THE NEW BRAZILIAN STANDARD FOR SEISMIC DESIGN

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ABSTRACT :

The Brazilian territory presents low seismicity, typical of a tectonic intra-plates region. However, at least two Brazilian regions have non-negligible seismicity: part of the Northeast Region, due to its proximity to the South Atlantic Ridge and the Brazilian Occidental Amazon, due to its proximity to the Pacific Plate border. Due this low seismicity, up to 2006 Brazil was practically the only South-American country without a seismic standard. Considering the already gathered seismological information and the theoretical studies recently performed, it has been progressively recognized that seismic effects cannot be disregarded in the structural design in Brazil. Then, in 2006, the new Brazilian Standard for the Design of Seismic Resistant Structures was concluded and issued. The seismological data, the considered probabilistic methodology and the probabilistic studies developed for defining the nominal values of horizontal accelerations in the several Brazilian regions are presented. Some aspects established in the Standard for the design of building structures are also commented.

KEYWORDS: Seismic design, concrete structures, standardization, probabilistic analysis

1. 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 for 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 seismicity of the Brazilian 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 Northeast 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 this low seismicity in most of its territory, up to 2006 Brazil was practically the 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, seismic requirements had been considered. For the nuclear industry, specific design criteria are defined by the Brazilian regulatory authority (CNEN – National Commission of Nuclear Energy), not only for the design of Nuclear Power Plants, but also for the design of research nuclear reactors of relevant inventory. But, 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 Brazil. Then, in 2006, the new Brazilian Standard for the Design of Seismic Resistant Structures, *NBR 15421*, was issued by ABNT.

Considering the studies of GFZ-Potsdam (1999) and the additional ones described in this paper, the seismic zonation of Brazil considered 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.

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 defined in the Figure correspond to a nominal probability of 90% of non-exceedance in 50 years, i.e., to a return period of 475 years.

This paper presents a summary of some important features of the *NBR 15421*. The available seismological data and the studies already performed for defining the probabilistic distribution functions of seismic magnitudes, in several Brazilian regions, are reviewed. The considered probabilistic methodology and the analyses performed for the definition of the nominal values of horizontal accelerations in these regions are presented.

