Seismic Vulnerability Assessment:
An Elementary School Case Study in Barreiro, Portugal

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ABSTRACT:
Earthquakes can cause severe damage and loss of important historical and architectonic patrimony. Before every rehabilitation intervention of these buildings, a careful evaluation and analysis of their seismic vulnerability should be conducted, in order to consider and analyze adequate seismic retrofit techniques, if required.
Barreiro is a city located in the outskirts of Lisbon, the Portuguese capital, being characterized by heterogeneity of the existent structures. As Lisbon, Barreiro is located in an important seismic zone, with considerable seismic forces to consider in structural design. However, no seismic vulnerability assessment study was ever made for this city or particular structures located within.
In this paper, a generalized survey conducted in the city of Barreiro regarding existent construction types is presented. In addition, the Japanese Evaluation Method of vulnerability assessment is explained and applied to a specific case study: Penalva Primary School. The case study chosen was modeled, analyzed and a modal analysis was performed. EC8 seismic actions were considered in the estimation of the seismic forces. This study intends to contribute to the knowledge of Barreiro city concerning its seismic performance, as well to evaluate one of the important infrastructures existent.

Keywords: Seismic Vulnerability Assessment, seismic structural behaviour, Japanese Evaluation method

1. BARREIRO EDIFICATIONS

The parish of Barreiro begins around XIII-XIV century with fishermen and salt extraction occupations. The expansion of Barreiro started with the establishment of the railroad in the ends of XIX century and the consequent industrial establishments that followed. Nowadays, the city has grown into a heterogeneity system of city planning, though the old city centre preserves the layout established after the Great Lisbon Earthquake in 1755 / a geometric grid of streets, parallel and perpendicular one to another.

Figure 1.1. Partial view of the Barreiro.

1.1. Diversity of buildings

According to the census performed in 2001 (Estrela, P. (2011)), Barreiro municipality has 10,298 buildings, distributed in eight parishes, with the types of construction shown in Table 1.1. Different types of buildings coexist, with a majority of reinforced concrete buildings, followed by brick masonry, with and without concrete slabs, earth structures and others. The same census operation showed some of the building are in poor conservation conditions with 10.87% of the buildings requiring major repairs in the structure. From this group of buildings, 454 correspond to constructions before 1980, built following former Portuguese construction standards with an underconsideration of the seismic action

Table 1.1. Types of buildings by year of construction: i) reinforced concrete; (ii) brick masonry with concrete slabs; (iii) brick masonry; (iv) earth structures or stone masonry. [Estrela, P., (2011)]

Until 1919	1919 to 1945	1946 to 1960	1961 to 1970	1971 to 1980	1981 to 1985	1986 to 1990	1991 to 1995	1996 to 2001	Total	Structure
0	123	539	1732	1561	313	229	176	523	5196	(i)
0	360	566	614	695	238	123	155	161	2939	(ii)
506	602	280	143	115	36	18	19	18	1737	(iii)
54	179	94	14	6	1	3	3	0	354	(iv)
14	31	13	2	0	10	0	0	2	72	Other
574	1295	1492	2532	2377	598	373	353	704	10298	-

1.2. Projection results of seismic events

Portugal has a moderate seismicity due to its location, close to the convergence of three tectonic plates: Eurasian, African and American. The earthquakes that affect Portugal are essentially of two types: interplates or intraplates. Benavente earthquake, in 1909, of magnitude 6.0 is an example of an intraplate earthquake. On the other hand, the most famous interplate earthquake is the 1755 Great Lisbon Earthquake, of an estimated magnitude of 9.0, associated to a tsunami event.

