COMPUTATIONAL IMPLEMENTATION FOR SEISMIC ASSESSMENT OF EXISTING STRUCTURES

IMPLEMENTAÇÃO COMPUTACIONAL PARA AVALIAÇÃO SÍSMICA DE ESTRUTURAS EXISTENTES

IMPLEMENTACIÓN COMPUTACIONAL PARA LA EVALUACIÓN SÍSMICA DE ESTRUCTURAS EXISTENTES

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Abstract
Increasing of seismic record in Brazil resulted in first Brazilian code of seismic NBR 15421:2006. Once publication succeed Brazilian sample building assessment must be developed in order to prevent or mitigate effects of horizontal accelerations from seismic. For preliminary screening of existent reinforced concrete structures qualitative Hirosawa method seems to be suitable to Brazilian reality. This paper aims to implement computationally seismic vulnerability assessment method in order to optimize assessments through opensource SMath Solver and programming language is C#. Adapted Hirosawa method compares resistance of building through seismic index of structure \( I_S \) and Seismic demand index \( I_{S0} \). Index \( I_S \) is a product of indexes (Basic seismic index of structure, Irregularity index, Time index) and index \( I_{S0} \) is formed by zone index, ground index and usage index. Model structure proposed by literature are analyzed in different levels of seismic acceleration as well as types of soil defined by Brazilian seismic code in order to demonstrate usability of tool. Graphical interface and results obtained from the application are showed aiding in decision-taking about new refined assessments or feasible interventions.

Keywords: Seismic vulnerability; Adapted Hirosawa method; Seismic-V; reinforced concrete structure.

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Computational Implementation for Seismic Assessment of Existing Structures

Resumo
O aumento do registro sísmico no Brasil resultou no primeiro código brasileiro de registro sísmico NBR 15421:2006. Uma vez concluída a publicação, deve-se desenvolver uma avaliação do edifício amostral brasileiro, a fim de prevenir ou mitigar os efeitos das acelerações horizontais decorrentes de abalos sísmicos. Para a triagem preliminar de estruturas de concreto armado existentes qualitativo Hirosawa método parece ser adequado para a realidade brasileira. Este artigo tem como objetivo implementar o método computacional de avaliação de vulnerabilidade sísmica, a fim de otimizar as avaliações através do OpenSource SMath Solver e a linguagem de programação é C#. O método de Hirosawa adaptado compara a resistência da construção através do índice sísmico da estrutura I_S e do índice de demanda sísmica I_S0. O índice I_S é um produto de índices (índice sísmico básico de estrutura, índice de irregularidade, índice de tempo) e o índice I_S0 é formado por índice de zona, índice de solo e índice de uso. A estrutura do modelo proposta pela literatura é analisada em diferentes níveis de aceleração sísmica, bem como tipos de solo definidos pelo código sísmico brasileiro, a fim de demonstrar a usabilidade da ferramenta. A interface gráfica e os resultados obtidos com o aplicativo são mostrados auxiliando na tomada de decisões sobre novas avaliações refinadas ou intervenções viáveis.

Palavras-chave: Vulnerabilidade sísmica; método Adaptado de Hirosawa; Sísmica-V; estrutura de concreto armado.

Resumen
El aumento del registro sísmico en Brasil resultó en el primer código sísmico brasileño NBR 15421:2006. Una vez que la publicación tenga éxito, se debe desarrollar la evaluación de la construcción de muestras brasileñas para prevenir o mitigar los efectos de las aceleraciones horizontales de los sísmicos. Para el examen preliminar de las estructuras de hormigón armado existentes, el método cualitativo de Hirosawa parece ser adecuado para la realidad brasileña. Este trabajo tiene como objetivo implementar el método de evaluación de vulnerabilidad sísmica computacional con el fin de optimizar las evaluaciones a través de OPENSOURCE SMath Solver y el lenguaje de programación es C#. El método de Hirosawa adaptado compara la resistencia de construcción a través del índice sísmico de la estructura I_S y el índice de demanda sísmica I_S0. El índice I_S es un producto de los índices (índice sísmico básico de estructura, índice de irregularidad, índice de tiempo) y el índice I_S0 está formado por el índice de zona, el índice de suelo y el índice de uso. La estructura del modelo propuesto por la literatura se analiza en diferentes niveles de aceleración sísmica, así como en los tipos de suelo definidos por el código sísmico brasileño con el fin de demostrar la usabilidad de la herramienta. Se muestra la interfaz gráfica y los resultados obtenidos de la aplicación que ayudan en la toma de decisiones sobre nuevas evaluaciones refinadas o intervenciones factibles.

