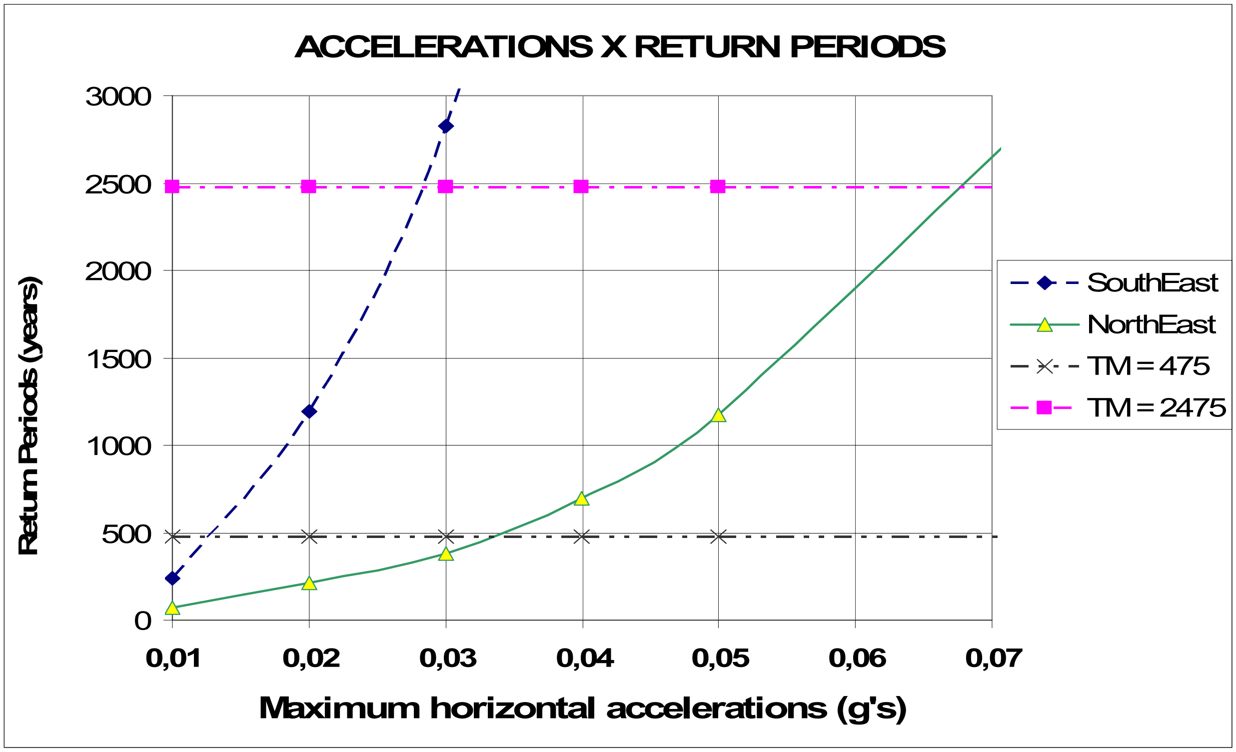

Figure 5. Maximum horizontal accelerations (PGA) and return periods (T_M)

Definition of the Nominal Horizontal Accelerations

The return period of 475 years has been defined by NBR 15421 as the basic criterion for defining the nominal values of the horizontal accelerations. Applying this criterion, the following nominal accelerations are obtained:

North-Eastern Region: $a_g = 0.034$ g (9a)
South-Eastern Region: $a_g = 0.013$ g (9b)

These values are conservative with respect to the ones defined by NBR 15421 (Fig.1):

North-Eastern Region: $a_g = 0.025 \text{ g} \leq a_g \leq 0.050$ g (10a)
South-Eastern Region: $a_g = 0.025$ g (10b)

These values are also checked against the criterion defined by ASCE/SEI 7-05 (2005).