Using the information obtained in the census survey and the seismic intensity scale EMS-98, a study on the effects of an earthquake similar to the Great Lisbon Earthquake was performed. Buildings were grouped in classes of vulnerability according to the classification of the seismic intensity scale EMS-98 as shown in Table 1.2. This classification only considered the typology of buildings and its structural types, without taking into account other factors, such as the conservation status of the buildings. On the other side, from historical records regarding the Great Lisbon Earthquake, intensity maps were produced and according to Matos, V. (2001), Barreiro registered an intensity of IX at that time. From EMS-98 scale, an earthquake of such intensity produces the following damages for each vulnerability class: A – collapse, B – very severe damages, C – severe damage, D – moderate damage and E – light damages.

Table 1.2. Classes of vulnerability [Estrela, P., (2011)]

Vulnerability Class	Type of Building
A	Adobe, Rammed Earth and loose masonry
B	Brick Masonry without concrete slab
C	Brick Masonry with concrete slab + Reinforced concrete until 1960
D	Reinforced concrete until 1985
E	Reinforced concrete after 1985

With all the previous information in mind, a projection was made for Barreiro municipality for an earthquake similar to the Great Lisbon Earthquake of 1755. Figure 1.2 represents the results obtained for Barreiro municipality, for a scenario similar to the earthquake of 1755, where the percentage of collapses will be less than 10%. The parish with more damage of the type "very severe" would be Barreiro city with a percentage of 50 to 75 % of buildings. This is a very high percentage that should be taken into account in the rehabilitation of edifications of Barreiro municipality.

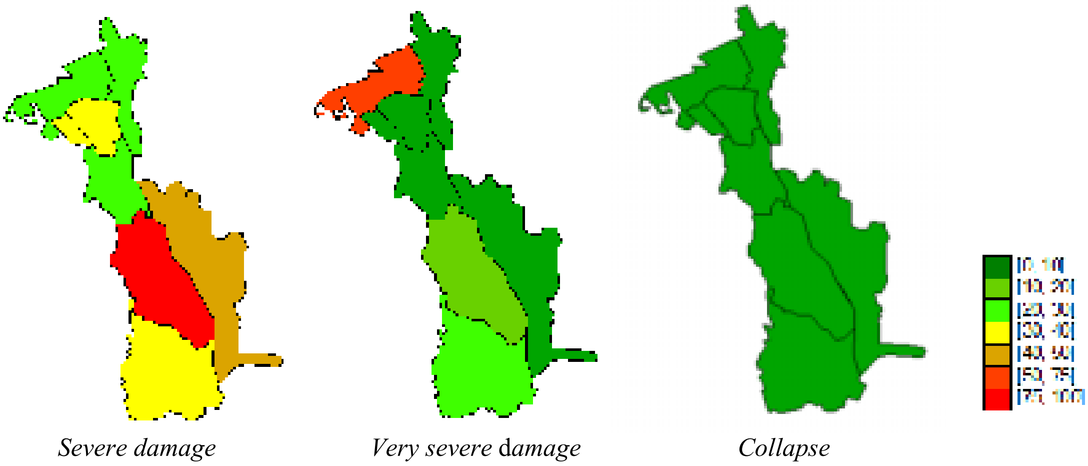

Figure 1.2. Projection of the consequences for an earthquake with the intensity of 1755. (Estrela, P., (2011))

2. METHOD FOR ASSESSMENT THE SEISMIC VULNERABILITY

The seismic vulnerability assessment performed in this study was made according to the Japanese Method. This method is adopted by the Japanese Ministry of Construction in order to evaluate promptly and effectively the seismic vulnerability of buildings of reinforced concrete and thus to assess the seismic safety of each building. The evaluation is performed based on the analysis of the seismic behaviour of each storey of the building storeysand in each direction (TJBDPA, (2005). The structural system that applies the method may vary between the system in porch and walls, and more recent studies (PAHO, (2000)) show that it's also applicable to masonry mixed buildings.

The method is based on three levels of evaluation (TJBDPA, (2005)), from the first one that shows the most simplified approach (and most conservative) to the third level, the most detailed one. However, the existence of three levels does not require that the evaluation passes through all of them. If the evaluation at level 1 is satisfactory, there is no need to pass to the next level. The method procedures are shown schematically in Figure 2.1.