Palabras clave: Vulnerabilidad sísmica; método de Hirosawa Adaptado; Sísmica-V; estructura de hormigón armado.

1. Introduction
1.1 Seismicity in Brazil

Seismicity in Brazil in general derives from reactivation of faults or even the creation of new ones due to strength of compression where south America is...
Subjugated. Particularly earthquakes recorded have magnitude lower than 5 except some occurrences. It is known earthquake depends on hypocenter, ground type and structures under magnitude 5.0 may suffer potential damage or loss of lives. In Brazil in 2022 was recorded to 111 km in southwest of city of Taraucá (State of Acre) an earthquake with depth of focus 621.9 km and magnitude 6.5. Looking for reducing damage in structures and mainly to avoid total or partial collapse that hinders rescue and due to international requirements, it was published in 2006 first Brazilian code of seismic NBR 15.421: Design of Seismic Resistant Structures [2]. Seismicity regions are geographic area with similar seismic activity defined in Brazilian code vary from 0 to 4 regions being the last one high region seismicity noticed in northeast of Brazil. Nonetheless major geographic area of Brazil is seismicity region 0, earthquake up to 5 have been recorded in State of Mato Grosso and São Paulo as reminded by Parisenti [3]. Figure 1 illustrates map of seismic acceleration in horizontal direction proposed by code NBR 15.421.

About Brazilian Samples Building is crucial to known seismic vulnerability once designs were developed without considering seismic actions. In order to achieve, qualitative methods are suggested to a rapid visual screening of sample
Building to identify level of safety. Hirosawa Method adjusted by Miranda [4] highlights due to rapid application and allows preliminary evaluation of buildings. This research seeks to implement computationally this method in opensource package SMath Solver, allowing to generate executable codes to verify seismic vulnerability of existing reinforced concrete structures. Program will be validated by applying in model structures defined in literature by Miranda [4].

2. Modified Hirosawa Method

Seismic Performance of reinforced concrete structures is evaluated comparing Seismic index of Structure $I_s$ and Seismic demand index of structure $I_{s0}$. It shall be calculated at each story and in each principal horizontal direction of a building. The Index $I_s$ is compared with $I_{s0}$. If $I_s \geq I_{s0}$ building possess safety against expected earthquake motions, otherwise if $I_s \leq I_{s0}$, building may possess uncertain performance against expected earthquake motion.

\[ I_s \geq I_{s0} \tag{1} \]

Index $I_s$ is shall be calculated considering basic seismic index of structure $E_0$, Irregularity index $S_D$, and time index $T_D$.

\[ I_s = E_0 \cdot S_D \cdot T_D \tag{2} \]

Where:

- $E_0$: Basic seismic index of structure
- $S_D$: Irregularity index
- $T_D$: Time index

Index $E_0$ evaluate the seismic performance of building taking in account number of story, story ultimate strength, story-shear and ductility of structures and model failure and if vertical member are column, extremely short column or wall.

Index $S_D$ seeks to modify the basic index of structure and examines shape complexity, vertical irregularity, stiffness. Items to be considered are floor plan,
plan regularity, narrow part, expansion joint, existence of basement, existing of pilotis and uniformity of story height.

Structural performance is impacted by time aging determined by time index T. This index evaluate deflection, cracking in wall, columns according Budling inspection. Seismic demand index of structure $I_{S0}$ shall be calculated by equation bellow:

$$I_{S0} = E_S \cdot Z \cdot G \cdot U$$  \hspace{1cm} (7)

Where $E_S$:

0,8 for first level screening, Z is Zone index related to seismic activities and seismic intensities expected in the region according to map from code ABNT NBR 15421 and the ground index G accounts the effects of amplification of the surface soil and geological conditions. The last one, usage index U names importance of building where $U = 1,0$ for general buildings.

Filho [5] proposes the use of surfaces to illustrate the behavior of Seismic index of Structure in function of Time index and Irregularity index. It is also applicable to seismic demand index of structure in function of zone index and use index of buildings.

