Life-Cycle of Structures and Infrastructure Systems

Editors

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LIFE-CYCLE OF STRUCTURES AND INFRASTRUCTURE SYSTEMS

Life-Cycle of Structures and Infrastructure Systems collects the lectures and papers presented at IALCCE 2023 - The Eighth International Symposium on Life-Cycle Civil Engineering held at Politecnico di Milano, Milan, Italy, 2-6 July, 2023. This Open Access Book contains the full papers of 514 contributions, including the Fazlur R. Khan Plenary Lecture, nine Keynote Lectures, and 504 technical papers from 45 countries.

The papers cover recent advances and cutting-edge research in the field of life-cycle civil engineering, including emerging concepts and innovative applications related to life-cycle design, assessment, inspection, monitoring, repair, maintenance, rehabilitation, and management of structures and infrastructure systems under uncertainty. Major topics covered include life-cycle safety, reliability, risk, resilience and sustainability, life-cycle damaging processes, life-cycle design and assessment, life-cycle inspection and monitoring, life-cycle maintenance and management, life-cycle performance of special structures, life-cycle cost of structures and infrastructure systems, and life-cycle-oriented computational tools, among others.

This Open Access Book provides both an up-to-date overview of the field of life-cycle civil engineering and significant contributions to the process of making more rational decisions to mitigate the life-cycle risk and improve the life-cycle reliability, resilience, and sustainability of structures and infrastructure systems exposed to multiple natural and human-made hazards in a changing climate. It will serve as a valuable reference to all concerned with life-cycle of civil engineering systems, including students, researchers, practitioners, consultants, contractors, decision makers, and representatives of managing bodies and public authorities from all branches of civil engineering.

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Life-Cycle of Structures and Infrastructure Systems

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Seismic safety assessment of "Palácio do Itamaraty" at Brasília reliability-based

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ABSTRACT: In Brasilia (Brazil) heritage buildings have been designed without considering seismic loads. The aim of the paper is to assess seismic behavior of reinforced concrete structure of "Palácio do Itamaraty". In this study, Monte Carlo simulation technique is implemented in Hirosawa method to examine structural level of safety. Reliability indexes for each floor are estimated and comparisons to target reliability indexes are made. The sensitivity of different input variables is also studied. Seismic indexes of structure for each floor remained greater than seismic demand indexes in all Brazilian seismic zones through Hirosawa method. Despite of, inadequate reliability indexes is noticed in all floor, which implies that structure is not enough to guarantee an adequate performance. Sensitivity analysis shows the influence of irregularity of structure in seismic response. The results highlight the importance of a probabilistic approach by Hirosawa Method to assertive decisions of conservation and rehabilitation of architectural heritage subject to seismic hazards.

1 INTRODUCTION

The "Palácio do Itamaraty" in Brasilia is a symbol of modern architecture designed by the architect Oscar Niemeyer. The headquarter of Ministry of Foreign Affairs of Brazil was opened in 1970 and from a structural point of view the building is carried by a sequence of reinforced concrete frames with floors and the span of the slab is quite large. Once this historic heritage owns architectural and historic relevance it must be preserved and conserved (ICCOMOS, 2013).

Due to low seismicity in Brazil, "Palácio do Itamaraty" was not designed to withstand seismic loads and few researchers have evaluated seismic vulnerability of Brazilian buildings. Nevertheless, increasing of seismic hazard in localized areas have been recorded (Petersen et al. 2018). Miranda (2021) developed an exhausted study of structures from Brazilian city with high seismicity. In this context, the purpose of the present work is to evaluate the seismic performance of "Palácio do Itamaraty" in a probabilistic approach. Assessment is carried out by Hirosawa method adopted by Japan Building Disaster Prevention Association (JBDPA) and adapted to Brazilian reality (Miranda, 2013). The uncertainties involved in the problem are taken into account by Monte Carlo simulation implemented in Hirosawa Method.

