XLI CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020 FOZ DO IGUAÇU PARANÁ - BRAZIL

Subsidies for the generation of artificial accelerograms

André de F. Stabile[1], Selma H. S. da Nóbrega[1], Petrus G. B. da Nóbrega[2]

[1]*Departamento de Engenharia Civil, Universidade Federal do Rio Grande do Norte*
Centro de Tecnologia, Campus Universitário, 59078-970, Natal-RN, Brasil
andrestabile1@hotmail.com, shsnobrega@gmail.com
[2]*Departamento de Arquitetura, Universidade Federal do Rio Grande do Norte*
Centro de Tecnologia, Campus Universitário, 59078-970, Natal-RN, Brasil
petrus@ufrn.edu.br

Abstract. Despite an evident relatively low seismic activity, Brazil is not free of earthquakes and the correct techniques must be used in order to design civil structures and to assess their seismic risk. NBR 15421:2006 is the Brazilian standard code for the design of seismic resistant structures and it defines four different methods for the structural analysis, depending on building location site: a simplified procedure, the equivalent horizontal forces method, the spectral method and the time-history analysis procedure. In fact, it is important to ensure strength to the structure as well as an adequate performance, what can be evaluated, for example, by the fragility curves results from the time-history analyses. However, NBR 15421 code presents only a design response spectrum and defines that input accelerograms should be compatible to this response spectrum. This paper presents an iterative computational procedure, based on stochastic structural dynamics concepts, to generate artificial accelerograms compatible with response spectra. After the methodology exposition, some applications highlighting the influence of important parameters and an example of time-history response are describe. A contribution to the technical discussion about this topic is important because the NBR 15421 revision process is coming soon.

Keywords: seismic design, response spectrum, accelerogram, earthquake.

1 Introduction

In common and usual sense, Brazil is a country free of earthquakes. Indeed, the country's geology and geographic position, in the middle of South American tectonic plate, contribute to a higher seismic stability than that presented by nearby countries. However, it is obvious, they do occur. There is one seismic acceleration map for Brazil and several studies suggest that it should be reviewed and updated (Nóbrega *et al*. [1]).

Although generally rare and presenting low magnitude, the intraplate earthquakes may cause damage, especially if they are not deep, which is their general feature in Brazil. The waves of a shallow earthquake with low magnitude may reach the surface with energy equivalent to another earthquake of great magnitude, but with a deep hypocenter, whose energy is partially dissipated in its trajectory.

In Brazil, the NBR 15421:2006 code, Design of seismic resistant structures – Procedure (ABNT [2]), is the document that sets the requirements for the seismic effects consideration in buildings. This code defines classifications, parameters, characteristic values, criteria and analysis methods. Among these methods, there are four possibilities, depending on the building location site: a simplified procedure, the equivalent horizontal forces method, the spectral method and the time-history analysis procedure.

It is really important to guarantee to the structure, in addition to the strength capacity (force-based engineering), also the adequate performance (performance-based engineering). A methodology for this purpose, for example, consists in determining the fragility curves, built from numerical analyses (static or dynamic) in models that adequately represent the behavior of the structure. For the seismic loading, obviously, the most appropriate analyses would be the dynamic ones.

However, only the latter two methods mentioned previously really consider the dynamical characteristics of the structural system. For the spectral method, NBR 15421 code presents a design spectrum response, whose details are defined according to the horizontal characteristic acceleration and the site class of the structure. For the time-history analysis procedure, however, there is no representative (real) accelerogram for Brazil, and the NBR 15421 code prescribes that the accelerogram should be compatible to the design spectrum response. That is, it is necessary to generate artificial accelerograms for the analysis of the structure.

The objective of this paper is to discuss about an iterative computational procedure to generate artificial accelerograms compatible to spectra response, based on stochastic structural dynamics concepts, and thus to make possible the time-history analysis.

2 Overview of dynamic methods defined by NBR 15421 code

2.1 Spectral method

In this section a brief exposition of the spectral method can be found, applied specifically to the NBR 15421, and a complete theoretical explanation is available at Clough and Penzien [3].

