Rev. IBRACON Estrut. Mater., vol. 15, no. 5, e15505, 2022

IBRACON Structures and Materials Journal
Revista IBRACON de Estruturas e Materiais

ISSN 1983-4195 ismj.org

ORIGINAL ARTICLE

Prospective study on risk-targeted seismic hazard maps for Northeastern Brazil: case study in Zone 1 of ABNT NBR 15421:2006

Estudo prospectivo de mapas de ameaça sísmica com risco-alvo para o Nordeste do Brasil: estudo de caso na Zona 1 da ABNT NBR 15421:2006

Eduardo Marques Vieira Pereira[a]
Gustavo Henrique Ferreira Cavalcante[a]
Rodrigo Bezerra Andrade[a]
Luiz Carlos Marcos Vieira Júnior[a]
Gustavo Henrique Siqueira[a]

[a]Universidade Estadual de Campinas – Unicamp, Faculdade de Engenharia Civil, Arquitetura e Urbanismo, Departamento de Estruturas, Campinas, SP, Brasil

Received 21 October 2021
Accepted 14 February 2022

Abstract: Given the tendency of risk-targeted seismic design maps worldwide, it is important that Brazil is inserted in this context as well. This study aims to apply the risk-targeting methodology for Northeastern Brazil, more specifically the region within Zone 1 of the Brazilian earthquake-resistant design code ABNT NBR 15421:2006. Different inputs for the methodology are explored and combined with existing hazard studies for the region, and their impact in the final map are evaluated. The results outline that, depending on the safety level required, the provisioned design accelerations could be lower than the commonly used in codes, but may as well be much higher. The results are also compared with the current code provisions and their differences are discussed, providing insights on the code provisioned level of safety.

Keywords: seismic hazard, failure probability, seismic design.

Resumo: Diante da tendência mundial de mapas de dimensionamento sísmico com risco-alvo, é importante que o Brasil seja inserido nesse contexto. Este estudo objetiva aplicar a metodologia de risco-alvo para o Nordeste do Brasil, mais especificamente a região dentro da Zona 1 da norma ABNT NBR 15421:2006. Diferentes dados de entrada para a metodologia são explorados e combinados com estudos já existentes de ameaça sísmica para a região, e seus impactos no mapa final são avaliados. Os resultados demonstram que, dependendo do nível de segurança exigido, as acelerações de projeto podem ser menores que as comumente adotadas nas normas, mas podem também ser consideravelmente maiores. Os resultados também são comparados com a norma atual e suas diferenças discutidas, fornecendo informações sobre o nível de segurança fornecido pela norma.

Palavras-chave: ameaça sísmica, probabilidade de falha, dimensionamento sísmico.

How to cite: E. M. V. Pereira, G. H. F. Cavalcante, R. B. Andrade, L. C. M. Vieira Júnior, and G. H. Siqueira, “Prospective study on risk-targeted seismic hazard maps for Northeastern Brazil: case study in Zone 1 of ABNT NBR 15421:2006,” *Rev. IBRACON Estrut. Mater.*, vol. 15, no. 5, e15505, 2022, https://doi.org/10.1590/S1983-41952022000500005

Corresponding author: Eduardo Marques Vieira Pereira. E-mail: eduardo.marquesvp@gmail.com
Financial support: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) - Processo: 134208/2019-6.
Conflict of interest: Nothing to declare.
Data Availability: The results of this study are openly available in https://github.com/emvpereira/Risk-targeted-accel-Northeastern-BR.

1 INTRODUCTION

Brazil is in the middle of the South American tectonic plate – one of the least seismically active regions worldwide, according to Assumpção and Veloso [1]. However, a considerable history of small-to-moderate earthquakes can be highlighted (Berrocal et al. [2], Assumpção et al. [3], [4]), some of which caused considerable damage, for example, the João Câmara earthquake in 1986 (Veloso [5]). If buildings in an earthquake-prone area are not properly designed, damage due to frequent small-to-moderate events should be expected (Nievas et al. [6], Minson et al. [7]). In 2006, the first earthquake-resistant design code in Brazil, ABNT NBR 15421:2006 (ABNT [8]), was launched, demonstrating the need for seismic design in Brazil.

The earthquake loads to be used to design structures have been traditionally associated to a predefined return period (RP) (or a probability of exceedance, PE) depicted through a map. Most codes adopt the long-established 475 years RP for the design accelerations, as does the Brazilian code [8]. More conservative hazard levels associated with a 2475 years RP have also been adopted in other countries such as the United States (before 2010), Canada, Australia, and New Zealand. This type of provisioned accelerations is referred to as the "Uniform Hazard" approach because the RP (or the PE) is the same for all seismic zones.

The earthquake hazard in a region, nonetheless, is properly described by a hazard curve (McGuire [9]), which depicts the probability of exceedance of all the possible accelerations at a site, with a specific return period representing only a single point of this curve. These curves present site-to-site variability in their shape due to the different features of each seismic zone (Luco et al. [10]), hence the same structure would have different failure probabilities at different sites. Silva et al. [11] found differences in the order of five times in Europe.

Increasing the design hazard level to rarer ground motions (e.g., 2475 years RP) improves the uniformity of the failure probability, but still does not ensure it and may lead to unnecessary high loads [10]. In this regard, risk-targeting approaches have emerged, as an alternative to the common Uniform Hazard maps, to provide Uniform Risk maps, i.e., design accelerations that provide a uniform failure probability across a region [10]. For example, Douglas et al. [12] and Kharazian et al. [13], using the risk-targeting methodology, identified different reductions or increase of the accelerations relative to the uniform hazard maps of 475 years RP depending on the seismicity of the site (i.e., low, moderate or high).

In 2010, ASCE-7 began to adopt a risk-targeted map in the seismic design provisions, in lieu of the 2% in 50-year PE (2475 years RP) uniform hazard map. Buildings designed according to that code are expected to have a uniform failure probability of 1% in 50 years countrywide. Similarly, the Indonesian code, SNI 1726:2012 (SNI [14]; see also Sengara et al. [15]), also adopted risk-targeted maps. This methodology has also been applied for several other regions worldwide, for instance, France [12], Spain [13], Romania (Vacareanu et al. [16]), Iran (Taherian and Kalantari [17], Talebi et al. [18]); and at continental scale for Europe [11] and South America (Petersen et al. [19]). A state of the art of the risk-targeting approach can be found in Douglas and Gkimprixis [20].

Nóbrega et al. [21] briefly explored the impact of increasing the RP of design accelerations to 2475 years in the state of Rio Grande do Norte (Brazil). In general, accelerations increased about 2-4 times. This is the expected difference in stable continental regions ([22]). For such regions, the 475 RP is generally not a good predictor of the maximum expected accelerations at a site ([22], Leyendecker et al. [23]). Therefore, some standards have begun to increase the RP to 2475 years, which indeed led to a more uniform failure probability in the United States (see [10]). At the same time, increasing the design hazard would obviously mean to increase construction costs in exchange for safer structures. Thus, it should be a thoroughly discussed decision.

This calls for consistent approaches that weigh the many factors affecting earthquake risk, shifting the discussion from the exclusively scientific sphere to all the stakeholders. This seems very convenient in Brazil, where most engineers are reluctant to apply the seismic design provisions of ABNT NBR 15421:2006 (see Miranda [24]), let alone the fact that developing countries suffer more when a natural disaster happens, because of social inequalities and poverty (Markhvida et al. [25]).

The risk-targeted design can be a way to avoid such a dichotomy between uniformly increasing and reducing the hazard level and, accordingly, the respective construction costs, as it allows for a more optimized structural design. Risk-targeting approaches offer a more rational and transparent process, where the desirable failure probability (or any other performance measure) is explicitly stated, and the seismic design loads are directly calibrated to achieve such feature.

For Brazil, there is only the work of Petersen et al. [19], whose risk-targeted maps encompassed South America. Petersen et al. [19] maps were generated based on ASCE 7-16 provisions [26] (acceptable collapse probability of 1% in 50 years). For tectonically active regions, very conservative values of failure probability would be impractical, because construction costs could become prohibitive (e.g., [17]). Depending on the cost of safety measures, the acceptance criteria can be relaxed (see ISO 2394 [27]). Contrastingly, Douglas et al. [12] considered the probability too high for France and adopted a more conservative criterion (i.e., 10^{-5}). Therefore, in this paper, we seek to explore the impact of different (and more restrictive) acceptance criteria, in view of similar works [11]- [13], as well as other parameters considered in the risk-targeting methodology.