According to this criterion, the nominal values of the horizontal accelerations are taken as 2/3 of the values corresponding to the return period of 2475 years. The following nominal accelerations are then obtained, still adequate with respect to the ones defined by NBR 15421:

North-Eastern Region: $a_g = 0.045$ g (11a)
South-Eastern Region: $a_g = 0.019$ g (11b)

Definition of the Equal Probability Spectra

The results presented in the Fig. 5 have been obtained applying the Toro's attenuation functions to the PGA ("Peak Ground Acceleration"), corresponding to the ZPA ("Zero Period Acceleration"). Using the Toro's coefficients given in Table 1, it is possible to obtain also the probabilistic curves for the maximum horizontal accelerations, for the different values of structural periods (T). In these analyses, 5% damping has been considered.

In this way, the curves shown in Figs. 6 to 8 have been obtained: maximum accelerations against return periods (T_M) for several structural periods, the North-Eastern Region and equal probability spectra for North-Eastern and South-Eastern Regions. The analysis of these spectra shows that the design spectra defined by NBR 15421 are conservative for design purposes.

Figure 6 shows also the approximate probabilistic Gumbel function that can be used for reliability analyses in the Brazilian North-Eastern, for the ZPA ("Zero Period Acceleration"):

$$p_f(a_h) = 1 - \exp[-\exp(-\alpha(a_h - u))] \quad (12a)$$

$$\alpha = 43{,}725; u = -0.1089; \mu = u + \frac{0{,}577}{\alpha} = -0{,}0957; \sigma = \frac{\pi}{\sqrt{6}.\alpha} = 0.0293 \quad (12b)$$