Japanese Seismic Index Method or Hirosawa Method has been used to evaluate seismic performance of existing reinforced concrete buildings with less than six stories (Calvi et al, 2009). Pan American Health Organization adjusted this methodology and have implemented in Latin America, mainly in Chile, Peru, Mexico and Ecuador (PAHO, 2000). Ozdemir et at (2005) proposed an adaptation and calibration to Turkish buildings using nonlinear static analyses of 12 buildings. Letelier & Parodi (2021) analyzed a sample of 116 buildings in Chile comparing their real behavior during the 2010 earthquake with seismic performance specified by Hirosawa method.

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2 SEISMIC ASSESSMENT

In first level of procedure, Hirosawa method seeks to evaluate the strength of a story on the basis of average stresses and the cross-sectional area of columns without demanding for ductility (Hiroyuki, 1981). The seismic index I_S for the total earthquake resisting capacity of a story is defined by the product of three indices (1): basic seismic index E_0, irregularity index S_D and time index T_D.

$$I_S = E_0 \cdot S_D \cdot T_D \tag{1}$$

and E_0:

$$E_0 = \left(\frac{n+1}{n+i}\right) \cdot a_1 \left[\frac{f_c}{20} \cdot \frac{\tau_c \cdot A_c)}{W}\right] \cdot F_c \tag{2}$$

where n = number of stories of a building, i = number of the story for evaluation, W = total weight, A_c = total cross-sectional area of columns in the story studied, τ_c = average shear stress at the ultimate state of columns, which may be taken as 7 kgf/cm^2 and F_c = ductility index of columns which may be taken as 1.0, a_1 = effective strength factor of the columns and should be taken as 1.0. The influence of the deterioration is taken into account in the index T_D varying from 0.7 to 0.8 according to inspection of the building (Hirosawa, 1992). For more advanced model see Biondini & Bianchi (2019). The methodology also estimates another index: seismic demand index of structure I_{S0} and should be calculated by eq. 3 regardless of the story building.

$$I_{S0} = E_S \cdot Z \cdot G \cdot U \tag{3}$$

where E_S = basic seismic demand index of structure, Z = zone index namely factor accounting for the seismic activities in the region of the site, G = ground index and considers the effects of the amplification of the surface soil and geological conditions and usage index (U) contemplates the use of the building. Seismic safety of structure shall be judged by $I_S > I_{S0}$. If this inequation is satisfied the building possess the seismic capacity required against the considered earthquake motions (JBDPA, 2001).

3 RELIABILITY ANALYSIS

3.1 *Probability of failure and reliability index*

According to Holicý & Vruouwenvelder (2005) one of the most important term in the theory of structural reliability is the probability of failure p_f Structural behavior may be defined as the set of basic variables $\mathbf{X} = [X_1, X_2, \cdots, X_n]$ and limit state is given by the limit state function and It is defined as g(**X**) **= 0.** In general, probability of failure p_f (4) remains below a given target probability. The failure is defined when a limit state is reached i.e. solicitation S exceeds resistance R. Probability of violation of limit state may be expressed as:

$$p_f = P\{g(X) \leq 0\} = \int \cdots \int_{g(X) \leq 0} f_X(x)dx < p_{target} \tag{4}$$

where $f_X(x)$ is the probability density function for the randomic variable X. Commonly reliability is quantified in terms of index of reliability:

$$\beta = -\Phi^{(-1)}(p_f) \tag{5}$$

where $\Phi^{-1}(\cdot)$ = inverse normal distribution. For system in series involving multiples mode of failure, Equation 6 demonstrates failure probability of system composed of m members and then probability of survivor in Equation 7:

$$p_f = P(F_1 \cup F_2 \cup F_3 \cup \cdots \cup F_m) \tag{6}$$

$$p_s = P\left(\bigcap_{i=1}^{m} G_i(X) \geq 0\right) = \int_{\bar{D}} \cdots \int f_X(x)dx \tag{7}$$

where $\overline{D}: \ \overline{F}_1 \ \cap \ \overline{F}_2 \cap \ \overline{F}_3 \cap \ \cdots \cap \overline{F}_m$ is the region or mode of survivor. A numerical approach is required and reliability analysis can be performed by Monte Carlo simulation (Melchers. 2001) where repeated analyses are carried out with random outcomes of the basic variables X generated in accordance to their marginal density function $f_{X_i}(x_i), \ i = 1, \ldots, \ n.$

3.2 *Target reliability level*

The Probabilistic Model Code (2001) suggests target reliabilities for the ultimate limit state considering several consequence classes and cost of safety measures (Table 1).

