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Effect of soil-building resonance on the seismic structural vulnerability of schools designated as post-disaster shelters in Montréal

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ABSTRACT

This paper presents an on-going research project that aims to study the effects of soil-building resonance on the seismic structural vulnerability of sixteen schools designated as post-disaster shelters in Montréal by the Civil Safety Department of the City of Montreal (C*entre de sécurité civile de Montréal)*. The assessment of the structural seismic vulnerability of these schools builds upon a previous study conducted at McGill University using a seismic screening method adapted from the American standard FEMA 154 (*Federal Emergency Management Agency*) and New Zealand guidelines. The method did not take into consideration possible soil-building resonance as a parameter contributing to the structural vulnerability. In the current study, a coefficient of soil-building resonance (C.R) is estimated based on the dynamic characteristics extracted from ambient vibration measurements (AVM) in the school buildings and outside on the adjacent local soil. The main structural vulnerability parameters are taken directly from the previous McGill study and they include the type of lateral load resisting system, building height, construction year, site seismicity, structural irregularities (vertical and in-plane) and local soil class defined in the seismic provisions of the National Building Code of Canada.

A deterministic structural vulnerability index (VI) of these school buildings is calculated based on the Analytical Hierarchy Process (AHP). The AHP is applied to estimate a weight factor for each of the parameters via pairwise comparison of their relative contribution to the structural vulnerability. The new proposed deterministic VI is classified into four classes: low, moderate, high and very high. The results obtained with this improved assessment procedure are compared to those obtained from the previous study, and the comparison shows that in some cases the addition of the soil-building resonance parameter increases the seismic vulnerability class of the building.

Keywords: AHP, Structural vulnerability index, Soil-building resonance, Seismic screening method.

INTRODUCTION

Previous studies and experience in past earthquakes have demonstrated that there is a need to assess the seismic vulnerability of school buildings even in zones of moderate seismicity [1]. In Quebec, this includes regions in the St. Lawrence River valley and the Ottawa River valley, with a concentration of school buildings in the Quebec City and Montreal areas [2]. For instance, the extensive damages to school buildings during the M8.0 Sichuan (China) earthquake in 2008 resulted in the deaths of hundreds of children and staff while at school [3]. Although such severe earthquakes are not likely in Quebec, school buildings remain potentially vulnerable to moderate shaking as many school buildings may have inadequate exit pathways, and students may not be able to exit safely and quickly when an emergency occurs [4]. In Quebec, most school buildings have structural irregularities, and many would likely have poor seismic performance if subjected to moderate to strong earthquakes because they were designed and built in the 1960s and 1970s before the introduction of modern earthquake-resistant design procedures in Canada. School buildings must remain structurally safe at all times [5], hence the importance of adequately assessing their seismic vulnerability.

This paper will mainly focus on the effects of potential soil-building resonance on the seismic structural vulnerability of schools in Montréal. First, a brief description of the buildings database is presented, followed by a review of soil-building resonance effects observed during past earthquakes. Then, the Analytical Hierarchy Process (AHP) that is used to improve the adapted seismic screening method developed by Tischer et al.[6, 7] is described. Finally, the global results of the improved screening procedure are presented with a discussion of the influence of the soil-building resonance parameter on the proposed deterministic vulnerability index.

SCHOOL BUILDINGS DATABASE

A wealth of information was collected through a previous study regarding the seismic vulnerability of sixteen schools designated as post-disaster shelters in Montréal [8], which forms the database of the current study. In terms of their lateral load resisting systems (LLRS), almost 80% of the school buildings have concrete frames with infill masonry shear walls, concrete shear walls and steel moment frames [8], as shown in Figure 1.