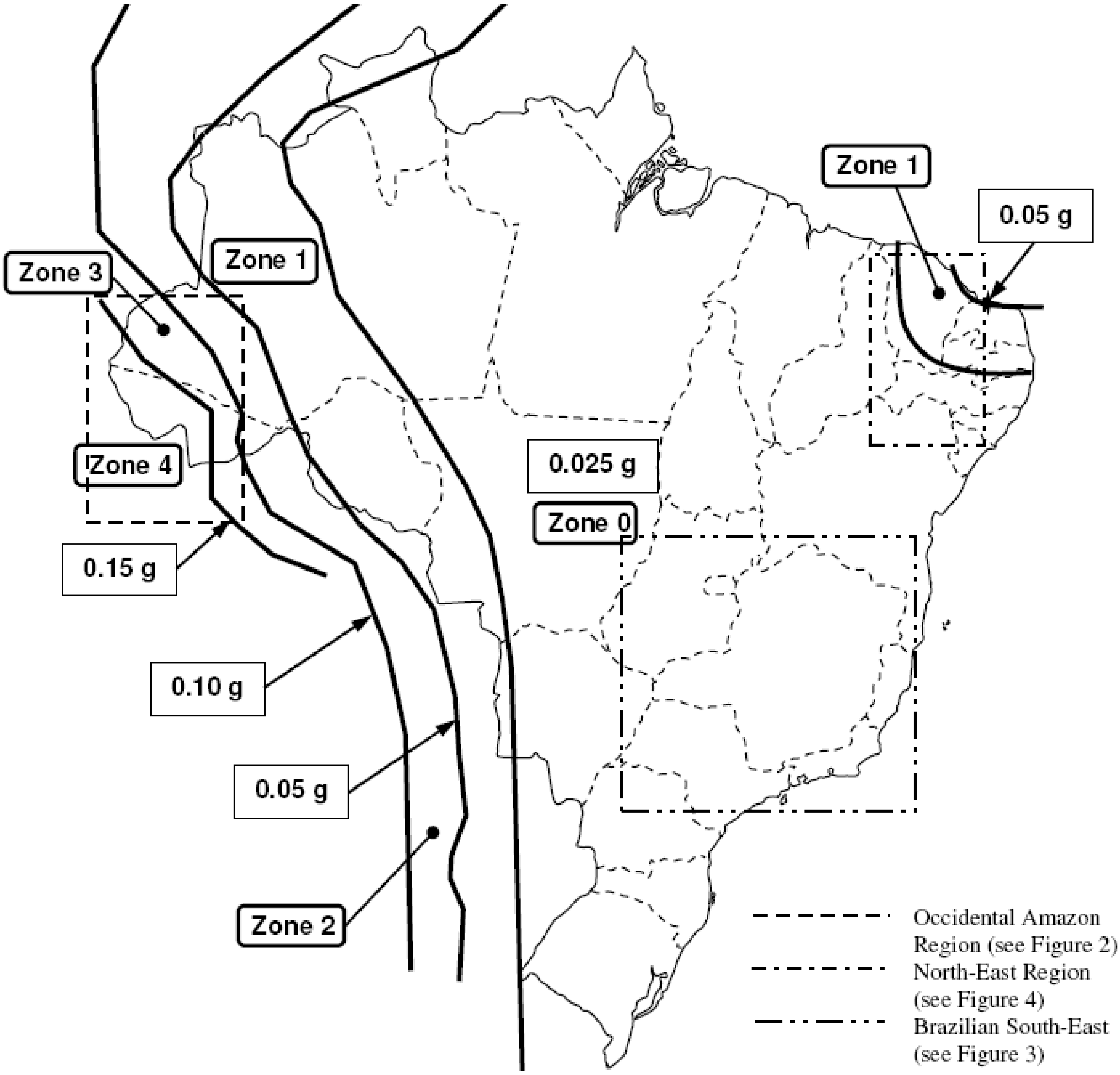

Figure 1. Seismic zonation of Brazil (Nominal horizontal accelerations in g's)

2. ANALYSIS OF THE SEISMOLOGICAL DATA IN BRAZIL

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 to be presented, the Brazilian territory is divided in three regions:

1. West part of the Brazilian North and Center-West Regions (Occidental Amazon);
2. North-East Brazilian States of Ceará, Rio Grande do Norte and Paraíba;
3. Remaining of the Brazilian territory.

2.1. 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 (1999). 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 accelerations). From the comparison between Figures 1 and 2 it is clear enough that this study confirms that the accelerations defined by *NBR 15421* are conservative for this region.

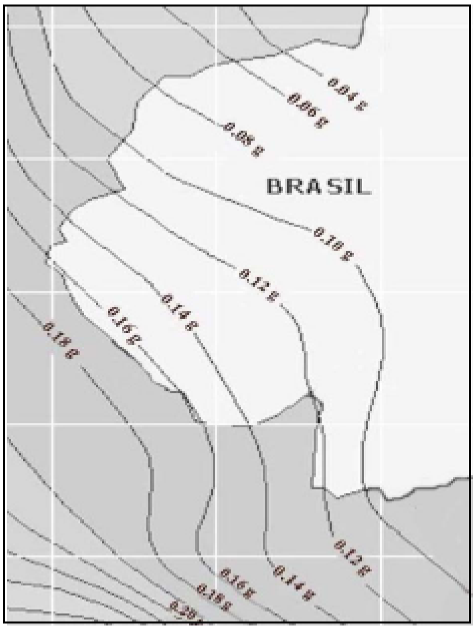

Figure 2. Accelerations for the Occidental Amazon.

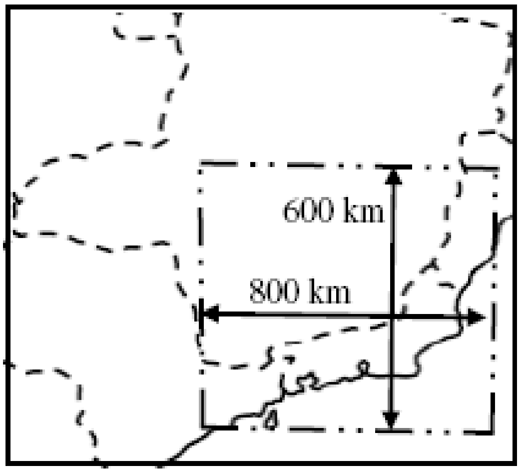

Figure 3. Rectangular area for the South-East Region

2.2. Analysis of North-Eastern Region

This region includes the Brazilian 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 and conservative enough for this region. The Figure 4 is reproduced from this reference. A rectangle, of 64,000 m^2 of area is shown; it is conservatively considered that all the seismicity of Ceará (CE in the figure) is concentrated and is uniformly distributed in this rectangular area. The following Gutenberg and Richter (1944) expression of seismic recurrence is considered, from the above mentioned paper, relating cumulative annual frequency and magnitude:

$$log_{10}(\sum N) = a - b.M = 2.92 - 1.01M \quad (2.1)$$

In this expression, *a* and *b* are the coefficients of the Gutenberg-Richter expression, dependent on the local seismicity. This expression can be also put in the form:

$$\sum N = \frac{1}{T_M} = c \,.\, exp(-d \,.\, M) \tag{2.2}$$

with $c = 10^a = 831.8$ and $d = -b.log_e 10 = 2.326$

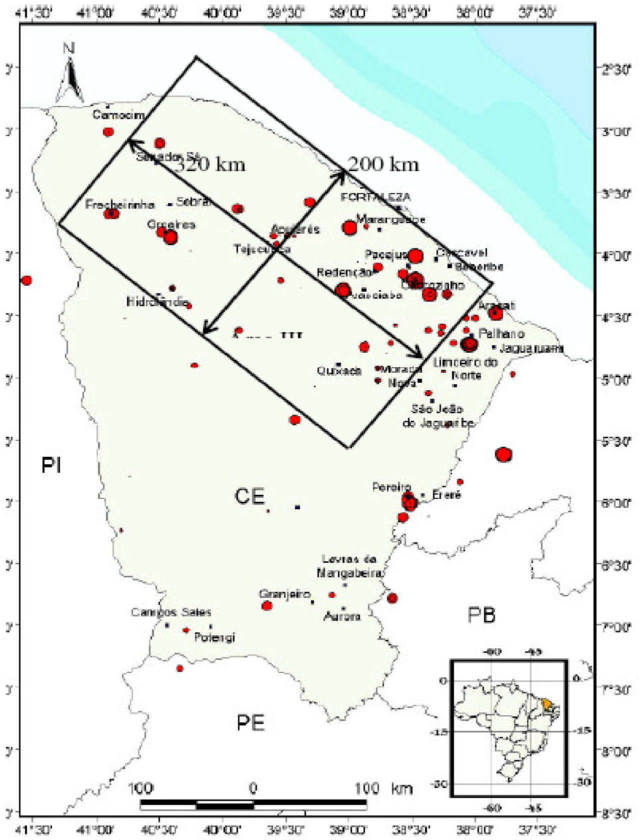

Figure 4. Definition of the area for the probabilistic study of the seismicity of Ceará.

In these relationships, $\sum N$ is the total number of earthquakes with magnitude equal or superior to M, in a one year period. The recurrence period $T_M(M)$ of an earthquake with magnitude at least equal to M is defined as $T_M(M) = 1/\sum N(M)$. In this paper, M is 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 application in the reliability analysis, the relationship (2.2) is transformed in a Gumbel function, relating a "probability of failure" $p_f(M, D)$, defined as the probability of occurrence of a earthquake with a magnitude at least equal to M, with a time period of duration (in years) equal to D. Considering a Poisson process:

$$log_e(1 - p_f) = -\frac{D}{T_M} \tag{2.3}$$

Substituting (2.2) in (2.3), follows:

$$p_f = 1 - exp[-D.c.exp(-d.M)] \tag{2.4}$$

This corresponds to consider a probability distribution represented approximately by a Gumbel function, with the parameters below, where a one-year reference period ($D = 1$ year) is considered:

$$\alpha = d = 2.326; u = \frac{log_e c}{d} = 2.891; \mu = u + \frac{0,577}{\alpha} = 3.139; \sigma = \frac{\pi}{\sqrt{6}.\alpha} = 0.551 \tag{2.5}$$

2.3. Remaining of the Brazilian Territory (South-East Region)

The Brazilian South-East Region comprises four states: São Paulo, Rio de Janeiro, Minas Gerais e 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. The rectangle indicated in Figure 1 encompasses approximately the Region. In the Figure 3 a rectangle is shown, of 480,000 m^2 of area, which corresponds to the most seismically active area of the South-East Region. It is conservatively considered that all the seismicity of the South-East Region is concentrated and is uniformly distributed in this rectangular area, and is representative of the remaining of the Brazilian territory, excepting for the two regions already discussed. The following Gutenberg-Richter expression is considered, from Almeida (2002):

$$log_{10}(\sum N) = 4.44 - 1.28M \tag{2.6}$$

In this relationship, $\sum N$ and M have the same meaning defined for expression (2.1). For the same reasons given for North-Eastern Region, in South-East 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-East Region, are equal to:

$$\alpha = 2.947; u = 3.469; \mu = 3.665; \sigma = 0.435 \tag{2.7}$$

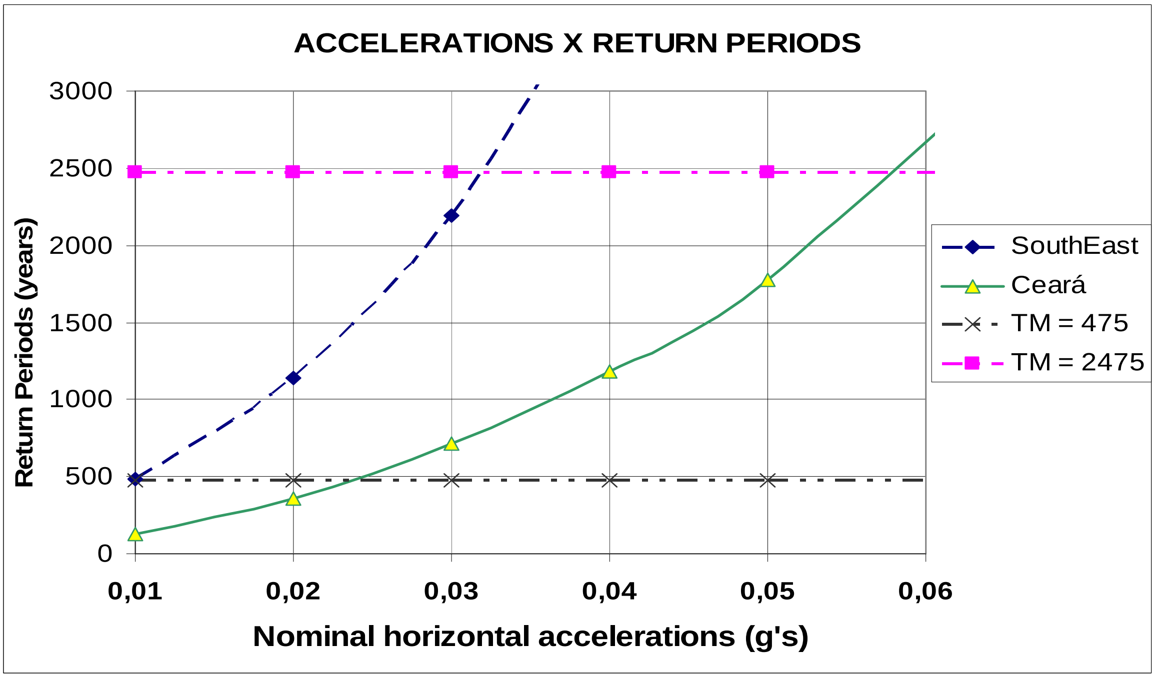

Figure 5. Nominal horizontal accelerations and Return Periods (T_M).

2.4. Definition of the probabilistic distributions of accelerations

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 Gumbel functions already defined for the probabilistic distribution of seismic magnitudes in Brazilian North-East and South-East Regions are considered.

The probability of seismic occurrence is considered as uniform in the two considered rectangles of Figures 3 and 4. The probabilistic functions of horizontal accelerations (ZPA) are determined in the point located exactly in the middle of each of the two rectangles. The computer program COMREL (Reliability Consulting Programs, 1998) is used in the probabilistic analyses.

The final results of the analyses are show in Figure 5: the relationship between maximum horizontal accelerations and return periods (inverse of the annual frequency of exceedance), for Brazilian North-East (Ceará) and South-East Regions. The horizontal lines defining the return periods of 475 and 2475 years, to be used next in the paper, are also depicted in the Figure.

3. 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-East Region: $a_g = 0.024\, g$ (3.1a)

South-East Region: $a_g = 0.010 g$ (3.1b)

These values are conservative with respect to the maximum ones defined by *NBR 15421* for these two regions (from Figure 1, respectively, $0.025\, g \leq a_g \leq 0.050\, g$ and $a_g = 0.025\, g$).

For the sake of comparison, these values are also checked against the criterion defined by *ASCE/SEI 7-05* (ASCE 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. Using this criterion, it is possible to check, from Figure 5, that the following obtained nominal accelerations are still adequate with respect to the ones defined by *NBR 15421*:

North-East Region: $a_g = 0.039\, g$ (3.2a)

South-East Region: $a_g = 0.021 g$ (3.2b)

4. SOME ASPECTS OF THE NBR15421

The fundamental considered reference standard for the elaboration of the *NBR 15421* is the Brazilian Standard for *Actions and Safety in Structures (NBR 8681)* (ABNT, 2003). In the aspects relatives to the seismic analysis and design, the *NBR 15421* is based in the standard *Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-05)* (ASCE, 2005).

The required strength under seismic conditions is defined by *NBR 8681* considering the effects of the factored loads, as defined below:

$$E_d = 1.2 E_g + 1.0 E_q + 1.0 E_{exc} \tag{4.1}$$

E_d, E_g, E_q and E_{exc} are the numerical values of the design load, and the effects of dead, live and seismic loads.