The method is based on the concept of a response spectrum, which indicates maximum absolute values of a specific response parameter for one degree of freedom (1 DOF) oscillators with varying periods. NBR 15421 establishes a design acceleration response spectrum, which is mathematically determined by eqs. (1a) to (1c). Figure 1 shows the design response spectrum.

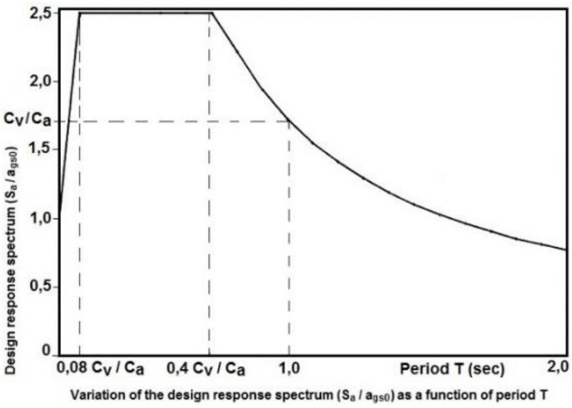

Figure 1. NBR 15421 design response spectrum (adapted from ABNT [2])

$$S_a(T) = a_{gs0}\left(18.75\,T\,\frac{C_a}{C_v} + 1.0\right) \quad for \quad 0 \le T \le 0.08\frac{C_v}{C_a}. \tag{1a}$$

$$S_a(T) = 2.5\,a_{gs0} \quad for \quad 0.08\frac{C_v}{C_a} \le T \le 0.4\frac{C_v}{C_a}. \tag{1b}$$

$$S_a(T) = \frac{a_{gs1}}{T} \quad for \quad T \ge 0.4\frac{C_v}{C_a}. \tag{1c}$$

In eqs (1), $S_a(T)$ is the spectral acceleration for a 1 DOF oscillator with period T, C_v and C_a are coefficients related to the site class (soil type) and a_{gs0} and a_{gs1} are the product of the horizontal characteristic acceleration by C_a and C_v , respectively.

A mode-superposition process should be performed using the response spectrum. The final result can be considered as a combination of a finite number of responses, each one corresponding to a simple oscillator with a natural period equal to one of the natural periods of the whole structure, determined by a modal analysis.

2.2 Time-history procedure

The time-history procedure is based on the time integration of the dynamic equilibrium equations of the analyzed structure. Many well-established numerical methods are available for that once an input accelerogram is chosen.

A hardship, however, arises when searching for such signals in Brazilian databases: they are a small number, there is no pre-defined representative accelerogram and it is difficult to access them. Moreover, a criterion imposed by NBR 15421, establishing that the adopted ground motion should have a response spectrum compatible with the code's design spectrum, limits even further the selection of natural records.

Such difficulties lead to the idea of generating artificial accelerograms, that can then be adjusted to match the design spectrum – and, consequently, a region's characteristic ground acceleration –, automatically fulfilling NBR 15421's requirements. In order to do so, an iterative procedure devoted to the generation of spectrum compatible artificial accelerograms, based on Clough and Penzien [3] and Nguyen [4], is described in the following section.

3 Artificial accelerograms generation and adjustment procedure

The chosen procedure can be divided into two distinct steps. The first one is concerned only with generating a time signal that has characteristics matching those presented by the earthquake records, using concepts of stochastic modeling. Once this task is complete the generated accelerograms are adjusted on the frequency domain by means of iteratively scaling their Fast Fourier Transforms (FFTs) in such a way that they are compatible to the design spectrum.

3.1 Signal generation

The ground motions induced by earthquakes are random phenomena, being better modelled stochastically, rather than deterministically. The procedure described in this section is based upon the work of Nguyen [4]. Its basis is the concept of a Power Spectral Density (PSD) function, that is strictly connected to the random process to be modelled. As explained by Vanmarcke [5] this function should be wide-banded, in order to correctly represent the equal contribution of different frequency components to the resulting signal.