The evaluation relates to the comparison of two indexes determined for each type of building and seismic action to be considered, according equations (2.1) and (2.2). Index I_S represents the Seismic Performance and I_{S0} represents the seismic behaviour, defined later in equations (2.3) and (2.4). In the case of (2.1) the seismic performance is satisfactory, while in the case of (2.2) is unsatisfactory.

$$I_S > I_{S0} \tag{2.1}$$

$$I_S < I_{S0} \tag{2.2}$$

If after the third level of evaluation it is concluded that the seismic vulnerability assessment is unsatisfactory, this means that intervention is required in order to improve structural behaviour. If rehabilitation is not desirable, either in structural or economic terms, this assessment may represent the demolition of the structure (Oliveira, C., Estrela, P., (2011)).

Each of the levels has into consideration different issues. The first level evaluation is performed with reference to the following points (TJBDPA, (2005)):

- Permanent loads and structural dimensions, for the calculation of the forces of structural elements;
- Cracks in concrete elements and deformations of the structure, to evaluate the time index;
- Configuration of the building to evaluate the irregularity index.

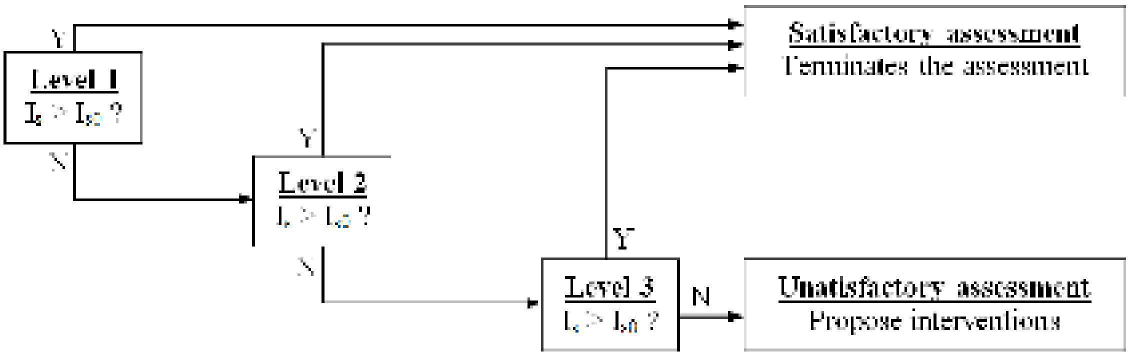

Figure 2.1. Implementation procedure of Japanese Method. (Oliveira, C., Estrela, P., (2011))

The second level includes information on:

- Permanent loads and structural dimensions, for the calculation of the forces of structural elements;
- Degree of occurrence and range of opening of cracks and structural deformation;
- Degrees and ranges of deterioration and aging.

As a supplement to the second level assessment, a visual inspection can be performed with eventual removal of finishing materials for complete evaluation. At this level, failure is regarded as being conditioned by the elements of ductile and brittle, constrained by short columns and concrete columns (Jennifer, M., (2011)).

The assessment on the third level should be performed when in none of the previous levels the structure presents a satisfactory performance. This proves to be the level of the highest degree of complexity to obtain the performance index seismic (Jennifer, M., (2011)). In addition to the information considered on second level, there should also be borne in mind (TJBDPA, (2005)):

- Strength and elastic modulus of concrete;
- Measures, dimensions and yield strengths of reinforcement bars;
- Capacity of the structural elements taking into account the type of construction, cracks and other conditions;
- Material forces, considering the carbonation of the concrete and their aging, as well as the oxidation of the reinforcement bars.

In this evaluation, it can be necessary to extract concrete cores for the analysis.