Table 1. Target reliabilities considering one year reference period according to JCSS (2001).

	Consequences of failure		
Relative cost of safety measure	Minor	Moderate	Large
Large	$\beta = 3.1$	$\beta = 3.3$	$\beta = 3.7$
Normal	$\beta = 3.7$	$\beta = 4.2$	$\beta = 4.4$
Small	$\beta = 4.2$	$\beta = 4.4$	$B = 4.7$

4 SENSITIVITY ANALYSIS

In order to determine the most contributing input variable to an output behavior in Hirosawa Method or even ascertain some interactions effects within the model Sensitivity Analysis are need (Ioss & Lemaitre, 2015). SA allows to verify how the model responses varies when the input parameters of the model vary (Marelli et al, 2017). Also, how the uncertainty in the input of a model can be apportioned to different sources of uncertainty in the model input (Saltelli et al. 2000). There are several methods to evaluate sensitivity, the most complete and most costly is Morris Method that consists in discretizing input space for each variable and then performing a giving number of one at a time design allowing to classifying inputs in groups of having negligible effects, inputs having large linear effects without interactions and. Morris method offers two sensitivity measures for each factor (8, 9): μ estimates the overall effect of the factor on the output and σ that measures nonlinearity and interaction effects of the input factor.

$$\mu_j = \frac{1}{r}\sum\nolimits_{i=1}^{r}\left|E_j^{(i)}\right| \tag{8}$$

$$\sigma_j = \sqrt{\frac{1}{r}\sum\nolimits_{i=1}^{r}\left(E_j^{(i)} - \frac{1}{r}\sum\nolimits_{i=1}^{r} E_j^{(i)}\right)^2} \tag{9}$$

5 APPLICATION

5.1 *Structural model*

The building is characterized by a squared plan with sides measuring about 84 m (Figure 1). The overall building height is about 14 meters. The three-story RC structure is composed of beam span of 6.0 m, 18.0 m and 36.0 m. The nominal material strength is $f_c = 40 MPa$ for concrete in compression. Beams depth varies depending on the floor between 40 cm to 120 cm and width also varies between 8 cm to 400 cm. The free interstory height differs in each story. For first floor height is 2.88 m, the second one is 3.50 m and the last one is 4.82 m. The geometry of cross-section varies in both shapes: trapezoid and rectangular. The structural modelling of "Palácio do Itamaraty" is exhibited in Figure 2.

Figure 1. The external view of the "Palácio do Itamaraty".

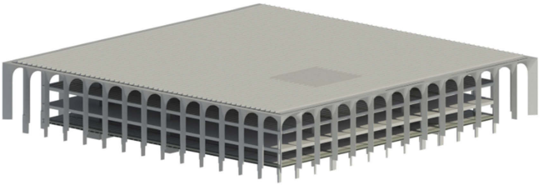

Figure 2. Structural model of the "Palácio do Itamaraty".

5.2 *Deterministic assessment*

Analysis of the seismic behavior of the structure were developed first in a deterministic approach of Hirosawa Method. The period of the structure is about 0.4765 second. Seismic index of each floor was estimated and a summary of information are presented in Table 2 and Table 3.

Table 2. Summary of input variables related to the floor 1 and 2 of "Palácio do Itamaraty".

	Floor 1	Floor 2
Level of floor	+0.00	+3.60
Weight of the building upper the story (W) in kgf	18298435.02	14646983.91
Floor area in m²	5774.30	4424.28
Sum of cross-sectional area of column (Ac) in cm²	380800.00	418200.00
Fundamental Period (Ta) in seconds	0.4765	0.4765
Basic seismic index of structure E_0	0.6474	0.7448
Irregularity Index S_D	1.2	1.14
Time Index T_D	0.7	0.7
Seismic index of Structure I_S	0.6215	0.6792

Note that seismic indices of first, second and fourth are increasing owing to basic seismic index E_0. This index takes in account cross sectional area of column and as the weight of the building upper the story decreases, the index E_0 increases. As presented in Table 3 cross sectional area reduces in third floor and impacts in index E_0. The lower value of seismic index $I_S = 0.6215$ is applied to all structure. Even though detailed inspection indicated the time index T = 0.8 due to the fact the age of building is upper to 30 years, it was considered the minimum

Table 3. Summary of input variables related to the floor 3 and 4 of “Palácio do Itamaraty”.