As the starting point, a white noise – which presents constant PSD over a finite range of frequencies, up to frequency ω_{cut}, and zero value otherwise – is initially chosen. The white noise, $S(\omega)$, as a function of the angular frequency, ω, is given by eq. (2):

$$S(\omega) = S_0 \quad for \quad 0 \leq \omega \leq \omega_{cut}. \tag{2}$$

The constant S_0 is evaluated via a limit, and an approximate closed form expression for its numerical evaluation can be found in Clough and Penzien [3]. This initial estimate of the PSD is filtered twice – by the Kanai-Tajimi and the Clough & Penzien filters. The first one takes into account specific soil conditions related to the analysis site. A detailed explanation on how to determine its parameters is given in Rofooei *et al.* [6]. The second one has mainly mathematical purposes, and is used to filter very low frequencies in $S(\omega)$, which, in turn, eliminates possible drifting problems that could arise when integrating the generated accelerogram. From this point onward the notation $S(\omega)$ will refer to the filtered process.

The time function $a^*(t)$, given by eq. (3), with coefficients determined by eq. (4), has power spectral density function corresponding to $S(\omega)$ and, therefore, features resembling those of earthquakes.

$$a^*(t) = \sum_{i=1}^{n} C_i \; cos(\omega_i t + \phi_i)\,. \tag{3}$$

$$C_i = \sqrt{2S(\omega_i)\Delta\omega}. \tag{4}$$

In eqs. (3) and (4) n represents the total number of harmonic components adopted to describe the process, ω_i represents the angular frequency of the i-eth harmonic component, $\Delta\omega$ is the angular frequency discretization step, C_i describes the amplitude of the i-eth harmonic component and ϕ_i are randomly chosen phase angles with constant probability density function in the interval $[0,2\pi)$.

Lastly, in order to represent the non-stationary characteristic of earthquake motions, an envelope function, $\gamma(t)$, such as the one proposed by Jennings *et al.* [7] – which has its shape depicted in Fig. 2 –, is multiplied by the generated signal, giving rise to the final artificial accelerogram, $a(t)$.

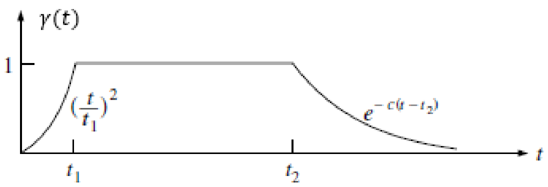

Figure 2. Jennings, Housner and Tsai envelope function (adapted from Clough and Penzien [3])

3.2 Adjustment procedure

The first step should be the normalization of the artificial accelerogram $a(t)$ to match the design spectrum's Peak Horizontal Acceleration (PHA), that is defined as the greatest horizontal acceleration to which the ground is subjected during an earthquake. This can easily be done by finding the maximum absolute value of $a(t)$ and multiplying the whole signal by the rate between this value and the PHA. Since the adjustment procedure is an iterative one, the normalized accelerogram will be hereby denoted $a^{(0)}(t)$, and its FFT by $A^{(0)}(i\omega)$. Another important parameter is the artificial acceleration response spectrum $S_a^{(0)}(\xi_d, T)$, where ξ_d represents the design damping ratio, prescribed as 5% by NBR 15421.

The actual adjustment begins after this step. It is possible to define the function $R^{(0)}(T)$ as the rate between the calculated artificial response spectrum, $S_a^{(0)}(\xi_d, T)$, and the design response spectrum, $S_a(T)$. Then, since there is a unique relation between T and ω, it is possible to scale the original FFT, $A^{(0)}(i\omega)$, obtaining an updated FFT, $A^{(1)}(i\omega)$. Taking the inverse FFT gives the updated accelerogram $a^{(1)}(t)$.

The procedure continues iteratively. In general, the expressions for the rate function and the updated FFT on the i-eth iteration are given by eq. 5:

$$A^{(i)}(i\omega) = \frac{S_a^{(i-1)}(\xi_d, \omega)}{S_a(\omega)} A^{(i-1)}(i\omega). \tag{5}$$

$S_a^{(i-1)}(\xi_d, T)$ denotes the acceleration spectrum determined on iteration i-1 with the specified design damping ratio. The updated accelerogram for iteration i can be obtained by inversing the FFT $A^{(i)}(i\omega)$.