3. Computational Code: Seismic-V 1.0 beta version

Seismic-V was developed in order to aid in preliminary phase of seismic vulnerability assessment and e a identify potentially hazardous buildings (Figure 2-a). In box pavimento requires number of story trough a slider varying from one floor up to eight floors according limited by the method (Figure 2-b). In second slider, is defined which floor is being evaluated. Next step program asks area of story, weight of the building upper the story under evaluation, sum of the cross-sectional area of the column and fundamental period of structure. After, it should be selected L, T or U-shaped plan.
Third box, *Subíndice*, allows to calculate Basic seismic index of structure $E_0$ where program asks compressive strength of concrete, height of story, column depth pillar so that to obtain average shear stress at the ultimate state of column (Figure 3-a). Afterwards, program calculates $E_0$. Visual inspection should be carried out and interview with owner to take $T$ minimum value to each item and relevance degree. Irregularity index $S_D$ is also calculated in this box.
Figure 3. (a) Calculation of indexes $E_0$ and $T_D$ (b) Calculation of indexes $S_D$

Last window application still receives data from user as region seismicity where structure belongs, geological soil conditions and factor of usage. Consecutively application brings together all indexes calculated before ($E_0$, $S_D$, $T_D$).
and their product results in seismic index of structure (Figure 4-b). Seismic demand index of structure must be among minimum and maximum demand. When compared \( I_s \) and \( I_{S0} \) two answers may be displayed; “Estrutura Segura” which means structure is safety if \( I_s \geq I_{S0} \) or “Verifique por outro método” which means Structure may have uncertain seismic performance against the assumed earthquake if \( I_s < I_{S0} \) and should be verified by next level of method. Reserve of resistant capacity is calculated by the relation seismic and demand index of structure and it is showed at the end of the window. All the indexes are exhibited to easy many simulations rapidly by just changing region seismicity, importance of building or even soil conditions.

Figure 4. (a)Index of seismicity (b) Result of Seismic index of Structure and e Seismic demand index of structure

Source: By Authors, 2023

4. Application Example

Model structures acquired from literature [4] were taken as application example of the program. The input values as sum of cross-sectional area of
column, weight of the building upper the story under evaluation, fundamental period of structure and indexes of structure \((E_0, S_D, T_D)\) are presented in table 1. Structure model I (Figure 5) has compressive strength of concrete 20 MPa. The height story is 2.80 and clear span is 4.00 m. Cross-sectional Columns is \((15\times25)\) cm\(^2\) and beams with cross-sectional \(15\times40\) cm\(^2\) and slabs in reinforced concrete with thickness of 10 cm. This structure model owns only one story in square plan \((20.90\,m \times 20.90\,m)\) with area of 436.81 m\(^2\) (Figure 6). According to literature, time index is \(T_d = 0.9\) and use index is \(U = 1.5\) (essential usage).

Figure 5. Model Structure

![Figure 5. Model Structure](image)

By Miranda, 2013

Figure 6. Plant of level floor +2.80 of Model Structure

![Figure 6. Plant of level floor +2.80 of Model Structure](image)

Source: By Miranda, 2013
Table 1. Input data of Model Structure I

<table>
<thead>
<tr>
<th></th>
<th>Floor 1</th>
<th>Floor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level of floor</td>
<td>+2.80</td>
<td>-</td>
</tr>
<tr>
<td>Weight of the building upper the story (W) in kgf</td>
<td>299,236,00</td>
<td>-</td>
</tr>
<tr>
<td>Floor area in m²</td>
<td>436,81</td>
<td>-</td>
</tr>
<tr>
<td>Sum of cross-sectional area of column Ac2 in cm²</td>
<td>13,500,00</td>
<td>-</td>
</tr>
<tr>
<td>Fundamental Period (Ta) in seconds</td>
<td>0,12</td>
<td>-</td>
</tr>
<tr>
<td>Basic seismic index of structure</td>
<td>0,32</td>
<td>-</td>
</tr>
<tr>
<td>$E_0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irregularity Index $S_D$</td>
<td>1,00</td>
<td>-</td>
</tr>
<tr>
<td>Time Index $T_D$</td>
<td>0,90</td>
<td>-</td>
</tr>
<tr>
<td>Seismic index of Structure $I_s$</td>
<td>0,28</td>
<td>-</td>
</tr>
</tbody>
</table>

Source: By Miranda, 2013

Output after processing in software Seismic-V are compared with those calculated by hand calculation in reference [4] and seen in table 2. For structure model I, time index $I$ was identically as adopted in the original example.