2.1. Seismic performance index, I_S

The Performance Index is obtained using the expression (2.3), provided in the Japanese Method (TJBDPA, (2005)), which results from the multiplication of three indices: basic index of seismic performance (E_0), index of structural irregularity (S_D) and index indicative of the deterioration of the structure along the time, also called time index (T).

$$I_S = E_0 \times S_D \times T \qquad (2.3)$$

In equation (2.3), the index E_0 depends directly on the resistant capacity of the structure, being determined by calculating the failure force of each storey. This value is given by the sum of the product of given structural element area by its average resistant stress. In turn, indexes S_D and T have the effect of reducing resistance for irregular or older structures.

2.2. Seismic behaviour index, I_{S0}

Taking into account the recommendations in the Japanese Method (TJBDPA, (2005)), the rate of seismic behaviour should be obtained as the product of: the basic content of the seismic behaviour (E_S), index zone (Z), index of soil (G) and importance index of the frame (U) – Equation (2.4).

$$I_{S0} = E_S \times Z \times G \times U \tag{2.4}$$

However, taking into account certain developments arising from the application of the Japanese Method and in view of its framework to the specific case of Portugal, the calculation of I_{S0} can be obtained using the equation (2.5) (Albuquerque, P., (2001)). To apply the equation (2.5) is necessary to have knowledge of: maximum acceleration of the rock (a_{gR}), coefficient of soil (S), factor of importance (γ_I), mass percentage mobilized in the fundamental mode of vibration (λ), acceleration of gravity (g) and a coefficient of importance of the structure (q).

$$I_{S0} = \frac{2.5 \times a_{gR} \times S \times \gamma_1 \times \lambda}{g \times q} \tag{2.5}$$

Also related to this equation, it should be noted that due to the variables associated with it, I_{S0} is not a value to assign to each storey, but attached to the whole structure.

3. APPLICATION OF THE METHODOLOGY TO PENALVA'S ELEMENTARY SCHOOL

The Penalva's Elmentary School is located in the parish of Santo António da Charneca, Barreiro municipality. Its geographical location falls in seismic zones 1.3 and 2.3 according to the Portuguese national annex of Eurocode 8 (EC8) (NP EN 1998-1 (2010)).

The school consists of three distinct bodies, separated by expansion joints and thus independent in structural terms: the main body (cafeteria and classrooms), body II (older with use of pre-elementary) and body III (school library facilities). The main body and III, inaugurated in 2010, result of expansion work of the school.

The structural solution adopted was a reinforced concrete structure with slab and beams, with direct foundation with beams.

Figure 3.1. Image of school body subject to assessment.

The method for seismic vulnerability assessment was applied to the main body of the school, due to its larger dimensions (see Figure 3.1)storey. Figures 3.2 and 3.3 show the plants of first and second storeys, respectively.

3.1. Structural modelling

Based on the characteristics of the building it was possible to model the structure at a computer program. The columns and beams were modelled using frame elements (concrete C20/25 and steel A400NR). The slab panels were modelled using finite-dimensional elements such as "shell-thin". Figures 3.4 and 3.5 represent views of the model. The foundations were modelled as fixed.

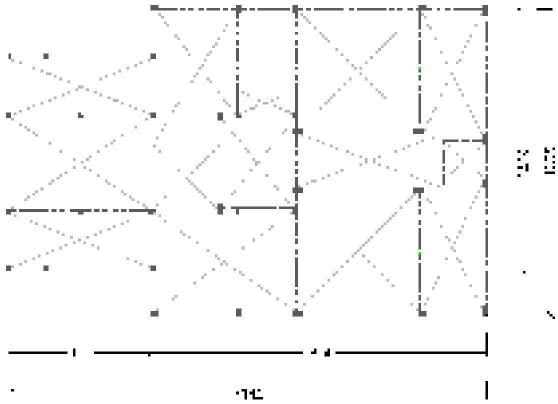

Figure 3.2. Dimensions of the 1st storey. (Estrela, P., (2011))