	Floor 1	Floor 2
Level of floor	+7.82	+13.24
Weight of the building upper the story (W) in kgf	11002432.15	773435.97
Floor area in m²	5342.28	6649
Sum of cross-sectional area of column (Ac) in cm²	401200.00	326200.00
Fundamental Period (Ta) in seconds	0.4765	0.4765
Basic seismic index of structure E_0	0.8154	0.8254
Irregularity Index S_D	1.14	1.14
Time Index T_D	0.7	0.7
Seismic index of Structure I_S	0.7436	0.7527

value in method T = 0.7. A class E soil is considered in this study. The seismic demand index of “Palácio do Itamaraty” concerning seismic activities in the Brasilia is estimated about I_{S0} = 0.08. Regarding the region with moderate seismic activity in Brazil (State of Ceará) the seismic demand index I_{S0} = 0.3922 still satisfies inequation $I_S > I_{S0}$. To describe the seismic index I_S for every floor, surfaces of seismic response are developed. Figure 3 presents seismic index I_S versus Irregularity Index S_D and Time Index T_D related to first floor.

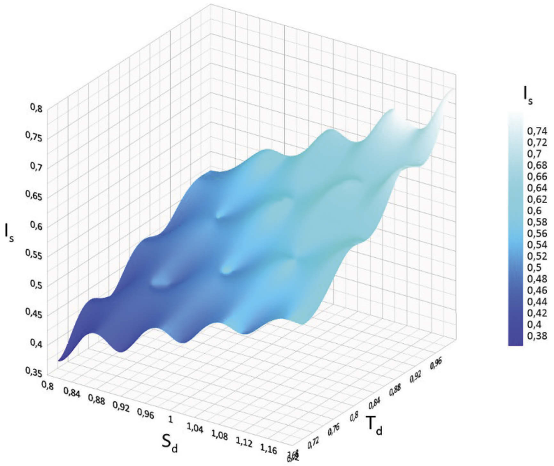

Figure 3. Surface of seismic index I_S.

5.3 *Numerical simulation and reliability assessment*

The assessment of seismic performance is based on probabilistic model assuming W, dead load, as normally distributed random variable (Ellingwood et al. 1982) and concrete compressive strength f_c is considered lognormal distributed random variable (Table 4). The time index (T_D) and irregularity index (S_D) is taken as random variable uniformly distributed between the values λ_{min} = 0.7 and λ_{max} = 1.0 and values λ_{min} = 0.4 and λ_{max} = 1.2, respectively.

Figure 4 exhibits reliability indices $\beta = -\Phi^{-1}(p_f)$ for each floor (SC 00 – Scenario 00). It is worth noting that lower probability of failure is detected in fourth floor $P_F \approx 0.0133$ and the elevated failure probability is found in first floor. The relation between dead load of structure and cross-sectional area of floor influences in reliability index. The number of simulation (n = 300.000) has been properly chosen in order to detect probability of failure. Comparing every single floor reliability index theses values are lower than the recommended limits provided by JCSS (Table 5). Even regarding three different scenarios (SC 01, SC 02 and SC 03) where time index T_D was set constant for each floor (Table 6) structure of “Palacio do Itamaraty” depicts inadequate probability of failure. For the scenario 01, β decreased when T_D was reduced to the minimum.

Table 4. Probability distribution and their parameters (mean value $\boldsymbol{\mu}$ and standard deviation $\boldsymbol{\sigma}$).

Random variables	Distribution type	μ	σ
Concrete Strength $\boldsymbol{f_c}$	Lognormal	6.0998	0.0998
Dead Load W	Normal	1.05**W**	0.10 μ
Cross-Sectional Area Ac	Normal	381600	39972.99

Table 5. Reliability indices for each floor.