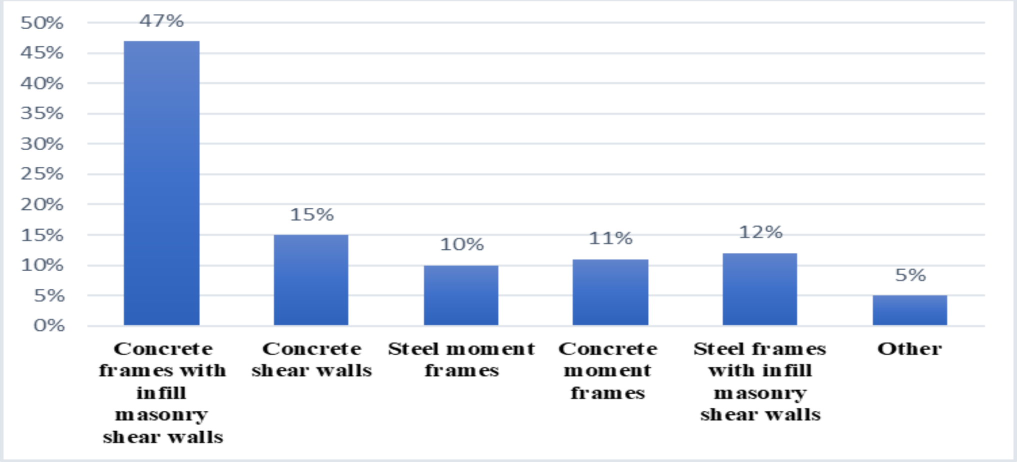


Figure 1. Distribution of LLRSs for the evaluated schools using the updated method by Tischer [8].

87% of these school buildings were constructed during the 1960s and 1970s [8]. The building height distribution is represented by the number of floors. Most of the schools are low rise: 85% of them are three stories or less and the tallest one is six-storey high [8]. 80% of the buildings have some form of structural irregularity as defined in the NBCC and 40% combine at least one vertical and one planar irregularity. In addition to these building parameters, the in situ dynamic properties of school buildings were determined using ambient vibration measurements (AVM). The local site conditions were estimated by in situ AVM tests from which the fundamental natural frequency of the soil was extracted.

EFFECTS OF SOIL-BUILDING RESONANCE ON SEISMIC PERFORMANCE

The soil-structure resonance phenomenon is an important aspect to consider when assessing the dynamic behavior of a structure subjected to an earthquake. Resonance will occur when the natural period of the site and the fundamental period of the building structure are close to each other [9], with a potential to amplify sway motions and floor accelerations in the building and possibly increase the level of damage in the structures [10]. Hence, a significant factor to predict earthquake damage is the relationship between the fundamental frequency of the building and the fundamental frequency of the soil on which the building is built. Figure 2 shows a schematic graph of the amplification of building accelerations due to soil-structure resonance.

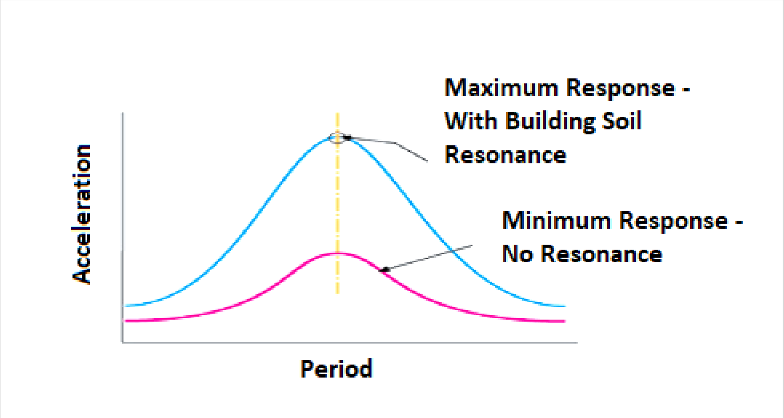


Figure 2. Effect of resonance on the seismic response of buildings [11].

A comprehensive study of this factor was conducted in Italy [12], in the aftermath of the October 31 and November 1, 2002 two earthquakes of magnitudes M 5.4 and M 5.3, respectively that hit the area at the border between Molise and Puglia in Southern Italy. The study analysed the effect of soil-building resonance on the lateral stiffness reduction of the building structures. To test if the soil-building resonance had increased the structural damage, floor response data were recorded inside the most damaged building after the October 31 earthquake, and during and after the second earthquake on the following day. The recorded data were analyzed to estimate the fundamental frequency of the building and its reduction due to damage. For validation purposes, the analysis of the building AVM records was done using many techniques such as the Short-Time Fourier Transform (STFT), Wavelet Transform (WT), Horizontal-to-Vertical Spectral Ratio (HVSR) and the Horizontal-to-Vertical Moving Window Ratio (HVMWR). In addition, three different techniques were applied to estimate the fundamental frequency of the soil supporting the building: noise HVSR, strong motion HVSR of seven aftershocks, and 1D soil column modeling based on a shear velocity profile derived from noise analysis of surface waves (NASW). The different measurements lead to the conclusion that the fundamental frequency of the most damaged building was in the same range as the fundamental frequency of the soil before the damage. We can note that all the natural frequencies (before, during and after the damage) are in the range 2.5 – 1.25 Hz [12].