The procedure should be repeated until the desired convergence is attained. The only criterion prescribed by NBR 15421 related to such convergence states that the artificial spectrum should not be inferior to the design one in a zone ranging from 0.2T to 1.5T, where T denotes the fundamental period of the studied structure. Figure 3 presents a flowchart summarizing the procedure. The green items are associated to tasks performed by a computational code that will be described in next section and white ones represent the user input.

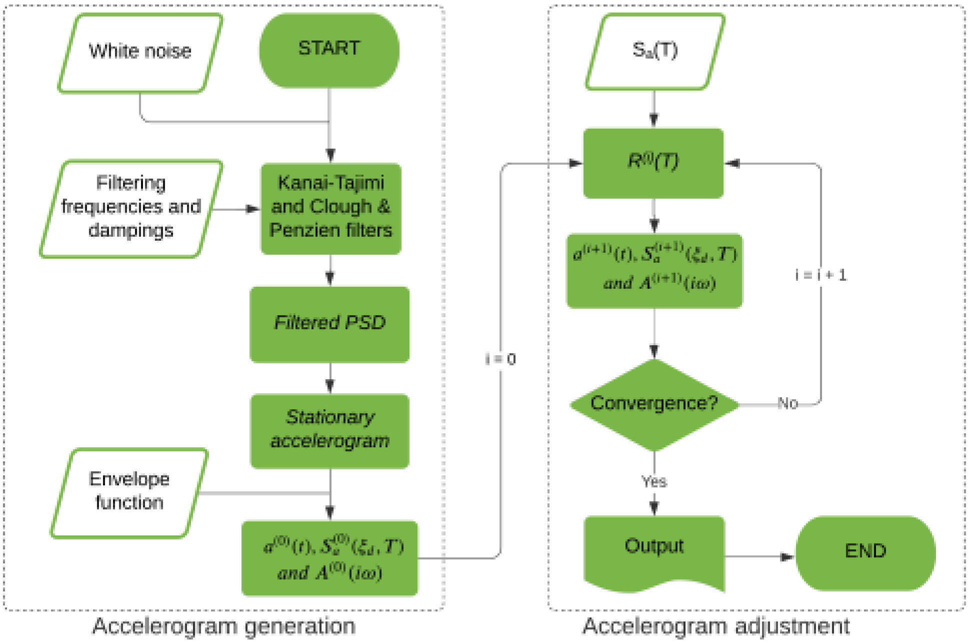

Figure 3. Flowchart of the described procedure

4 Application

This section's purpose is to exemplify the above-mentioned procedure and to discuss and clarify the effect of some relevant parameters in the generated accelerograms/spectra.

In order to determine the design spectrum to be matched, a region in the middle of the state of Rio Grande do Norte, in Brazil, was selected. A ground acceleration of $a_{gs} = 0.04g$, obtained by interpolation from the values prescribed by NBR 15421, was determined for this zone and it was supposed a type B site (rock). Taking this into account, the site class coefficients are determined as $C_v = C_a = 1.0$, which, in turn, leads to $a_{gs0} = a_{gs1} = 0.04g$. This spectrum, determined by eqs. (1), is plotted in Fig. 4 and will be referred to as the target spectrum.

For the generation of the artificial accelerograms, the software Code_Aster (version 14.4) was used, a program developed by Électricité de France (EDF) for the analysis of structures and thermomechanics based on the Finite Element Method, distributed under a GNU General Public License. It has an artificial accelerograms generator and follows the same procedure as described in this paper.

4.1 Convergence of the adjusted accelerogram

To analyze the influence of the number of iterations on the convergence towards the target spectrum, artificial accelerograms adjusted by 5, 10, 15 and 20 iterations, as well as the not adjusted one, were generated.

A convergence indicator was defined as the sum of the square of the difference between the target spectrum and the spectrum associated with an artificial accelerogram at each point in which it was calculated. Its value is shown for each one of the accelerograms in Tab. 1.