In this paper, prospective risk-targeted maps are generated for the Zone 1 of the Brazilian seismic design code [8], in Northeastern Brazil comprising states of Ceará, Rio Grande do Norte and Paraíba, of Northeastern Brazil. Different assumptions are considered and their impact on the final hazard map is evaluated and compared with current design provisions. The results are insightful on the level of safety provided by the current provisions, and on the required design accelerations if a more rigorous seismic performance is to be met.

2 ESTIMATE OF COLLAPSE PROBABILITY

Given a single location, the structural response due to earthquakes of a particular return period is inherently variable. This stems from the fact that (i) for the same intensity level different events will cause slightly different structural responses (record-to-record variability) and (ii) for a specific event, there are uncertainties in the system's properties (e.g., member's strength and damping). Due to such factors, there is a probability of collapse for any acceleration level (such as the design ground motion). This means that the frequency of collapse of a structure is not simply equal to the frequency of an event exceeding the design ground motion, but rather also depends on these uncertainties. The collapse probability of a system can be described by the total reliability theorem in Equation 1 (Melchers and Beck [28]), also known as "risk integral" [20]:

$$\lambda_i = \int_{IM} P\left[C|IM\right] \cdot p\left(IM\right) dIM \tag{1}$$

Where P[C|IM] is the probability that a structure would collapse as a function of the intensity measure (IM) level representing the ground motions, called Collapse Fragility Function, and p(IM) is the probability of occurrence of an IM level, given by the derivative of the hazard curve. Basically, Equation 1 means that the total probability of failure is a sum of the individual probability of failure for each intensity measure level weighted by the frequency that the intensity level is exceeded. From Equation 1, it is possible to notice that changes in the shape of the functions P[C|IM] and p(IM) affect the value of λ_i, and why a return period (representing only a single value of p(IM)) is unable to provide a uniform λ_i across a region.

For the sake of the example, let us borrow the collapse limit state fragility developed in Pereira et al. [29] (Figure 1a) and perform the integral in Equation 1 using 40 hazard curves (Figure 1b) from the study of Petersen et al. [19] for different sites in Brazil (red crosses in the map). All the hazard curves have the same acceleration related to the 475 years return period (≈0.06g). The resulting annual collapse probabilities obtained from Equation 1 ranges from 1.16×10^{-4} to 4.15×10^{-4}, a difference of nearly 3.5 times. This means that, despite the same 475-year RP acceleration, the seismic design would provide a considerably different safety margin for the same structure in these 40 different sites. It is clear, from this, that one could make use of risk-targeted maps in Brazil.

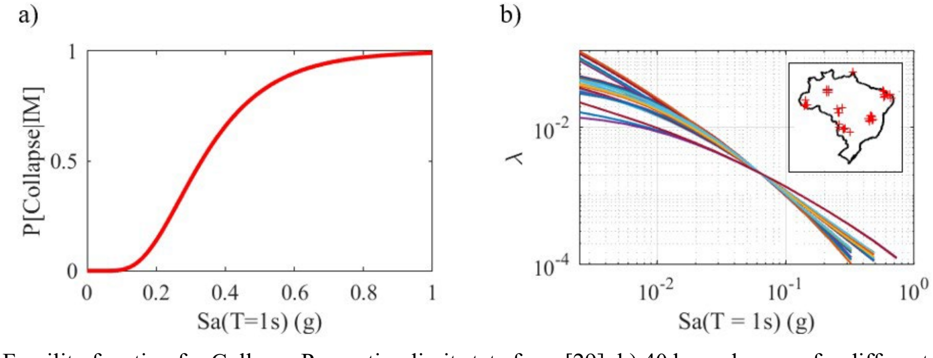

Figure 1. a) Fragility function for Collapse Prevention limit state from [29]; b) 40 hazard curves for different sites in Brazil from [19].

3 RISK-TARGETING METHODOLOGY

The conventional risk-targeting approach by Luco et al. [10] is adopted herein (Figure 2). It consists in an iterative process involving a generic Collapse Fragility Function (CFF), assumed to follow a log-normal distribution, parametrized by a dispersion (β) and the failure probability at the design acceleration IM_D, $P[C|IM_D]$. The value of $P[C|IM_D]$, IM_D and β are used to find the median (or the mean) of the CFF, using log-normal distribution's properties, then the full shape of the curve. In the process, the CFF is progressively shifted towards higher values of IM_D, and the failure probability ($p_{f,i}$) is calculated at each increment *i* using Equation 1. The shifting of the CFF reduces the failure probability, and the process is terminated when the convergence of the target failure probability ($p_{f,i} = p_{f,T}$) is reached, meaning that the final IM_D is the acceleration that provides the desirable failure probability ($p_{f,T}$). A summary of the methodology is depicted in Figure 2.

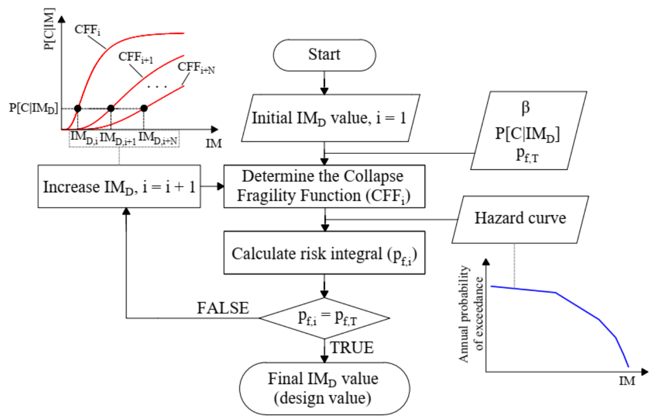

Figure 2. Conventional risk-targeting methodology, as per Luco et al. [10].

It should be noted that risk is typically expressed as the product between the failure probability and its consequences. The consequences of collapse vary between different construction types (e.g., high and low-rise buildings or ordinary and essential buildings) but this methodology does not account for this – it is assumed that the consequences are driven only by the collapse itself, whereas in fact there are other direct and indirect consequences.

The states of Ceará (CE), Rio Grande do Norte (RN), and Paraíba (PB), in Northeastern Brazil, are selected as case study (Figure 3), because they present a well-known relatively higher seismicity in Brazil's territory [3]-[5], [29]. Considerably populated state capitals are also located near the regions with the highest hazard in the case of CE and RN. Moreover, the three states are in Zone 1 of [8], where seismic design is required. The hazard curves developed by Petersen et al. [19], publicly available, are adopted in this paper. Petersen et al. [19] conducted a probabilistic seismic hazard and risk assessment for South America, which one of the outputs were hazard curves for a grid of 0.1° spacing of latitude and longitude in South America. The region adopted as the case study comprises 2111 grid cells. National, or local, hazard studies should always be preferred as they always consider local features better, but, given the paucity of national studies, [19] is enough for the purpose of this study. Some limitations of the hazard model are discussed in a subsection afterwards.

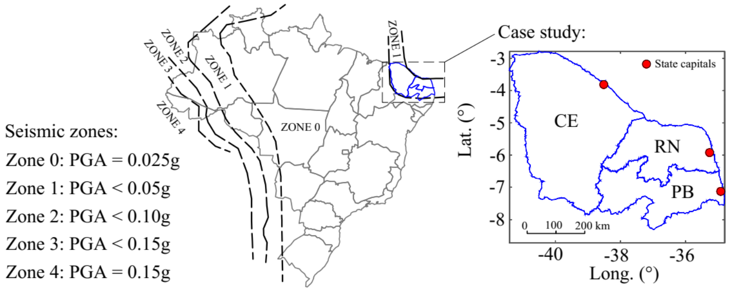

Figure 3. Brazil map with the seismic zoning according to [8], and the case study states.