Table 2. Indexes calculated by software Seismic-V

<table>
<thead>
<tr>
<th></th>
<th>Seismic-V (By Authors, 2023)</th>
<th>Miranda (2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Index $E_0$</td>
<td>0,3158</td>
<td>0,32</td>
</tr>
<tr>
<td>Index $S_D$</td>
<td>0,99</td>
<td>1,00</td>
</tr>
<tr>
<td>Index $T_D$</td>
<td>0,9</td>
<td>0,9</td>
</tr>
<tr>
<td>Seismic index of Structure $I_s$</td>
<td>0,2814</td>
<td>0,28</td>
</tr>
</tbody>
</table>

Source: By Authors, 2023

Seismic demand indexes of structure were estimated by software Seismic-V and simulate structure in any scenarios as changing Zone index and considering any type of soil classified in code NBR 15421. Theses outputs are given in table 4 and compared with reference [4] (table 3).

Table 3 Seismic demand indexes $I_{SD}$ of Model Structure I

<table>
<thead>
<tr>
<th>Zone index</th>
<th>Ground index A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0,03</td>
<td>0,03</td>
<td>0,04</td>
<td>0,05</td>
<td>0,08</td>
</tr>
<tr>
<td>1</td>
<td>0,05</td>
<td>0,06</td>
<td>0,08</td>
<td>0,10</td>
<td>0,16</td>
</tr>
<tr>
<td>2</td>
<td>0,10</td>
<td>0,13</td>
<td>0,15</td>
<td>0,20</td>
<td>0,31</td>
</tr>
<tr>
<td>3 e 4</td>
<td>0,15</td>
<td>0,19</td>
<td>0,23</td>
<td>0,28*</td>
<td>0,39</td>
</tr>
</tbody>
</table>

Source: calculated by Miranda (2013)
Table 4. Seismic demand indexes $I_{SD}$ of Model Structure I obtained by program Seismic-V

<table>
<thead>
<tr>
<th>Zone index</th>
<th>Ground index</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seismic-V</td>
<td>Seismic-V</td>
<td>Seismic-V</td>
<td>Seismic-V</td>
<td>Seismic-V</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.0249</td>
<td>0.0311</td>
<td>0.0374</td>
<td>0.0498</td>
<td>0.0778</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.0498</td>
<td>0.0622</td>
<td>0.0747</td>
<td>0.0996</td>
<td>0.1556</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.0996</td>
<td>0.1245</td>
<td>0.1494</td>
<td>0.1992</td>
<td>0.3113</td>
<td></td>
</tr>
<tr>
<td>3 e 4</td>
<td>0.1494</td>
<td>0.1868</td>
<td>0.2241</td>
<td>0.2801*</td>
<td>0.3922</td>
<td></td>
</tr>
</tbody>
</table>

Source: By Authors, 2023

Output obtained by Seismic-V are close to Miranda [4], as given before in table. As it occurred in original example, seismic index of Ground index ‘E’ was lower than inferior seismic demand. In this situation, application display a message: “Verifique por outro método”, suggesting user to evaluate structure in more refined methods. In other scenarios, different message was displayed: “Estrutura segura”, proving structure may have enough seismic performance against seismic expected.

Surface of seismic index for model structure (Figure 7) were generated considering Basic seismic index of structure $E_0 = 0.32$. Values of $T_D$ and $S_D$ vary from 0.7 to 1.0 and 0.8 to 1.0, respectively.

Figure 7 Surface of seismic index

Source: By Authors, 2023

Also surface of seismic demand indexes connecting use index of building change from 1.0 to 1.5 and zone index beginning from 0.025g to 0.15g (Figure 8)
5. Conclusions

This word proposed a computational implementation of Modified Hirosawa Method to verify preliminary seismic vulnerability of reinforced concrete buildings. From comparison established with literature examples, program Seismic-V seems to be viable tool for first screening structures and may be applied in a large sample of buildings. For the same Building, the application allows to simulate its vulnerability in various scenarios whether be changing zone index, importance of building or soils conditions. Displaying values of each index easy the understanding of which variable impacts directly in seismic behavior of structures. As limitation the tool does not store inputs in a database to compare seismic performance of different typology of Building. As future implementation it will be generated surface of seismic indexes and seismic demand indexes according to proposed by Filho [7]. It is emphasized the routine is in beginning of development and integrates research about seismic vulnerability from Laboratory of Rehabilitation of Built Environment of University of Brasilia.

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REFERENCES