ANALYTICAL HIERARCHY PROCESS (AHP)

AHP, introduced by Saaty (1977) [13], is one of the most common multicriteria decision-making methods. It is based on the calculation of the relative importance of each parameter via pairwise comparison. Then, it transforms the comparison into numerical values that are further processed in a mathematical matrix format. The relative importance of the parameters is identified by assigning a weight factor to each of them based on the scale of preference between each pair of parameters as shown in Table 1.

Table 1. Saaty's AHP scale of preference between two parameters [14].

Intensity of importance	**Degree of preference**	**Explanation**
1	Equally	Two factors contribute equally to the objective
3	Moderately	Experience and judgment slightly to moderately favor one factor over another
5	Strongly	Experience and judgment strongly or essentially favor one factor over another
7	Very strongly	A factor is strongly favored over another and its dominance is showed in practice
9	Extremely	The evidence of favoring one factor over another is of the highest degree possible
2,4,6,8	Intermediate	Used to represent compromises between the preferences in weights 1,3,5,7 and 9
Reciprocals	Opposites	Used for inverse comparison

Moreover, the important feature of the AHP method is its consistency for weighting the factors. The consistency index is defined by Saaty in Eq. (1).

$$\mathrm{CI}=\frac{\lambda_{max-N}}{N-1} \tag{1}$$

where λ max is the largest or principal eigenvalue of the pairwise comparison matrix and N is the order of the matrix. The average random consistency index (RI) is calculated as shown in Table 2 and the consistency ratio CR is obtained from Eq. (2).

$$CR = \frac{CI}{RI} \tag{2}$$

If CR is equal to zero (CI = 0), the comparison is completely consistent. If CR is larger than 0.1 the comparison is not consistent, and the pairwise comparison and weighting of the different parameters must be repeated. The random consistency indices presented in Table 2 are obtained by the computation of the mean random consistency index (MRCI) by conducting many simulations using large number of samples [15].

Table 2. AHP random consistency indices (RI) [14].

N	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.5	1.49	2	1.5

ADAPTED SEISMIC SCREENING METHOD FOR THE EVALUATION OF SCHOOL BUILDINGS [6, 8].

This section summarizes the score assignment procedure proposed by Tisher (2012) [6-8] to assess the seismic vulnerability of school buildings in Montreal. It was applied to 101 school buildings designated as post-critical emergency shelters by the City of Montreal. The method considers six parameters: building height, lateral load resisting system, construction year, presence of structural irregularities, potential for pounding of adjacent building(s), and local soil conditions (soil classes are according to the National building Code of Canada). The method was based on the capacity spectrum approach and adopted the same principles as the FEMA154 [11], with the introduction of the effect of structural irregularities.

This method estimates the seismic structural vulnerability of buildings by an overall score S, which is equal to the summation of the basic structural hazard score (BSH) and various score modifiers related to each of aforementioned parameters, as indicated in Eq. (3).

$$S = BSH + \Sigma \text{ (score modifiers)} \qquad (3)$$

For a given earthquake hazard, the BSH reflects the building performance based on the LLRS type. The score modifiers consider other features that make the building more or less vulnerable. The BSH is defined in Eq. (4) as the negative logarithm of the probability of structural collapse under a specified extreme ground motion, so-called the maximum considered earthquake (MCE).