As already mentioned in Section 1, Petersen et al. [19] generated risk-targeted maps for South America consistent with the ASCE 7-16 provisions [26] using the aforementioned hazard curves. Some differences between the approaches therein [19], [26] and the one adopted in this paper are addressed in the following:

(i) ASCE 7-16 provisions [26] are based on an acceptable p_f of 1% in 50 years (2×10^{-4} in one year), and P[C|IM_D] of 0.1. Herein, more stringent values of probabilities (i.e., lower p_f and P[C|IM_D]) are explored, based on more recent risk-targeting studies conducted for other regions worldwide, especially low seismicity ones like Brazil [11]-[13];

(ii) Design accelerations in [19] and in [26] are in fact a combination of probabilistic (risk-targeted) and deterministic accelerations. The deterministic accelerations are estimated based on the knowledge of the existent hazardous faults, and some predefined judgement-based lower limits, e.g., peak ground acceleration of 0.50g. The final accelerations to be adopted in the map are the lesser between the deterministic and the probabilistic values. Interested readers should refer to Leyendecker et al. [23] and Stewart et al. [30] for further information on this. The deterministic accelerations are not considered in this study because of the lack of knowledge regarding existent faults (e.g., Costa et al. [31]) and the absence of a discussion regarding any predefined values for Brazil. This shall be explored in the future as more data on existent faults become available.

(iii) In [26], design accelerations are multiplied by 2/3. This is based on an existent safety margin, due to code design conservatism [23], [30], which, to the best of our knowledge, has never been stated for buildings in Brazil. Therefore, this is not explored in the results of this paper. Other risk-targeted assessments carried out did not consider these features as well [11]-[13], [16]-[18];

As consequences of item (i), two values are considered in this study for the annual $p_{f,T}$: 2×10^{-4} and 10^{-5}. The former was considered by [10], [17], [18] and [26], whereas the latter was adopted by [12] and [13], and it is also consistent with ISO 2394 [27]. Both values represent a lower and an upper bound of the values of p_f encountered in the literature, therefore intermediate values (e.g., [11]) should bring intermediate accelerations compared with the results of this paper.

Higher and lower design accelerations are expected for the lower and the upper values of $p_{f,T}$, respectively. Some discussion regarding the plausibility and reasonableness of such values as case study is necessary. The few existent reliability assessments for structures in Brazil (Beck and Souza Júnior [32]; Santos et al. [33],) demonstrated annual failure probabilities ranging from 2.15×10^{-4} to 6.80×10^{-8}, encompassing the two target values adopted herein. Recent reliability-based calibration studies for the Brazilian codes ([32]; Santiago et al. [34]; Santiago et al. [35],) adopted 2.7×10^{-5} for the target annual failure probability, which is in fair agreement with the lower bound investigated in this paper. The inferior bound is also consistent with international standards for acceptable individual risk of fatality due to structural failure, a probability of 10^{-6} per year for low seismicity regions [11]. The individual risk can be directly related to the structural failure probability using fatality rate models, as described by [11]. Using the range of fatality models discussed in [11] and the individual risk value, the target failure probabilities range from 2×10^{-5} to 3.57×10^{-6}, with 10^{-5} being obtained using the final model adopted by [11]. All that said, it is considered that both 2×10^{-4} and 10^{-5} are values worthy of investigation.

The value of P[C|IM_D] is intrinsic to the structure and, in a way, measures their performance when subjected to the design ground motion; lower values of P[C|IM_D] imply inherently stronger structures, and therefore the final risk-targeted design accelerations required shall be lower. The values of P[C|IM_D] adopted in the literature range from 10^{-5} to 10^{-1} [10]- [19]. Martins et al. [36] found that for buildings designed according to modern seismic provisions, these values should be placed roughly between 10^{-7} to 10^{-2}. The performance of structures designed according to [8] has never been appraised within a probabilistic framework. However, Pereira [37] evaluated non-seismic reinforced concrete buildings designed according to Brazilian codes and found probabilities between 10^{-3} and 10^{-2} for the Collapse Prevention limit state, therefore adopting values in this range and lower seems reasonable. Since the value of P[C|IM_D] was found to considerably influence the results [12], [16], and given the lack of studies, two values of P[C|IM_D] are investigated: 10^{-3} and 10^{-4}.

For the fragility's dispersion β, only the value of 0.6 is considered. Values found in other works [10]-[19] range mostly from 0.5 to 0.8. High values of β alongside low values of P[C|IM_D] can generate collapse fragilities with unrealistic shapes, i.e., very low failure probabilities even for very high values of accelerations, as demonstrated by [12]. Therefore, $\beta = 0.6$ seems a reasonable compromise between the values found in the literature, and it is also adopted in ASCE 7-16 [26] provisions. Different values for β were also tested, providing smaller design accelerations for higher dispersions, which is consistent with the finds by [11] and [13]. For simplicity, results are presented only for $\beta = 0.6$.

Risk-targeted accelerations are generated for PGA, Sa(T = 0.2s), and Sa(T = 1.0s). The PGA map is meant to be used to generate a response spectrum (RS) compatible with ABNT NBR 15421:2006 [8], since the PGA and the site class are the only input needed. The other two risk-targeted maps (Sa(T = 0.2s) and Sa(T = 1.0s)) can be used to develop a RS compatible with alternative methodologies, such as the one in ASCE 7-16 [26]. A possible change in the code [8] RS shape has begun to be discussed ([21], Alves and Santos [38]); therefore, it seems convenient to contribute to this. Moreover [18], demonstrated that risk-targeting affects each spectral ordinate differently. Hence, the three maps can be useful for research and practice purposes.

Another issue is the spectral ordinate that the code spectrum in [8] refers to. Hazard curves from [19] are based on the geometric mean of both orthogonal components of ground motions. However, it is unclear if the code's response spectrum is based on the geometric mean or the maximum component between the two orthogonal directions. The code does not state this explicitly. The only published work (Santos and Lima [39]), to our knowledge, explaining some of the assumptions of [8], mentions the use of a ground motion prediction equation akin to the geometric mean of the spectral ordinates, but mentions no conversion to the maximum component. Thereby, the results generated in this paper refer to the geometric mean. If one wishes to convert the accelerations to another type of spectral ordinate, factors are available in the literature (e.g., [26]).

In the next subsection, brief comments on the hazard model by [19] are carried first to enlighten some aspects of the results. Then the impact of the different input on the hazard map is evaluated in terms of the final accelerations, and in terms of the Risk Coefficient [10], which is the risk-targeted acceleration divided by the uniform hazard acceleration associated with a return period (Equation 2). The Risk Coefficient is evaluated relative to 475 years and 2475 years RP accelerations ($C_{R,475}$ and $C_{R,2475}$, respectively) from the hazard assessment of [19] for each grid cell. Subsequently, the risk-targeted accelerations are compared with the current design provisions by [8]. The results of the risk-targeting assessment are made available at an on-line repository in GitHub (https://github.com/emvpereira/Risk-targeted-accel-Northeastern-BR)

$$C_{R,RP} = \frac{IM_{D}, risk-targeted}{IM_{D,RP}} \quad (2)$$

3.1 Brief discussion on the hazard model

The color map in Figure 4a depicts the PGA values by [19]; note that PGA values were multiplied by 0.9 [26] to be consistent with soil class B (same as [8]). The hazard maps developed by [19] outline a zone with a high hazard among the states of PB and RN (Figure 4a). As noted by Pereira et al. [29], this higher hazard zone appears to be inconsistent compared with the national catalogue or hazard assessments for the region (e.g., [4], [21]). In the following, this issue is briefly addressed. Results of the risk-targeting approach are presented afterwards.

In [19], the hazard maps were generated using the smoothed seismicity approach, in which the seismic zones are based on the occurrence of past earthquakes, and since they used an international catalogue, the locations and magnitudes of the events may not be as precise as the ones presented in national catalogues. In Figure 4b, the declustered catalogue used in [19] (filled blue circles) is compared with the national catalogue (obtained in http://moho.iag.usp.br/rq/event, last accessed September 11th, 2021) (unfilled circles). A particular event is also marked with a star (discussed in the following). Two earthquakes of the catalogue used by [19] draw attention in Figure 4b, one in western RN and one near the border between PB and RN (pointed by an arrow), because they seem not to appear in the national catalogue. Note that the catalogue used by [19] considers only events with moment magnitude (M) higher than 5.0; that is why there are much fewer filled blue circles in Figure 4b.