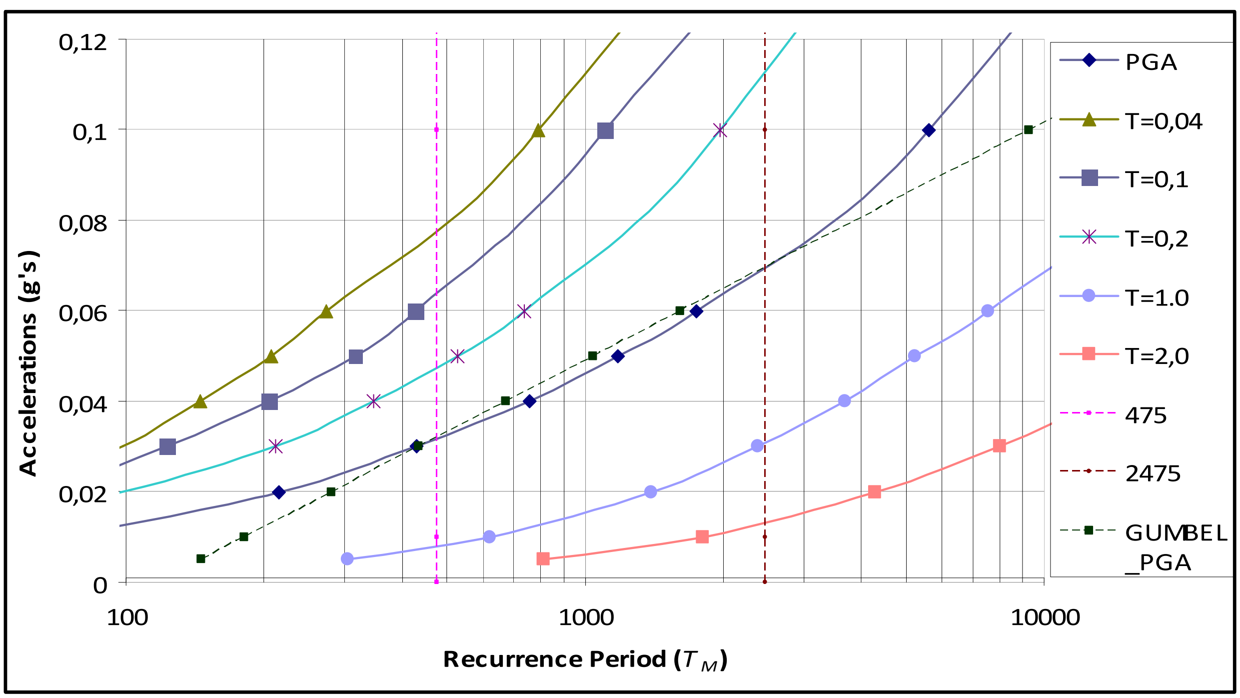

Figure 6. Maximum accelerations and return periods (T_M) for the North-Eastern Region