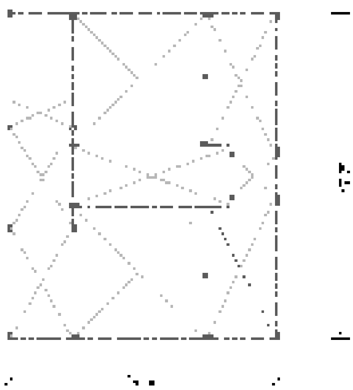

Figure 3.3. Dimensions of the 2nd storey. (Estrela, P., (2011))

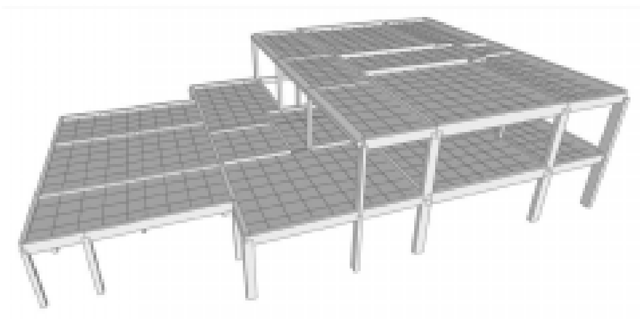

Figure 3.4. Scheme of modelling (3D).

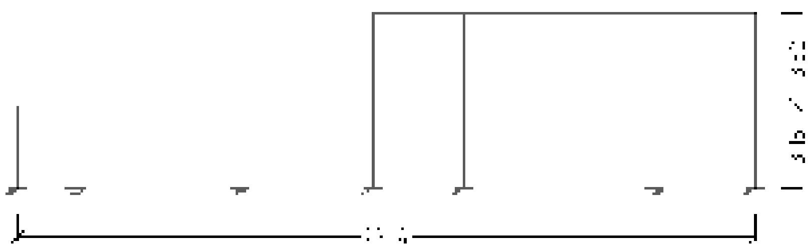

Figure 3.5. Scheme of modelling (larger direction in plant). (Estrela, P. (2011))

3.2. Modal analysis

The modal analysis aims to assess the vibration modes of the structure, their frequencies and periods. This fact relates to the need for this information to calculate the Seismic behaviour index (I_{S0}). Using the computer program, we obtained the information show in Table 3.1 for the first three vibration modes.

Table 3.1. Modal information (Oliveira, C., Estrela, P., (2011))

Vibration mode	Period (sec.)	Frequency (Hz)	Mobilized mass (%)		
			Displacement X	Displacement Y	Rotation Z
1	1.069	0.936	3.36	75.68	33.33
2	1.030	0.970	82.74	3.84	29.58
3	0.848	1.179	0.70	2.40	22.68

It was concluded that the first vibration mode of the structure corresponds to translational movement in YY direction, mobilizing 75.68 % of toal mass.

3.2. Elastic response spectrum

According to EC8, the elastic response spectrum is given by the equations (3.1) to (3.4), in order to vibration period (T), T_B, T_C and T_D, and it is shown in Figure 3.6.

$$0 \leq T \leq T_B : \quad S_e(T) = a_g \times S \times \left[1 + \frac{T}{T_B} \times (\eta \times 2.5 - 1) \right] \tag{3.1}$$

$$T_B \leq T \leq T_C : \quad S_e(T) = a_g \times S \times \eta \times 2.5 \tag{3.2}$$

$$T_C \leq T \leq T_D : \quad S_e(T) = a_g \times S \times \eta \times 2.5 \times \left[\frac{T_C}{T} \right] \tag{3.3}$$

$$T_D \leq T : \quad S_e(T) = a_g \times S \times \eta \times 2.5 \times \left[\frac{T_C \times T_D}{T^2} \right] \tag{3.4}$$

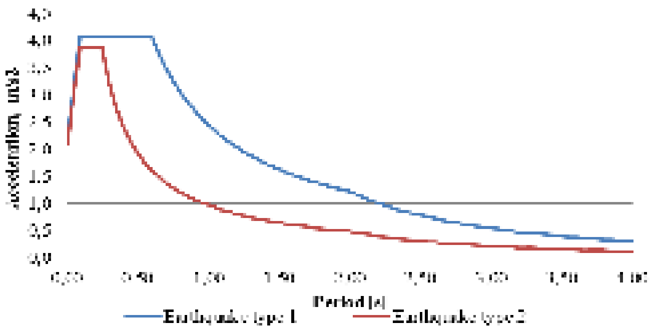

Figure 3.6. Elastic response spectrum.