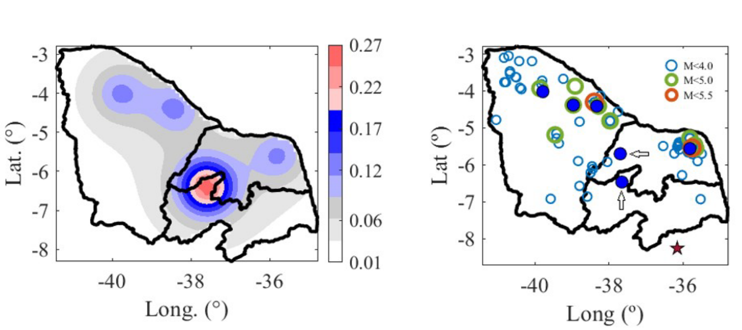

Figure 4. a) 475 years return period PGA map by [19] for B/C boundary soil class; b) Earthquakes in the region: national catalogue (unfilled circles), catalogue by [19] (filled blue circles), and São Caetano earthquake in 2006 (red star).

Regarding the event in western RN (horizontal arrow), it is an historical earthquake that occurred in 1808 with ≈M5.0. This event appears in the catalogue compiled by Berrocal et al. [2]. The other event (vertical arrow), however, appears to have occurred in the state of Pernambuco near the São Caetano county (see Lopes et al. [40]), below PB (the star marker in Figure 4b), because there is an event in the national catalogue that occurred at the exact same time (May 20th of 2006, at 4:26AM). In addition, it is an M5.0 event in [19], whereas in the national catalogue it is M3.6. The consideration of these events caused the seismic hazard to be relatively high in this zone, unlike what is seen in other national studies. The rest of the events appear in the national catalogue, evidently in slightly different locations, as shown in Figure 4b, and with similar magnitudes.

In terms of accelerations (Figure 4a), 60% of the grid cells have PGA [19] larger than the code's [8], which is 0.05g for the entire region, but this number reduces to 20% for $PGA/PGA_{code} > 2$, and these cells are located right at the previously mentioned zone. The point of this comment is to illustrate that, in most of the analyzed territory, accelerations are not so different in terms of what is expected between different hazard assessments (e.g., Douglas et al. [41], Gkimprixis et al. [42]), not to mention the fact that they were developed using very different methodologies. As mentioned, Petersen et al. [19] used smoothed seismicity models, whereas in [8] a diffuse seismicity was used; the former also used logic trees to account for the epistemic uncertainties. In fact, high hazard zones by [19] are nearly concentrated where the earthquakes in the catalogue occurred, which is a consequence of the methodology.

4 RESULTS AND DISCUSSIONS

4.1 Risk-targeting approach results

The results of the risk-targeting in terms of the maximum and minimum accelerations obtained within the grid describing the studied region are summarized in Table 1 for each intensity measure. The risk-targeted design acceleration maps (units of g) are presented in Figure 5. As expected, higher values of $P[C|IM_D]$ and lower values of $p_{f,T}$ caused higher accelerations. The consideration of $P[C|IM_D] = 10^{-3}$ and $p_{f,T} = 10^{-5}$ clearly generated the highest accelerations (Figure 5c), with a maximum PGA of 0.71g, followed by a maximum of 0.49g using $P[C|IM_D] = 10^{-4}$ and $p_{f,T} = 10^{-5}$ (Figure 5d).

Table 1. Comparison between the risk-targeted minimum and maximum accelerations.

IM	$p_{f,T}$	$P[C\| IM_D]$	Min. (g)	Max. (g)
PGA	2×10^{-4}	10^{-3}	0.0099	0.2457
		10^{-4}	0.0072	0.1690
	10^{-5}	10^{-3}	0.0243	0.7121
		10^{-4}	0.0170	0.4890
Sa(T = 0.2s)	2×10^{-4}	10^{-3}	0.0216	0.3807
		10^{-4}	0.0153	0.2614
	10^{-5}	10^{-3}	0.0507	1.0763
		10^{-4}	0.0351	0.7382
Sa(T = 1s)	2×10^{-4}	10^{-3}	0.0088	0.0552
		10^{-4}	0.0063	0.0379
	10^{-5}	10^{-3}	0.0216	0.1528
		10^{-4}	0.0150	0.1050

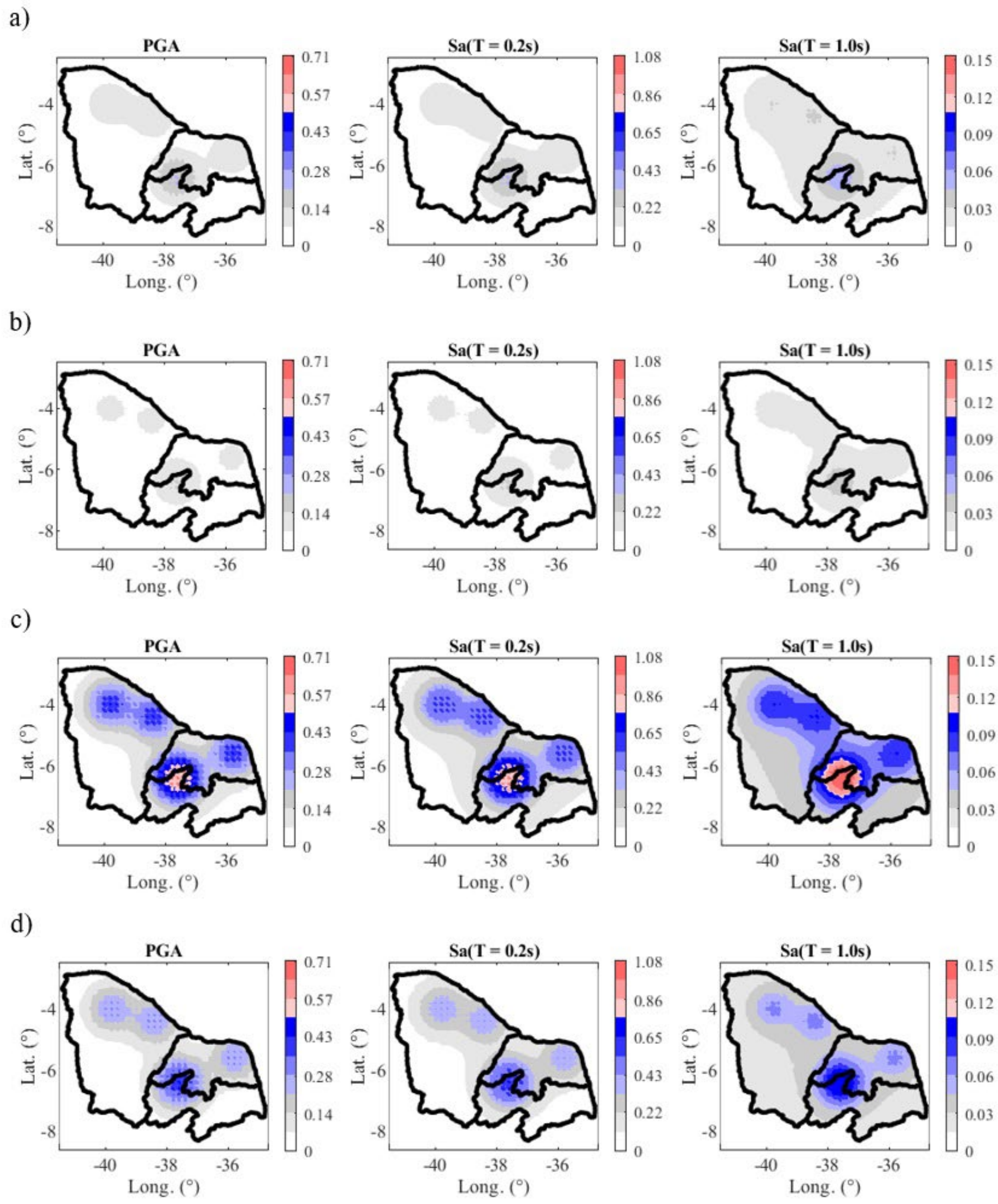

Figure 5. Maps with risk-targeted accelerations in units of g: a) $P[C|IM_D] = 10^{-3}$ and $p_{f,T} = 2 \times 10^{-4}$; b) $P[C|IM_D] = 10^{-4}$ and $p_{f,T} = 2 \times 10^{-4}$; c) $P[C|IM_D] = 10^{-3}$ and $p_{f,T} = 10^{-5}$; d) $P[C|IM_D] = 10^{-4}$ and $p_{f,T} = 10^{-5}$.