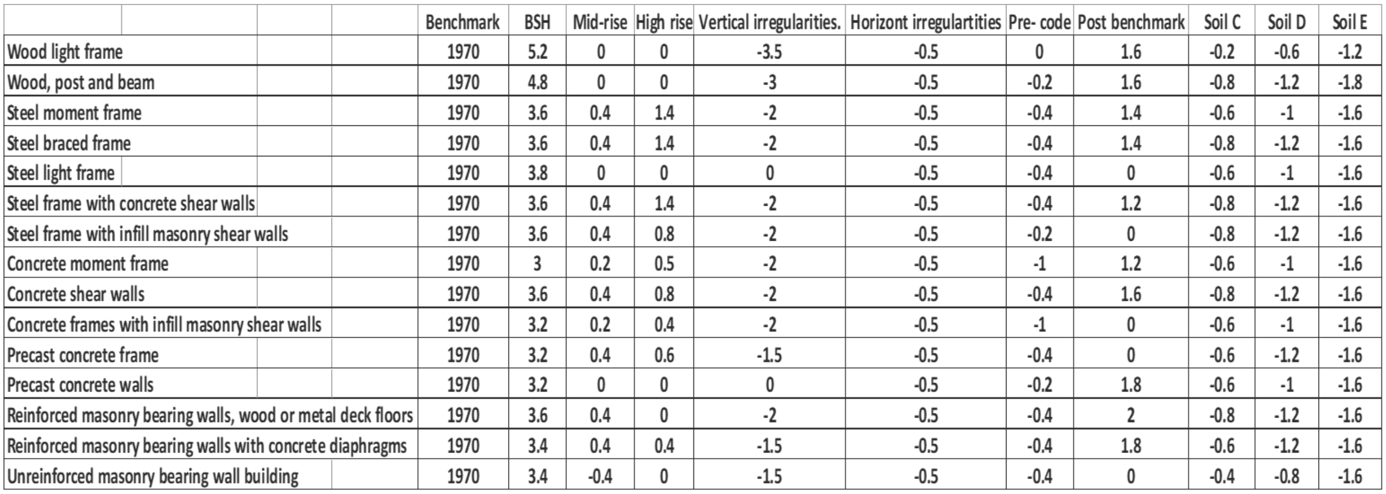
$$BSH = -\log_{10} [P \text{ (collapse MCE)}] \qquad (4)$$

The probability of collapse is estimated using the capacity spectrum method and fragility curves corresponding to various lateral load resisting systems [16]. The expected seismic behaviour of a building is described by generic capacity curves. The capacity curves give a relation between the lateral force and sway displacement in the structure and are defined by building type, height and quality of construction [16]. The conditional probability of collapse of the building is expressed in Eq. (5) as the product of the probability of the building being in complete damage state and the collapse rate which is the fraction of the same type of buildings that reach complete damage state.

$$P \text{ (collapse given MCE)} = p \text{ (complete } |\text{dpi) x collapse rate} \qquad (5)$$

Where P (complete |dpi) is the probability of being in complete damage state given a spectral displacement dpi and the collapse rate is based on judgment and limited data for each type of building. Then, the BSHs of each type of building are evaluated based on the probability of collapse. To calculate the score modifiers, provisional scores are calculated using the same procedure as for the BSH, but the only difference is the capacity and the acceleration spectra. Thus, the score modifier will be obtained by subtracting the provisional score from the corresponding BSHs. The proposed score modifiers are listed in Table 3.

Table 3. Basic score and score modifiers according to Tischer's adapted screening method [6].



	Benchmark	BSH	Mid-rise	High rise	Vertical irregularities.	Horizont irregulartities	Pre- code	Post benchmark	Soil C	Soil D	Soil E
Wood light frame	1970	5.2	0	0	-3.5	-0.5	0	1.6	-0.2	-0.6	-1.2
Wood, post and beam	1970	4.8	0	0	-3	-0.5	-0.2	1.6	-0.8	-1.2	-1.8
Steel moment frame	1970	3.6	0.4	1.4	-2	-0.5	-0.4	1.4	-0.6	-1	-1.6
Steel braced frame	1970	3.6	0.4	1.4	-2	-0.5	-0.4	1.4	-0.8	-1.2	-1.6
Steel light frame	1970	3.8	0	0	0	-0.5	-0.4	0	-0.6	-1	-1.6
Steel frame with concrete shear walls	1970	3.6	0.4	1.4	-2	-0.5	-0.4	1.2	-0.8	-1.2	-1.6
Steel frame with infill masonry shear walls	1970	3.6	0.4	0.8	-2	-0.5	-0.2	0	-0.8	-1.2	-1.6
Concrete moment frame	1970	3	0.2	0.5	-2	-0.5	-1	1.2	-0.6	-1	-1.6
Concrete shear walls	1970	3.6	0.4	0.8	-2	-0.5	-0.4	1.6	-0.8	-1.2	-1.6
Concrete frames with infill masonry shear walls	1970	3.2	0.2	0.4	-2	-0.5	-1	0	-0.6	-1	-1.6
Precast concrete frame	1970	3.2	0.4	0.6	-1.5	-0.5	-0.4	0	-0.6	-1.2	-1.6
Precast concrete walls	1970	3.2	0	0	0	-0.5	-0.2	1.8	-0.6	-1	-1.6
Reinforced masonry bearing walls, wood or metal deck floors	1970	3.6	0.4	0	-2	-0.5	-0.4	2	-0.8	-1.2	-1.6
Reinforced masonry bearing walls with concrete diaphragms	1970	3.4	0.4	0.4	-1.5	-0.5	-0.4	1.8	-0.6	-1.2	-1.6
Unreinforced masonry bearing wall building	1970	3.4	-0.4	0	-1.5	-0.5	-0.4	0	-0.4	-0.8	-1.6