3.4. Application of the assessment methodology (Level 1)

3.4.1. I_S Index

In order to determine I_S index, E_0, S_D and T indexes should be calculated.

The T index showed no difficulty in its determination, due to the very young age structure. During the visit to the school, anomalies were not detected in terms of: deformation, cracks, chemical use and fire records. In view of the methodology proposed by Estrela, P., (2011), where T index is defined taking into

consideration the standard used in the structural design, and once the structure has been built under RSA, the current standard (to be soon replaced by EC8), *T* index has a global final value 0.90.
To obtain the value of S_D, several parameters were taken into account , namely, the relationship between areas, uniformity in height and relationship between higher and lower sides, among others. Upon further study of each parameters gave the final value of S_D to the first level of 0.90 (storey 1 and storey 2). This value is not unitary due to the parameter "relationship between the areas". Since the ratio between the smallest and the total surface area less than 30%, according to figure 3.7, S_D is to 0.90.

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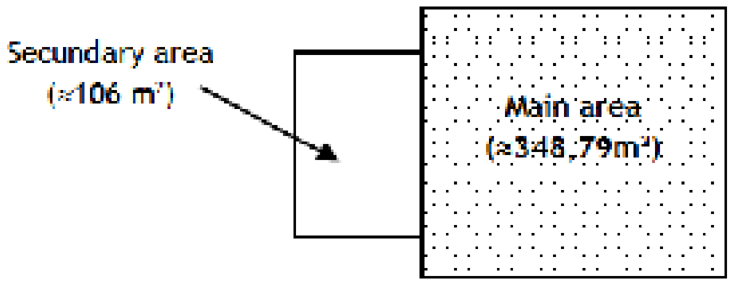

Figure 3.7. Relationship between areas on the 1st storey. (Oliveira, C., Estrela, P., (2011))

The index representing the structural performance results on the first level of analysis for existing vertical structural elements. Since in this structure bearing walls or short columns do not exist (according to the definitions of the standard), the equation TJBDPA, (2005) is simplified as given in equation (3.5):

$$E_0 = máx\begin{cases} \frac{n+1}{n+i} \times (\alpha_1 C_C) \times F_W \\ \frac{n+1}{n+i} \times (\alpha_3 C_C) \times F_W \end{cases} \tag{3.5}$$

In equation (3.5), *n* represents number of storeys of a building, C_C represents strength index of columns (calculated by equation (3.6)), F_W is the ductility index of the walls (which may be taken as 1.0) and *i* represents the number of the storey for evaluation (eg: first storey is numbered as 1). The parameters α_1 and α_2 represent, respectively, effective strength factor of the columns at the ultimate deformation of the walls and effective strength factor of the columns at the ultimate deformation of extremely short columns.

$$C_C = \frac{\tau_C \times A_C}{\sum W} \times \beta_C \tag{3.6}$$

To calculate the equation (3.6) is necessary to know the values of: average shear stress at the ultimate state of columns (τ_C, N/mm^2); total cross-sectional area of columns in the storey concerned (A_C, mm^2); ratio between compressive strength concrete (N/mm^2) and 20 N/mm^2 (β_C), as show in TJBDPA, (2005); and total weight supported by the storey concerned (approximately 12 kN/m^2) .
The calculation of the Seismic Performance Index of structure analysed results in the data shown in Table 3.2.