The adoption of $p_{f,T} = 10^{-5}$ caused accelerations ≈2.8 times higher on average than for $p_{f,T} = 2 \times 10^{-4}$. The adoption of $P[C|IM_D] = 10^{-3}$ generated accelerations on average ≈1.45 times higher than for $P[C|IM_D] = 10^{-4}$, keeping $p_{f,T}$ constant. The coefficients of variation of the increment is ≈0.09 and ≈0,01 when variating $p_{f,T}$ and $P[C|IM_D]$, respectively. This small coefficient of variations of the increment between grid cells indicate that different values of

$p_{f,T}$ and $P[C|IM_D]$ do affect the value of the design motions but may have a slight effect on the disparities of accelerations across a region.

These above comments outline how important the definition of the acceptable failure probability is to the determination of the design accelerations in the risk-targeting process and can considerably affect the results. The effect of $P[C|IM_D]$ demonstrated to be considerable as well, and this outlines the importance of carrying out studies to evaluate the seismic performance of existing and new structures designed according to [8] in Brazil so that these seismic fragility parameters are properly defined.

The common practice in seismic design (including in [8]) is to increase internal forces by an Importance Factor that ranges from 1.0 for ordinary buildings to 1.5 for essential buildings to provide an additional safety margin because of the building's importance. The results, nonetheless, demonstrate that reducing $p_{f,T}$ may require considerably higher values of design accelerations than those proposed using the Importance Factor values from [8], which poses a question on what would be the required reliability for such essential buildings, or what is the reliability provided by the Importance Factor. If 2×10^{-4} is to be adopted as the target failure probability for ordinary buildings, and 10^{-5} for essential buildings, an Importance Factor higher than 1.5 is needed, since accelerations increase about three times between these two values of $p_{f,T}$. Of course, higher values than 10^{-5} could be adopted to avoid very high design loads for such essential buildings. The main problem is the uncontrolled risk level provided by the Importance Factor that may not be adequate for essential buildings.

The values of accelerations observed considering $p_{f,T}$ as 10^{-5} might be unfeasible in the Brazilian context, even for essential buildings, and this could be an indication that the higher $p_{f,T}$ (or an intermediate value) may be more suitable for the country. A secondary alternative to overcome this could be the definition of deterministic caps for the accelerations (i.e., predefined accelerations), as adopted by [19] and [26], but this would require an in-depth discussion on the values to be adopted.

The resulting risk coefficients relative to the 475 and 2475 return periods accelerations are presented in Table 2 and risk coefficients map in Figure 6. Regarding $C_{R,475}$, it can be observed that it resulted in less than one for most of the cases, meaning that the 475 RP acceleration is probably more than enough to guarantee an adequate safety for these cases. The exceptions are for $p_{f,T} = 10^{-5}$ with PGA and Sa(T = 0.2s), and for $p_{f,T} = 2 \times 10^{-4}$ but only with Sa(T = 0.2s). This means that fixing a return period does not provide a uniform margin of safety among different periods of vibration and can lead to non-conservative results. Regarding $C_{R,2475}$, only in one case the coefficient exceeded unity. Therefore, increasing the RP of the design motions to 2475 years would not necessarily ensure an appropriate safety. Depending on the acceptance criteria and on the period of the structure, it could be even unnecessary, and a smaller RP should be aimed for design.

Table 2. Comparison between the risk coefficients.

IM	$p_{f,T}$	$P[C\|IM_D]$	$C_{R,475}$			$C_{R,2475}$		
			Min.	**Max.**	**Mean**	**Min.**	**Max.**	**Mean**
PGA	2×10^{-4}	10^{-3}	0.26	0.71	0.42	0.14	0.210	0.17
		10^{-4}	0.19	0.49	0.29	0.10	0.14	0.12
	10^{-5}	10^{-3}	0.63	2.47	1.23	0.33	0.73	0.50
		10^{-4}	0.44	1.70	0.85	0.23	0.50	0.34
Sa(T = 0.2s)	2×10^{-4}	10^{-3}	0.60	1.08	0.75	0.29	0.33	0.31
		10^{-4}	0.42	0.74	0.52	0.20	0.23	0.21
	10^{-5}	10^{-3}	1.38	3.59	2.09	0.72	1.08	0.85
		10^{-4}	0.96	2.46	1.43	0.50	0.75	0.59
Sa(T = 1s)	2×10^{-4}	10^{-3}	0.14	0.30	0.19	0.05	0.15	0.08
		10^{-4}	0.10	0.21	0.14	0.03	0.11	0.06
	10^{-5}	10^{-3}	0.38	0.77	0.53	0.13	0.40	0.23
		10^{-4}	0.26	0.54	0.37	0.09	0.28	0.16

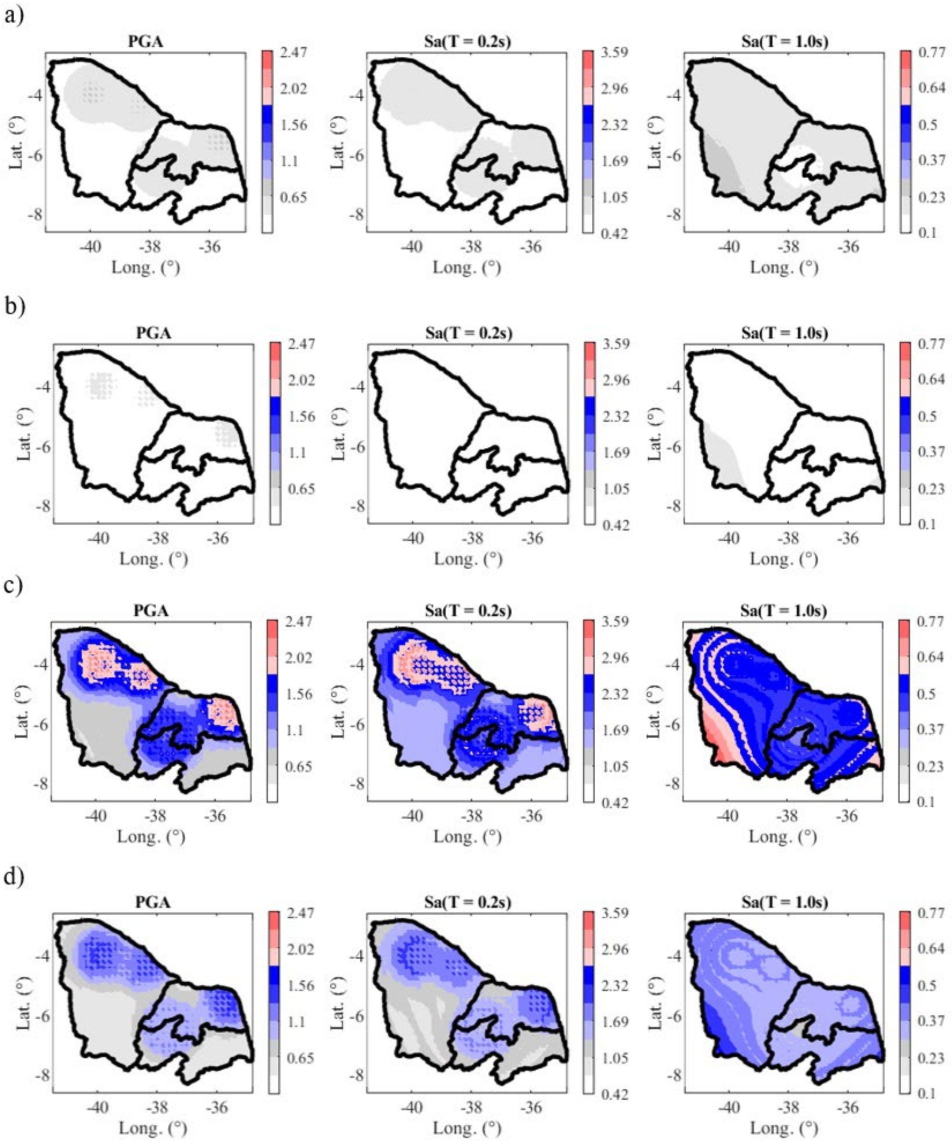

Figure 6. Maps with $C_{R,475}$: a) $P[C|IM_D] = 10^{-3}$ and $p_{f,T} = 2 \times 10^{-4}$; b) $P[C|IM_D] = 10^{-4}$ and $p_{f,T} = 2 \times 10^{-4}$; c) $P[C|IM_D] = 10^{-3}$ and $p_{f,T} = 10^{-5}$; d) $P[C|IM_D] = 10^{-4}$ and $p_{f,T} = 10^{-5}$.