β	Floor	Probability of Failure
1.6955	1^{st}	0.0450
1.9885	2^{nd}	0.0234
2.1596	3^{rd}	0.0154
2.2179	4^{th}	0.0133

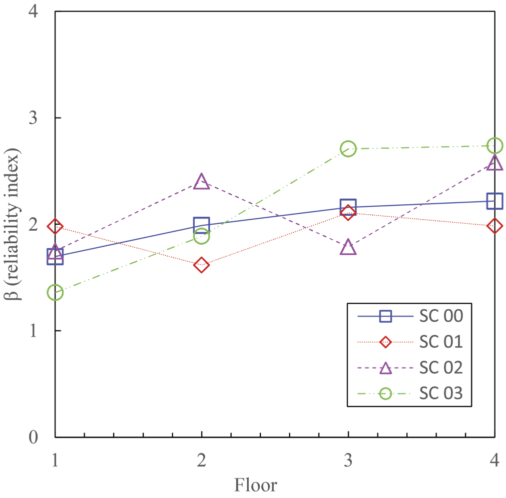

Figure 4. β versus floor of building.

Table 6. Reliability indices with T_D for each floor set constant.

	Scenario 01		Scenario 02		Scenario 03	
Floor	Time index T_D	β	Time index T_D	β	Time index T_D	β
1^{st}	0.95	1.9784	0.85	1.7474	0.7	1.3590
2^{nd}	0.7	1.6167	1.0	2.4035	0.8	1.8874
3^{rd}	0.8	2.1072	0.7	1.7886	1.0	2.7075
4^{th}	0.75	1.9834	0.95	2.5814	1.0	2.7370

The sensitivity of seismic behavior obtained from the model with respect to the uncertain input variables are presented in Figure 5. It can be seen that the most influential basic variable in this analysis is the irregularity index (S_D) that quantifies the effect of the shape, complexity and the stiffness unbalance distribution and also followed by the concrete strength (fc), cross-sectional area (Ac), weight (dead load W), Time Index (T_D). It is also observed that model linearly depends on the inputs and there is no input interaction once $\sigma_j \ll \mu_j^* \forall j$.

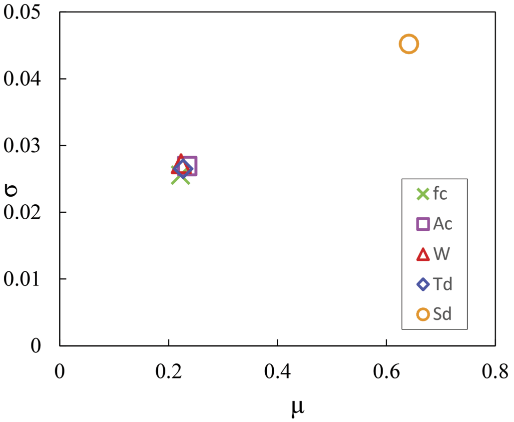

Figure 5. Sensitivity of seismic index.

6 CONCLUSIONS

A probability-based approach to qualitative assessment of seismic behavior of existing building has been presented. This approach considering uncertainties related to the materials and load was implemented in Hirosawa Method. Furthermore, the sensitivity of seismic behavior of structure regarding the basic variables was studied. It has been showed that “Palácio do Itamaraty” do not possess the seismic capacity required against the considered earthquake motions once seismic index of structure is lower to seismic demand index.

The unacceptable failure probability is noticed in all floor, which implies that the structure is not enough to guarantee an adequate performance. Moreover, Sensitivity analysis showed the influence of irregularity of building in the seismic response of structure by Hirosawa Method followed by cross-sectional area, deterioration, total weight of structure and concrete strength.

The results showed that small contraction in total cross section area columns of third floor did not affect reliability index. In contrast constant time index modified directly probability of failure and since the level of deterioration was low, the reliability expanded but still remained below JCSS target reliabilities. Though Hirosawa Method structure of “Palácio do Itamaraty” has acceptable performance against seismic load because was established the lower importance factor and risk category of building (category I) referring to buildings that represent a low risk to human life in the event of failure. Thereby if it alters category of risk the seismic demand index will be upper than seismic index of structure and meet the reliability indices.

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