The overall score results of each building represent its structural vulnerability index that is further classified into four levels according to the ranking system shown in Table 4.

Table 4. Seismic vulnerability ranking system used in Oregon with FEMA154 [17].

Seismic vulnerability	Probability of collapse under MCE	Index value
Very high	100%	≤ 0.0
High	10% to 100%	0.1 - 1
Moderate	1% to 10%	1.1 – 2
Low	Less than 1%	≥ 2

METHODOLOGY

In order to evaluate the seismic structural vulnerability of schools that will take into account the possible soil-structure resonance effects as a parameter, a new VI equation needs to be synthetized as described next, using the AHP approach.

The first step in the methodology is the extraction of the dynamic properties of buildings such as the fundamental frequency and the damping ratio from AVM records: this was done by Tischer [6] for 69 school buildings using ARTEMIS [18] and the extracted properties were validated during this study using the software Sensequake – 3D SAM [19]. Since AVM measurements were also taken at the building sites, the fundamental frequency of the soil is extracted, and the coefficient of soil-building resonance is simply obtained by dividing the fundamental frequency of the adjacent soil by the fundamental frequency of the school building. Based on this coefficient, the school buildings vulnerable to resonance are identified.

Two analytical equations are derived using the AHP approach. The first equation represents the structural vulnerability without taking into consideration the influence of the soil-building resonance parameter in order to calibrate the method and validate its results with the adapted screening method developed by Tischer et al [6-8].

The second equation takes into account the contribution of the soil-building resonance ratio. Then, the vulnerability indices are calculated from these two equations using the scores shown in Table 3. The obtained coefficient of resonance was integrated in the equation as a negative value. The final step consists of scaling the new structural vulnerability index to classify the vulnerability of each school building.

VULNERABILITY INDEX FROM AHP

The first step in applying the AHP approach is to proceed to the pairwise comparison between the parameters (potential of pounding is excluded) according to Saaty's scale and develop the two matrices shown in Tables 5 and 6 that are used to calculate the weight factor of each parameter. The sum of the weights (last column in the tables) is equal to 1, as each weight represents the percentage of the contribution of each parameter to the total structural vulnerability of a building.

As indicated previously, AHP was first applied without taking into consideration the coefficient of resonance, so that the first matrix (Table 5) is of order 5. The second matrix (Table 6) is of order 6 as it includes the coefficient of soil-building resonance.

The weight results obtained in Table 6 indicate that the coefficient of soil-building resonance has the highest contribution (24%) among the six parameters. These results are contrasted to those presented in Table 5, where the LLRS type is dominant (31%), which is consistent with the fact that the BSH is the highest score of the sum in Eq. (3) and directly represents the influence of the LLRS type.

Table 5. Priority and normalized weights of five parameters from the adapted screening method according to AHP.