But more importantly, a different pattern of distribution of the risk coefficient is observed in Figure 6 between intensity measures. In general, for Sa(T = 1s) the risk coefficient resulted higher in the areas with low hazard (see also Figure 4a). On the other hand, for Sa(T = 0.2s) and PGA the risk coefficient was higher in high hazard regions, but not in proportional manner, since the highest $C_{R,475}$ are not observed in the high hazard region of Figure 4a. A similar trend was also observed by [13] for Spain.

The comments in the last two paragraphs raise awareness that the adoption of a fixed response spectrum shape solely with PGA as an input, as most codes do (including [8]), may underestimate or overestimate differently the design loads depending on the period of vibration and the location of the structure, even when the PGA is risk-targeted. Similar conclusions were also drawn by [18] for Iran. Improved equations for the determination of the response spectrum or the provision of more discrete spectral ordinates (i.e., for multiple periods) should be adopted to overcome this issue.

4.2 Comparison with current code provisions

In this section, the risk-targeted accelerations in each cell of the grid are compared with the code's response spectrum in [8] for the three IMs (Figure 7). The values of the code provisioned PGA, Sa(T = 0.2s) and Sa(T = 1s) for soil class B are 0.05g, 0.125g and 0.05g, respectively. The intent of this section is not to draw conclusions on the adequacy of the Brazilian code, but simply to compare the provisioned accelerations with the risk-targeted results. Results are presented in Figure 8, where the shaded areas represent the sites where the risk-targeted accelerations exceed the code provisioned and the color bar represents the ratio between these two.

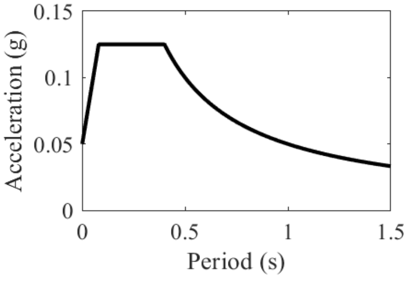

Figure 7. a) Code response spectrum [8].

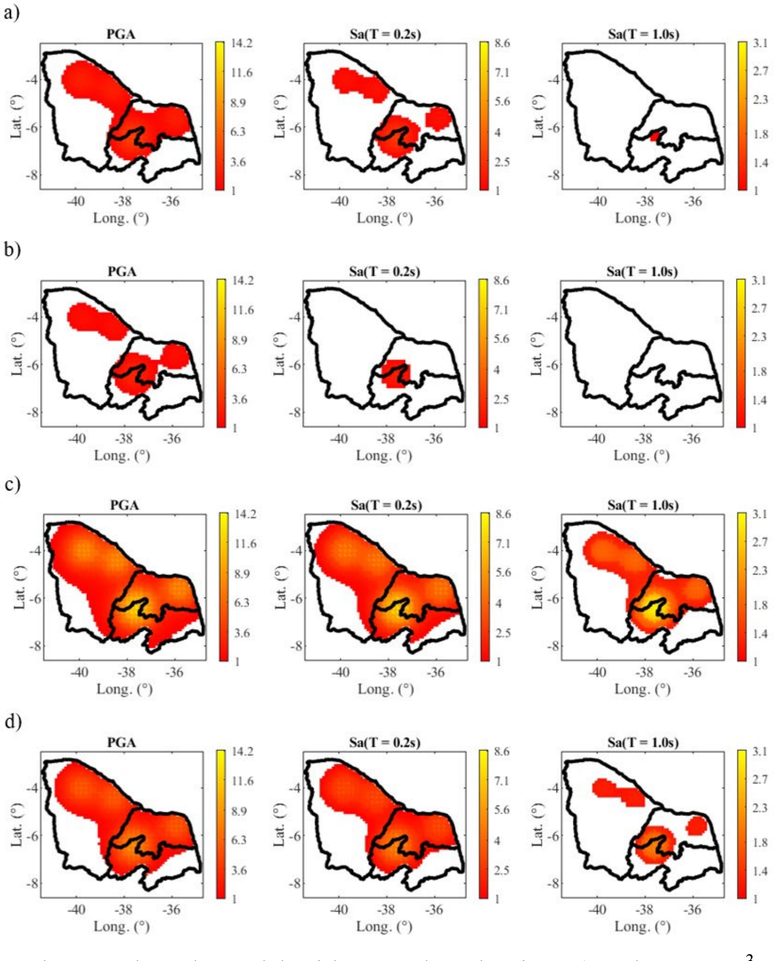

Figure 8. Comparison between the code's and the risk-targeted accelerations: a) $P[C|IM_D] = 10^{-3}$ and $p_{f,T} = 2 \times 10^{-4}$; b) $P[C|IM_D] = 10^{-4}$ and $p_{f,T} = 2 \times 10^{-4}$; c) $P[C|IM_D] = 10^{-3}$ and $p_{f,T} = 10^{-5}$; d) $P[C|IM_D] = 10^{-4}$ and $p_{f,T} = 10^{-5}$.

It is noticeable that there is not a uniform safety margin for the three IMs considered, since the shaded area considerably varies among figures. The difference is higher for low periods (i.e., PGA and Sa(T = 0.2s)), which affects mostly low-rise buildings. Interestingly, in Figure 8b the risk-targeted Sa(T = 1s) resulted lower than the code's in the whole region, whereas in Figure 8a there is only a small area. It seems, therefore, that the safety level provided by [8] is somewhat consistent with the one in [26] for long period structures (i.e., medium to high-rise frames). These results for Sa(T = 1s) are somehow expected, since the shape of the RS of the Brazilian code is more similar to the RS of tectonically active regions, that is, accelerations decay at larger periods than for the stable continental regions.

In Table 3, the risk-targeted accelerations are compared with the code provisioned accelerations for the capitals of the three states in Zone 1 of [8] (see Figure 3), because of the high exposure of these sites. Risk-targeted accelerations were taken from the grid cell in the coordinates 38.5°W 3.8°S, 35.2°W 5.9°S, and 34.90°W 7.1°S for the cities of Fortaleza (CE), Natal (RN) and João Pessoa (PB), respectively. As expected, João Pessoa presents the lowest accelerations; and the risk-targeted acceleration resulted lower than the code's for all three IM. Results for Natal and Fortaleza are similar; and the code spectrum seems to be consistent (or more conservative, except for PGA) with the safety level intended by [26].

Table 3. Ratio between risk-targeted accelerations and code accelerations for the state capitals in Zone 1.

IM	$p_{f,T}$	$P[C\|IM_D]$	Fortaleza (CE)	Natal (RN)	João Pessoa (PB)
PGA	2×10^{-4}	10^{-3}	1.60	1.40	0.32
		10^{-4}	1.10	0.96	0.23
	10^{-5}	10^{-3}	4.99	4.68	0.79
		10^{-4}	3.41	3.21	0.55
Sa(T = 0.2s)	2×10^{-4}	10^{-3}	1.04	0.86	0.29
		10^{-4}	0.72	0.59	0.20
	10^{-5}	10^{-3}	3.35	2.56	0.74
		10^{-4}	2.30	1.76	0.51
Sa(T = 1s)	2×10^{-4}	10^{-3}	0.46	0.40	0.22
		10^{-4}	0.31	0.29	0.16
	10^{-5}	10^{-3}	1.30	1.20	0.59
		10^{-4}	0.89	0.83	0.41

A secondary issue should be brought to attention. Currently [8], says that structures in Zone 1 of the code (see Figure 3) need to be designed only using a simplified procedure that consists in applying 1% of the floor's weight as lateral loads (0.01W), which, evidently, has no relation to any return period. It is unclear, however, if this procedure is enough to guarantee structures with adequate safety. Given that 0.01W provides very low lateral loads relative to other seismic design methods (see Dantas et al. [43], Paiva Neto et al. [44]), it is unlikely to affect the design of low or medium-rise ordinary residential buildings, since the code minimum reinforcement ratio would likely prevail, or to exceed the lowest risk-targeted accelerations (e.g., in Figure 5b and 5d). The question remains if the out-of-plumbness and wind design loads would provide safe enough structures, but we believe that this is unlikely because such lateral loads would not be considerable either, at least for ordinary residential buildings. Therefore, we understand that our results bring attention to the need for the use of the more rigorous design procedure in [8] in Zone 1, instead of the simplified procedure, especially for low-rise buildings.