Table 1. Adjustment indicator as a function of the number of iterations

Iterations	None	5	10	15	20
Indicator (m^2/s^4)	0.1928	0.0347	0.0199	0.0158	0.0131

It can be noted that, as the number of iterations increases, the indicator value decreases rapidly at first and tends to a limit when reaching around 15 to 20 iterations. Figure 5 shows the convergence between the target spectrum and the ones for no adjustment, 10 and 20 iterations.

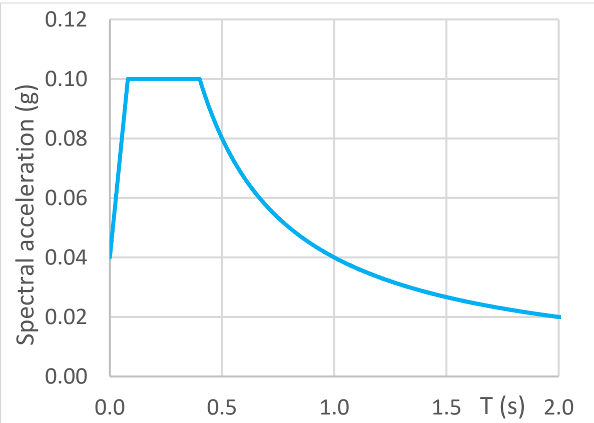

Figure 4. Target (design) spectrum

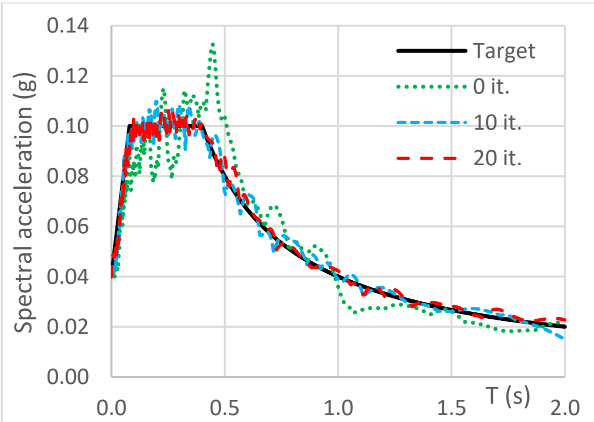

Figure 5. Influence of the number of iterations in spectrum convergence

4.2 Clough & Penzien filtering frequency

When applying the Clough & Penzien filter it is important to correctly choose the filtering frequency. A very low frequency would not correct the drifting effect, but, conversely, a too high frequency would remove not only the drift, but also most of the low frequency content of the signal.

With the purpose of assessing the influence of the chosen Clough & Penzien's filtering frequency on the ground displacement at the end of the analysis period, a parametric study is carried out. Values of frequency varying from 0 to 0.150 Hz at a rate of 0.025 Hz were taken into account.

Table 2 shows the final ground displacement, obtained by double integration of the generated accelerograms, for these frequency values. For all accelerograms twenty iterations were performed in the adjustment procedure.

Table 2. Final ground displacement as a function of Clough & Penzien's filtering frequency

Frequency (Hz)	None	0.025	0.050	0.075	0.100	0.125	0.150
Final displacement (m)	0.18974	0.05668	0.01316	0.01097	0.00131	0.00097	0.00005

The frequency value associated to a chosen final displacement tolerance can be regarded as the best option. From Tab. 2, this value can be determined to be around 0.1 Hz. Figures 6 and 7 display the ground displacement time-history when the Clough & Penzien filter is not applied and when a 0.1 Hz filtering frequency is used.