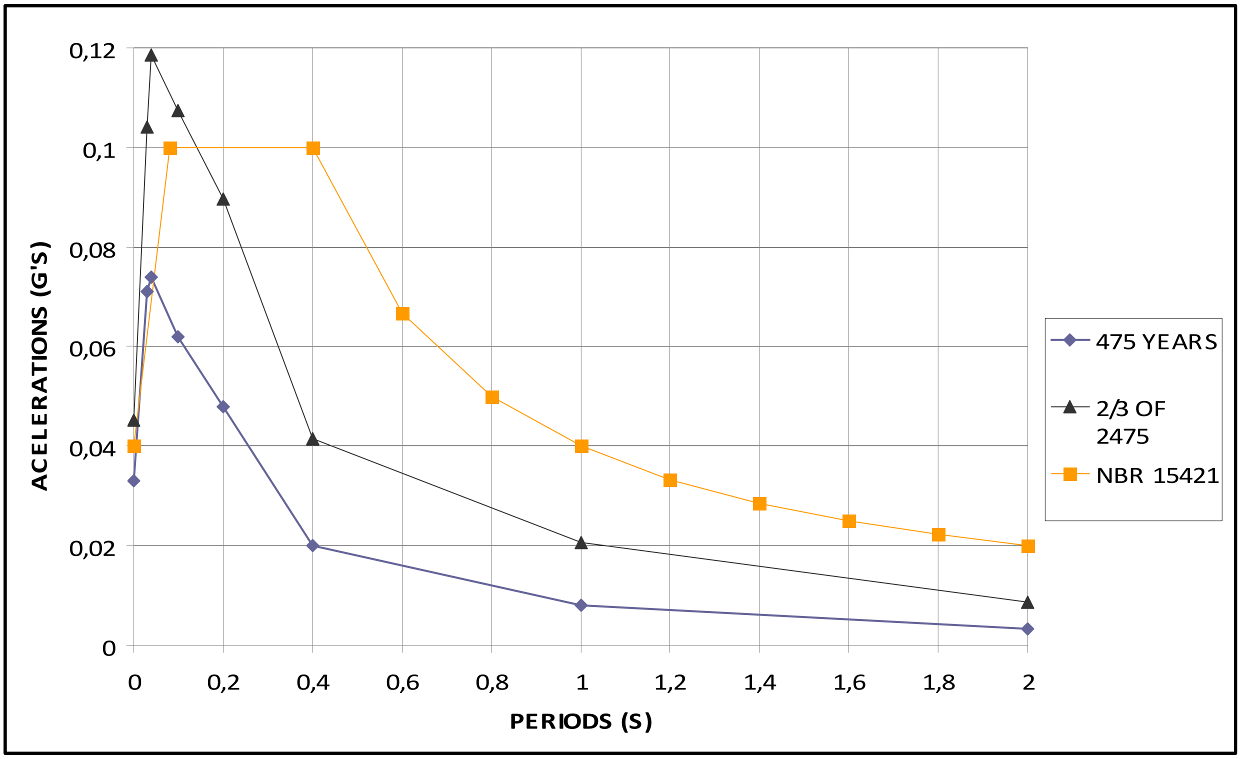

Figure 7. Equal probability spectra for the North-Eastern Region

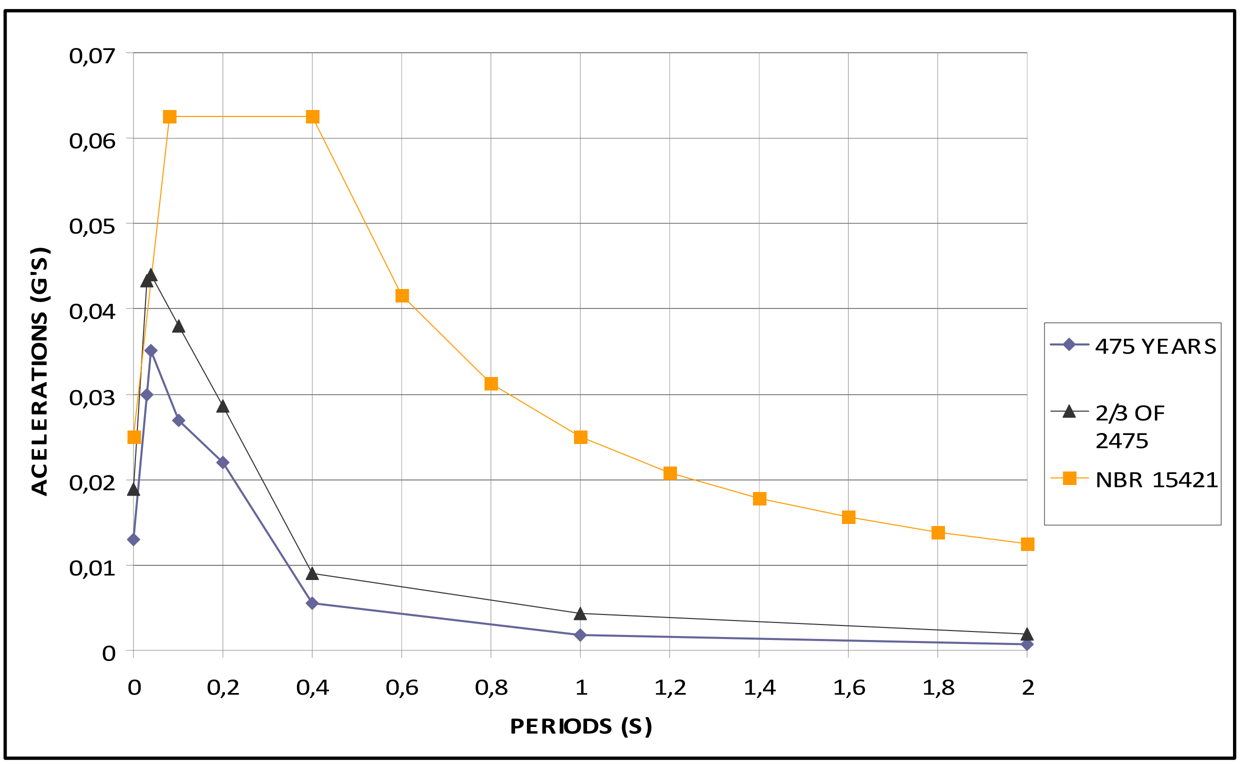

Figure 8. Equal probability spectra for the South-Eastern Region

Conclusions

This paper presents a summary of the seismological data considered in the elaboration of the new NBR 15421, Brazilian Standard for the Design of Seismic Resistant Structures. The available studies for defining the probabilistic distribution functions of seismic magnitudes, in several Brazilian regions, have been reviewed. The analyses for obtaining the probabilistic distribution of accelerations have been presented. With basis in these analyses, the nominal values of the maximum horizontal ground accelerations defined in NBR 15421 have been checked and found to be conservative enough. Also as results of the performed analyses, equal probability design spectra have been generated. These spectra have been compared with the design spectra defined by the NBR 15421 for showing that also these spectra are adequate for design purposes.

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