The *NBR 15421* establishes, as defined in Figure 1, five Seismic Zones, according to the values of the nominal accelerations a_g. For the structures in the Seismic Zone 0, no seismic requirements are defined. For the structures in the Seismic Zone 1, the seismic effects can be considered through the simultaneous application to the building floors, in each of the orthogonal directions, of horizontal loads equal to 1% of the permanent floors weights.

For the structures in the Seismic Zones 2, 3 and 4, seismic analyses according to the Equivalent Lateral Forces Procedure, Modal Response Spectrum Analysis and Linear Response History Procedure, as defined respectively in items 12.8, 12.9 and 16.1 of *ASCE/SEI 7-05* are allowed. The design response spectrum to be considered in the analyses is graphically defined in Figure 6, where S_a is the spectral horizontal acceleration.

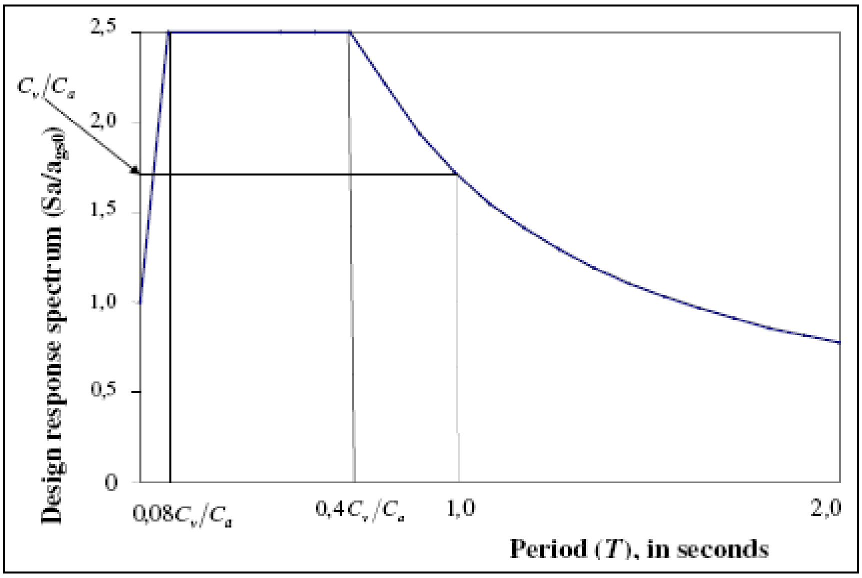

Figure 6. Design response spectrum of horizontal accelerations

This design spectrum is defined as a function of the parameters C_a, C_v, a_{gs0} and a_{gs1}. The soil amplification coefficients, C_a and C_v, are defined in Table 4.1, as a function of the characteristics of the local soil profile (Soil Class) and of the nominal soil acceleration a_g, defined in Figure 1. The criteria for the definition of the Site Classes are basically the same ones defined in Chapter 20 of the *ASCE/SEI 7-05*. For values of $0.10g \le a_g \le 0.15g$, the values of C_a and C_v can be obtained by linear interpolation.

Table 4.1. Site Coefficients C_a and C_v

Site Class	Designation of the Site Class	C_a		C_v	
		$a_g \le 0.10g$	$a_g = 0.15g$	$a_g \le 0.10g$	$a_g = 0.15g$
A	Hard rock	0.8	0.8	0.8	0.8
B	Rock	1.0	1.0	1.0	1.0
C	Very stiff soil and soft rock	1.2	1.2	1.7	1.7
D	Stiff soil	1.6	1.5	2.4	2.2
E	Soft soil	2.5	2.1	3.5	3.4

The parameters a_{gs0} e a_{gs1}, spectral accelerations for the periods of 0.0sec e 1.0sec, already including the effects of soil amplification, are defined in Equations (16a) and (16b):

$$a_{gs0} = C_a . a_g \tag{4.2a}$$

$$a_{gs1} = C_v . a_g \tag{4.2b}$$

5. CONCLUSIONS

A brief overview of *NBR 15421*, the new Brazilian standard for seismic design has been presented. A summary of the seismological data and studies in which the standard is based has been discussed. For the structures in the Seismic Zone 0, no seismic requirements are defined. For the Seismic Zone 1, only a minimum horizontal acceleration equal to 0,01g is to be considered. The areas where seismic effects are important, in Seismic Zones 2 to 4, are the less populated areas of Brazil. It can be then concluded that a significant impact, due to an increase in the construction costs decurrent of the new Standard, is to be expected only in these scarcely populated areas.

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