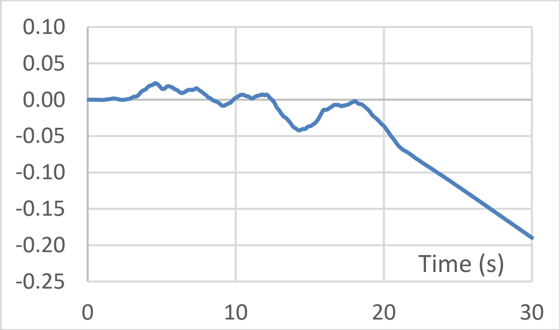

Figure 6. Ground displacement (m) without filtering effect

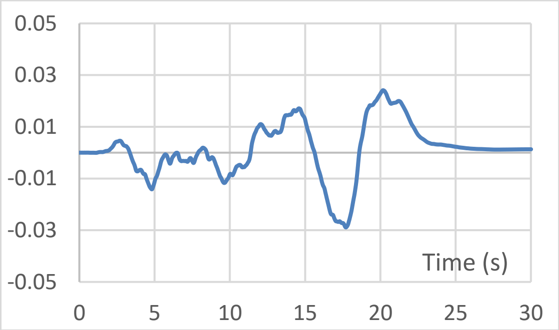

Figure 7. Ground displacement (m) with a 0.1 Hz Clough & Penzien filter

4.3 Envelope function

Lastly, the effect of Jennings, Housner and Tsai envelope function, whose form of application was described in section 3.2, is examined. Figure 8 shows an accelerogram generated without taking it into account, while Fig. 9 uses a function that has $t_2 - t_1 = 15s$ (refer to Fig. 2), that measures the strong motion duration. A better explanation of this parameter can be found in Kramer [8].

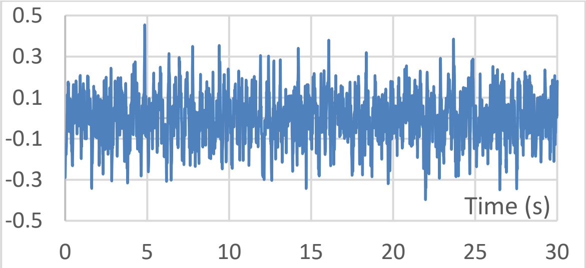

Figure 8. Ground acceleration (m/s²) without the effect of the envelope function

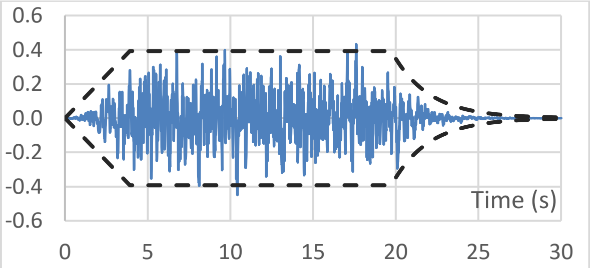

Figure 9. Ground acceleration (m/s²) with an envelope function and strong motion duration of 15s

From the figures it can be observed that the envelope function prevents the strong phase of the ground motion from starting instantly, at time $t = 0$. The parameters t_1 and t_2 should be calibrated so that the strong motion duration of the artificial accelerogram matches that related to real earthquakes in the studied site. For the interested reader, a number of empirical correlations can be found in specific literature, e.g. Dobry *et al.* [9].

It can also be remarked that the maximum absolute value of displacement slightly exceeds the PHA. This happens as an effect of the adjustment and, as stated by Clough and Penzien [3], the final accelerogram should not be further normalized to the design spectrum acceleration level.

4.4 Analysis result

In order to contribute to a better understanding of the seismic analysis, a reinforced concrete chimney structure, presented by Franco and Medeiros [10], was analyzed. Its height is 113m, with external and internal diameters approximately equal to 5.4 m and 4.7 m, respectively. The total weight is 1068 tf, and the damping ratio is 5%. Other geometrical and material properties can be found in the reference.

The transitory analyses considered twenty transient cases with artificial accelerograms corresponding to the normative spectrum. Twelve vibration modes associated to an accumulated modal mass of slightly above 90% were used. Figure 10 shows the displacement time-history obtained for the top of the chimney structure, what cannot be acquired by the Spectral method.