4 CONCLUSIONS

Risk-targeted seismic hazard maps have emerged as an alternative to the widely adopted uniform hazard maps with accelerations related to a fixed return period. In this paper, risk-targeted seismic hazard maps are generated for the upper region of Northeastern Brazil considering different input for the methodology. The results demonstrate that accelerations lower than those associated with a 475 or a 2475 return period may be enough to ensure safe structures in some regions, even when more rigorous acceptance criteria are required.

The adoption of the more stringent criteria for the failure probability caused the risk-target design accelerations to remarkably increase (by a factor of three in some sites). Therefore, it seems of paramount importance the definition of what would be the acceptable risk in Brazil and, based on the results, this definition has potential to substantially modify the design provisions. The value of the Risk Coefficient depends on the intensity measure (i.e., the period of vibration) and the structure's site (i.e., site with relatively low or high hazard); therefore, the adoption of sole PGA, risk-targeted or with a fixed return period, to build a design response spectrum can be non-conservative for some structures in some sites. This calls for a more detailed code spectrum.

The results of this paper are obviously conditioned to the hazard model adopted [19], and the discussion in Section 3.1 poses the question of its adequacy. Local hazard assessment studies are obviously better than the ones conducted at large scale such as [19]. Despite that, given the paucity of hazard assessment studies in Brazil, this choice is deemed reasonable, and we believe that this paper provides valuable information about the seismic risk in the country, thus it contributes towards the improvement of design provisions. For sites near the state capitals (high exposure), the reliability provided by [8] demonstrated to be consistent with [26].

The conventional risk-targeting methodology adopted by Luco et al. [10] is adopted in this paper, but other alternatives should be explored in the future. More recent risk-targeting approaches can be used (Gkimprixis et al. [45]). For that, pure reliability theory also has its means and can enable alternatives (e.g., additional safety coefficients) and, therefore, should also be considered as an option. The target performance (failure probability herein) could be stated in terms of other measures, for example, costs of failure, downtime, fatality rates, costs of repair, and indirect impacts. Regardless, the point is that more robust procedures should be used to establish the seismic design requirements in Brazil. We believe that changing the status quo of hazard maps can instigate society's interest and its acceptance of the importance of earthquakes in the country. Further studies should also address the performance of structures designed according to ABNT NBR 15421:2006 [8] in a probabilistic framework to complement the results in this paper and enable a reappraisal of some of the assumptions (e.g., β and P[C|IMD]).

This is an exploratory study, not a proposal, which uses readily available hazard curves developed at continental scale study, therefore the results herein should be used with parsimony by engineers when designing buildings, and unconditionally never if they are lower than what is recommended by the national code. The results are made available in an on-line GitHub repository (https://github.com/emvpereira/Risk-targeted-accel-Northeastern-BR), especially for research purposes. Additional results generated for validation and not presented in this paper are also available. These risk-targeted accelerations shall be used in future studies to investigate the impact in the design of new structures in terms of reinforcement ratio, members' cross-section and increase of construction costs.

ACKNOWLEDGEMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001; and by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) process: 134208/2019-6.

REFERENCES

[1] M. S. Assumpção and A. V. Veloso, "The 1885 M 6.9 earthquake in the French Guiana-Brazil border: the largest midplate event in the nineteenth century in South America," *Seismol. Res. Lett.*, vol. 95, no. 5, pp. 2497–2510, 2020, http://dx.doi.org/10.1785/0220190325.

[2] J. Berrocal et al., *Sismicidade do Brasil*. São Paulo, Brasil: Esperança, 1984.

[3] M. S. Assumpção et al., "Intraplate seismicity in Brazil," in *Intraplate Earthquakes*, P. Talwani, ed. Cambridge, England: Cambridge University Press, 2014, pp. 50-73, https://doi.org/10.1017/CBO9781139628921.004

[4] M. S. Assumpção, M. Pirchiner, J. Dourado, and L. Barros, "Terremotos no Brasil: preparando-se para eventos raros," *Boletim da Sociedade Brasileira de Geofísica*, vol. 96, pp. 25–29, 2016. Accessed: Oct. 21, 2021. [Online]. Available: https://sbgf.org.br/noticias/images/Boletim_96-2016.pdf

[5] J. A. V. Veloso, *O Terremoto que Mexeu com o Brasil*. Brasília, Brazil: Thesaurus, 2011.

[6] C. I. Nievas, J. J. Bommer, H. Crowley, J. van Elk, M. Ntinalexis, and M. Sangirardi, "A database of damaging small-to-medium magnitude earthquakes," *J. Seismol.*, vol. 24, no. 2, pp. 263–292, 2020, http://dx.doi.org/10.1007/s10950-019-09897-0.

[7] S. E. Minson, A. S. Baltay, E. S. Cochran, S. K. McBridge, and K. R. Milner, "Shaking is almost always a surprise: The earthquakes that produce significant ground motion," *Seismo. Soc. Am.*, vol. 92, no. 1, pp. 460–468, 2021, http://dx.doi.org/10.1785/0220200165.

[8] Associação Brasileira de Normas Técnicas, *Projeto de Estruturas Resistentes a Sismos – Procedimento,* ABNT NBR 15421, 2006.

[9] R. K. McGuire *Seismic Hazard and Risk Analysis.* Oakland, CA, USA: EERI, 2004.

[10] N. Luco, B. R. Ellingwood, R. O. Hamburger, J. D. Hooper, J. K. Kimball, and C. A. Kircher "Risk-targeted versus current seismic design maps for the conterminous United States," in *Proc. SEAC 2007 Convention*, California, USA, 2007.

[11] V. Silva, H. Crowley, and P. Bazzurro, "Exploring risk-targeted hazard maps for Europe," *Earthq. Spectra*, vol. 32, no. 2, pp. 1165–1186, 2016, http://dx.doi.org/10.1193/112514eqs198m.

[12] J. Douglas, T. Ulrich, and C. Negulescu, "Risk-targeted seismic design maps for mainland France," *Nat. Hazards*, vol. 65, no. 13, pp. 1999–2013, 2013, http://dx.doi.org/10.1007/s11069-012-0460-6.

[13] A. Kharazian, S. Molina, J. J. Galiana-Merino, and N. Agea-Medina, "Risk-targeted hazard maps for Spain," *Bull. Earthquake Eng.*, vol. 19, no. 13, pp. 5369–5389, 2021, http://dx.doi.org/10.1007/s10518-021-01189-8.

[14] Badan Standardisasi Nasional, *Tata Cara Perencanaan Ketahanan Gempa Untuk Struktur Bangunan Gedung Dan Non Gedung,* SNI 1726:2012, 2012.

[15] I. W. Sengara et al. "New 2019 risk-targeted ground motions for spectral design criteria in Indonesian seismic building code," in *Proc. 4th Int. Conf. on Earthquake Eng. & Disaster Mitigation*, 2020, https://doi.org/10.1051/e3sconf/202015603010

[16] R. Vacareanu et al., "Risk-targeted maps for Romania," *J. Seismol.*, vol. 22, no. 2, pp. 407–417, 2018., http://dx.doi.org/10.1007/s10950-017-9713-x.

[17] A. R. Taherian and A. Kalantari, "Risk-targeted seismic design maps for Iran," *J. Seismol.*, vol. 23, no. 6, pp. 1299–1311, 2019., http://dx.doi.org/10.1007/s10950-019-09867-6.

[18] M. Talebi, M. Zare, E. N. Farsangi, M. R. Soghrat, V. Maleki, and S. Esmaeili, "Development of risk-targeted seismic hazard maps for the Iranian plateau," *Soil. Dyn. Earthquake Eng.*, vol. 141, pp. 106506, 2021., http://dx.doi.org/10.1016/j.soildyn.2020.106506.