Table 3.2. Summary of the values obtained for I_S.

	T	S_D	E_0		I_S	
			X	Y	X	Y
1st storey	0,90	0,90	0,39	0,39	0,32	0,32
2nd storey	0,90	0,90	0,47	0,47	0,38	0,38

For the results noted the fact that the value obtained is the same for both directions due to the absence of resistant walls (which would change the setting for the columns and resistance depending on the alignment of the wall and respective openings). Another aspect to be considered is that of the second storey can be expected that due to the modification factor $(n+1)/(n+i)$ the value of I_S was smaller. However, the reduction factor is not sufficient to attenuate the effects which are reflected by the second storey to be smaller, less weight has to be carried and which together with the characteristics of structural elements results in a higher index E_0.

3.4.2. I_{S0} Index

The Seismic Behaviour index is obtained by equation (2.5), developed by the author Albuquerque, P., (2001), adapted to the reality of the legislation applicable in Portugal. Recalling that same expression, it is necessary to take into account the seismic zoning of the building (Barreiro) for each type of seismic action: 1.3 e 2.3. It should be noted that the structure under consideration is part of the class III of importance, according to EC 8 is attributed.
It is shown in Figure 3.8 a comparative chart of I_S and I_{S0} indexes. It is concluded that in the second storey there is a higher strength capacity reserve than the first storey, mainly due to different mass than the second storey features.

Table 3.3. Parameters for calculation of the seismic behaviour index by equation (2.5).

Parameters	Earthquake type 1	Earthquake type 2
a_{gR} (m/s^2)	1,500	1,700
S	1,365	1,375
γ_1	1,450	1,250
Q	2,00	
λ	75,68 %	
I_{S0}	0,287	0,282

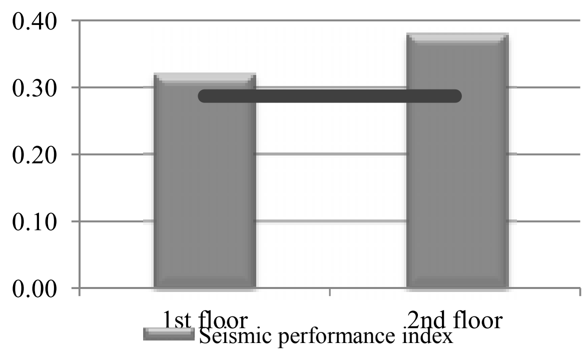

Figure 3.7. Comparison between I_S and I_{S0} for vulnerability assessment.

4. FINAL REMARKS

The Japanese Method for assessing the seismic vulnerability, in the course of implementing it to the main body of Penalva's school confirmed to be a prompt method and easy to apply.

It was concluded that the structure under study presents a satisfactory seismic performance in the first level of assessment, which besides being the simpler one is also the most conservative. The second level recommended would considered to more precisely the resistance of storeys and their structural elements, in particular in respect to the strength and ductility of the vertical structural elements and its ultimate strength. In this second level, the lowest ultimate strength values are obtained for each element and for each mode of failure (either bending or shear). The horizontal structural members (slabs and beams) are considered undeformable corresponding to assume an attitude of the diaphragm drive.

Also according to Albuquerque, P., (2001) the Seismic Behaviour Index is equivalent to a seismic coefficient (in the nomenclature of RSA called β). This coefficient is given by the ratio between basal shear forces and the total weight of the building.

Table 4.1. Parameters for calculation of the seismic behaviour index by equation (2.5).

Basal shear forces (kN)		Weight (kN)	β		I_{S0}
X	Y		X	Y	
972.63	907.15	5976.82	0.163	0.152	0.287

By analysing these data, we conclude that the expression adopted for the calculation of I_{S0} is conservative, which means to be on the safe side, since it leads to higher values of I_{S0}. In some cases, this may force a transition to the second level of evaluation, ensuring that the conclusion obtained from the application of the methodology is safe.

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