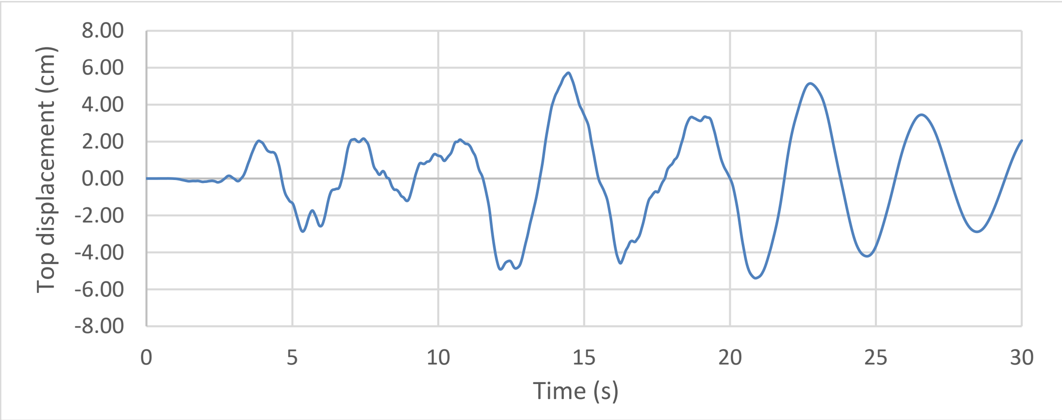

Figure 10. Chimney structure top displacement time-history

5 Conclusion

A procedure for the generation of artificial accelerograms, as well as their adjustment to match a target spectrum, based on an initial estimate of the ground motion, determined by a filtered white noise, and its adjustment through scaling in the frequency domain was presented.

Applications related to the NBR 15421 design spectrum were made, highlighting the influence of important features of the procedure. Namely, the effect of the number of iterations to achieve convergence between the design response spectrum and the artificially generated one, as well as the influence of the low frequency filter were studied. The importance of the envelope function was also exemplified.

Main results consist in an optimal number of iterations found to be ranging between 15 and 20 iterations and an ideal filtering frequency to be about 0.1 Hz.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] P. G. B. Nóbrega, et al. Sobre os mapas de perigo sísmico para o projeto de estruturas. In: *Congresso Brasileiro do Concreto, 61*. Fortaleza: IBRACON, 2019. Available at: https://www.researchgate.net/publication/336672092.

[2] ABNT Associação Brasileira de Normas Técnicas. *NBR 15241:2006: Projeto de estruturas resistentes a sismos – Procedimento*. ABNT: Rio de Janeiro, 2006.

[3] R. W. Clough and J. Penzien. *Dynamics of Structures.* McGraw-Hill, 1993.

[4] A. T. Nguyen. *Analyse systématique du concept de comportement linéaire équivalent en ingénierie sismique.* PhD thesis, Université Paris-Est, 2017. Available at: https://www.researchgate.net/publication/324886830.

[5] E. H. Vanmarcke, "Structural response to earthquakes". In: C. Lomnitz and E. Rosenblueth (ed.), *Seismic Risk and Engineering Decisions*, pp. 287-337

[6] F. R. Rofooei, A. Mobarake, G. Ahmadi. Generation of artificial earthquake records with a nonstationary Kanai-Tajimi model. *Engineering Structures*, vol. 23, pp. 827-837, 2001. DOI: 10.1016/S0141-0296(00)00093-6.

[7] P. C. Jennings, G. W. Housner and N. C. Tsai. Simulated earthquake motions. *Technical Report.* Earthquake Engineering Research Laboratory, 1968. Available at: https://resolver.caltech.edu/CaltechEERL:1968.EERL.1968.001.

[8] S. L. Kramer. *Geothecnical Earthquake Engineering*. Prentice Hall, 1996.

[9] R. Dobry, I. M. Idriss, E. Ng. Duration characteristics of horizontal components of strong-motion earthquake records. *Bulletin of the Seismological Soceiety of America*, vol. 68, n. 5, pp. 1487-1520, 1978. Available at: https://pubs.geoscienceworld.org/ssa/bssa/article-abstract/68/5/1487/117840/

[10] M. Franco, S. R. P. Medeiros. O método do "vento sintético" – Novas considerações. *TQSNews*, n. 33, pp. 38-46, 2011.