[19] M. D. Petersen et al., "Seismic hazard, risk, and design for South America," *Bull. Seismol. Soc. Am.*, vol. 108, no. 2, pp. 781–800, 2018., http://dx.doi.org/10.1785/0120170002.

[20] J. Douglas and A. Gkimprixis "Risk targeting in seismic design codes: the state of the art, outstanding issues and possible paths forward," in *Seismic Hazard and Risk Assessment*, R. Vacareanu and C. Ionescu, eds. New York, USA: Springer, 2018, pp. 211-223, https://doi.org/10.1007/978-3-319-74724-8_14

[21] P. G. B. Nóbrega, B. R. S. Souza, and S. H. S. Nóbrega, "Towards improving the seismic hazard map and the response spectrum for the state of RN/Brazil," *Rev. IBRACON Estrut. Mater.*, vol. 14, no. 3, pp. e14302-1-16, 2021., http://dx.doi.org/10.1590/S1983-41952021000300002.

[22] International Federation for Structural Concrete, *Displacement-based Seismic Design of Reinforced Concrete Buildings, fib Bulletin 25*. Lausanne, Switzerland: CEB-FIP, 2003.

[23] E. V. Leyendecker, R. J. Hunt, A. D. Frankel, and K. S. Rukstales, "Development of maximum considered earthquake ground motion maps," *Earthq. Spectra*, vol. 16, no. 1, pp. 21–40, 2000, http://dx.doi.org/10.1193/1.1586081.

[24] P. S. T. Miranda, "A influência das ações sísmicas nas edificações brasileiras em concreto armado," Ph.D. dissertation, FEUP, Porto, Portugal, 2021. [Online]. Available: https://repositorio-aberto.up.pt/handle/10216/133133

[25] M. Markhvida, B. Walsh, S. Hallegatte, and J. Baker, "Quantification of disaster impacts through household well-being losses," *Nat. Sustain.*, vol. 3, pp. 538–547, 2020., http://dx.doi.org/10.1038/s41893-020-0508-7.

[26] American Society of Civil Engineers, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures,* ASCE/SEI 7-16, 2016.

[27] International Organization for Standardization, *General principles on reliability for structures,* ISO 2394, 2015.

[28] R. E. Melchers and A. T. Beck, *Structural reliability analysis and prediction*. 3rd ed. Hoboken, NJ, USA: John Wiley & Sons, 2018.

[29] E. M. V. Pereira, G. H. F. Cavalcante, I. D. Rodrigues, L. C. M. Vieira Júnior, and G. H. Siqueira, "Seismic reliability assessment of a non-seismic reinforced concrete framed structure designed according to ABNT NBR 6118:2014," *Rev. IBRACON Estrut. Mater.*, vol. 15, no. 1, pp. e15110, 2022, http://dx.doi.org/10.1590/S1983-41952022000100010.

[30] J. P. Stewart, N. Luco, J. D. Hooper, and C. Crouse, "Risk-targeted alternatives to Deterministic ground motion caps in U.S. seismic provisions," *Earthq. Spectra*, vol. 36, no. 2, pp. 904–923, 2020, http://dx.doi.org/10.1177/8755293019892010.

[31] C. Costa et al., "Hazardous faults of south america; compilation and overview," *J. S. Am. Earth Sci.*, vol. 104, pp. 102837, 2020, http://dx.doi.org/10.1016/j.jsames.2020.102837.

[32] A. T. Beck and A. C. Souza Júnior, "A first attempt towards reliability-based calibration of Brazilian structural design codes," *J. Braz. Soc. Mech. Sci. Eng.*, vol. 32, pp. 119–127, 2010, http://dx.doi.org/10.1590/S1678-58782010000200004.

[33] D. M. Santos, F. R. Stucchi, and A. T. Beck, "Reliability of beams designed in accordance with Brazilian codes," *Rev. IBRACON Estrut. Mater.*, vol. 7, pp. 723–746, 2014, http://dx.doi.org/10.1590/S1983-41952014000500002.

[34] W. C. Santiago, H. M. Kroetz, and A. T. Beck, "Reliability-based calibration of Brazilian structural design codes used in the design of concrete structures," *Rev. IBRACON Estrut. Mater.*, vol. 12, pp. 1288–1304, 2019, http://dx.doi.org/10.1590/S1983-41952019000600004.

[35] W. C. Santiago, H. M. Kroetz, S. H. C. Santos, F. R. Stucchi, and A. T. Beck, "Reliability-based calibration of main Brazilian structural design codes," *Lat. Am. J. Solids Struct.*, vol. 17, 2020, http://dx.doi.org/10.1590/1679-78255754.

[36] L. Martins, V. Silva, P. Bazzurro, and M. Marques, "Advances in the derivation of fragility functions for the development of risk-targeted hazard maps," *Eng. Struct.*, vol. 173, pp. 669–680, 2018, http://dx.doi.org/10.1016/j.engstruct.2018.07.028.

[37] E. M. V. Pereira, "Estudo da fragilidade sísmica de pórticos de concreto armado com irregularidades estruturais," M. S. thesis, Unicamp, Campinas, Brasil, 2021. [Online]. Available: https://hdl.handle.net/20.500.12733/1640954.

[38] F. V. Alves and S. H. C. Santos "Abalos mapeados," *Rev. Estr*., vol. 10, pp. 29-33, 2021. [Online]. Available: http://abece.com.br/Revista_estrutura/Edicao10/FlipBook.html#p=1

[39] S. H. C. Santos and S. S. Lima, "The new Brazilian standard for seismic design," in *Proc. The 14th World Conf. on Earthquake Eng.*, Beijing, China, 2014. [Online]. Available: https://www.iitk.ac.in/nicee/wcee/article/14_08-01-0004.pdf

[40] A. E. Lopes, M. S. Assumpção, A. F. Nascimento, J. M. Ferreira, E. A. Menezes, and J. R. Barbosa, "Intraplate earthquake swarm in Belo Jardim, NE Brazil: reactivation of a major Neoproterozoic shear zone (Pernambuco Lineament)," *Geophys. J. Int.*, vol. 180, no. 3, pp. 1303–1312, 2010, http://dx.doi.org/10.1111/j.1365-246X.2009.04485.x.

[41] J. Douglas, T. Ulrich, D. Bertil, and J. Rey, "Comparison of the ranges of uncertainty captured in different seismic-hazard studies," *Seismo. Res. Letters*, vol. 85, no. 5, pp. 977-985, 2014, https://doi.org/10.1785/0220140084

[42] A. Gkimprixis, J. Douglas, and E. Tubaldi, "Seismic risk management through insurance and its sensitivity to uncertainty in the hazard model," *Nat. Hazards*, vol. 108, no. 2, pp. 1629–1657, 2021, http://dx.doi.org/10.1007/s11069-021-04748-z.

[43] R. O. O. Dantas, S. H. S. Nóbrega, and P. G. B. Nóbrega "Uma discussão prática e didática da norma brasileira NBR 15421 para o projeto de estruturas considerando ações sísmicas," in *Proc. 56º Congresso Brasileiro do Concreto*, Natal, Brazil, 2014. [Online]. Available: https://www.researchgate.net/publication/333194676

[44] J. B. Paiva Neto, P. G. B. Nóbrega, and S. H. S. Nóbrega "Avaliação da resposta sísmica de edifícios de concreto na região nordeste segundo métodos da NBR 15421," in *Proc. 58º Congresso Brasileiro do Concreto*, Belo Horizonte, Brazil, 2016. [Online]. Available: https://www.researchgate.net/publication/333194656

[45] A. Gkimprixis, E. Tubaldi, and J. Douglas, "Comparison of methods to develop risk-targeted seismic design maps," *Bull. Earthquake Eng.*, vol. 17, no. 7, pp. 3727–3752, 2019, http://dx.doi.org/10.1007/s10518-019-00629-w.

Author contributions: EMVP: conceptualization, methodology, formal analysis, visualization, writing-original draft; RBA and GHFC: funding acquisition, writing-original draft; LCMVJ and GHS: project administration, resources, writing-review.

Editors: Sergio Hampshire C. Santos, Guilherme Aris Parsekian.