	Parameters	LLRS	Year of Construction	Local Soil	Irregularities	Height of building	Priority	Weight
P_1	**LLRS**	1.00	2.00	2.00	1.00	3.00	1.64	0.31
P_2	**Year of Construction**	0.50	1.00	0.50	0.33	2.00	0.70	0.13
P_3	**Local Soil**	0.50	2.00	1.00	0.50	1.00	0.87	0.16
P_4	**Irregularities**	1.00	3.00	2.00	1.00	1.00	1.43	0.27
P_5	**Height of Building**	0.33	0.50	1.00	1.00	1.00	0.70	0.13

Table 6. Priority and normalized weights of six parameters from the adapted screening method according to AHP.

	Parameters	LLRS	Year of Construction	Local Soil	Irregularities	Height of building	Coefficient of Resonance	Priority	Weight
P_1	LLRS	1.00	2.00	2.00	1.00	3.00	0.50	1.35	0.21
P_2	year of Construction	0.50	1.00	0.50	0.33	2.00	0.33	0.62	0.10
P_3	Local Soil	0.50	2.00	1.00	0.50	1.00	1.00	0.89	0.14
P_4	Irregularities	1.00	3.00	2.00	1.00	1.00	0.50	1.20	0.19
P_5	Height of Building	0.33	0.50	1.00	1.00	1.00	1.00	0.74	0.12
P_6	Coefficient of Resonance	2.00	3.00	1.00	2.00	1.00	1.00	1.51	0.24

Using the Priority scores and the Weight factors of the last two columns in Tables 5 and 6, the VI index of the 101 school buildings of the database is calculated according to Eq. (6):

$$VI = a * b * c * d * \sum \boldsymbol{X_i} * P_i \qquad (6)$$

Where X_i is the weight of the parameters resulting from the AHP, and P_i represents the parameter score. The coefficients a to d vary with the type of LLRS system: a is equal to 1.2 in steel moment frames, b is equal to 1.3 in steel braced frames, c is equal to 1.3 for concrete shear walls. The coefficient d is equal to 0.8 if the local soil is of class E. Otherwise, all these coefficients are equal to 1.

The resulting vulnerability index is evaluated according to a new scale corresponding to the developed equation, as defined in Table 7. It should be noted that the developed equation of the vulnerability index was specifically applied on the schools of the database that are located on the Island of Montreal where seismic hazard is considered moderate.

Table 7. Structural vulnerability classes according to the proposed method.

Seismic vulnerability	Index	Mitigation
Very high	0 – 0.2	High priority
High	0.2 – 0.45	Necessary
Moderate	0.45 – 0.75	Optional
Low	>0.75	Not necessary

RESULTS

The estimation of the coefficient of soil-building resonance (C.R) shows that 18 school buildings out of 69 for which local soil AVM measurements were available are in the range of possible soil-structure resonance, which represents 26% of the total school buildings, as shown schematically in Figure 3. These results indicate also that 16 out of 18 school buildings (90%) affected by the soil-structure resonance, are built on soil classes D (8) and E (8).

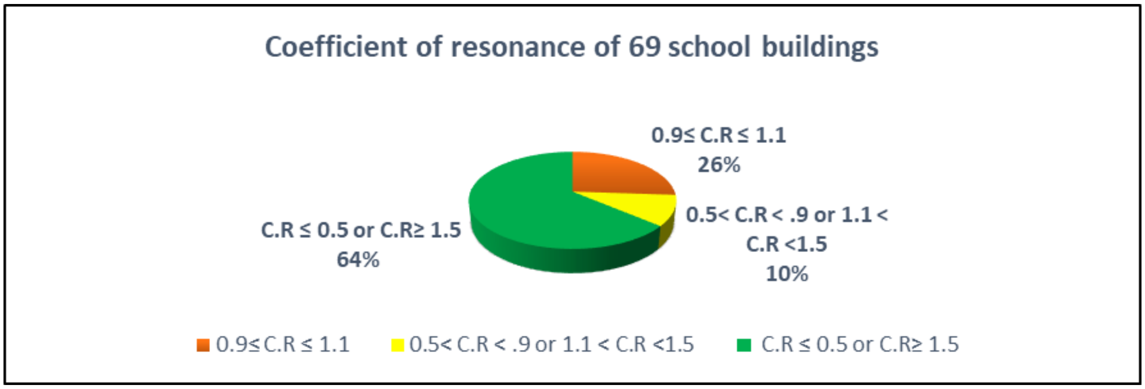


Figure 3. Distribution of coefficients of soil-building resonance for 69 buildings located in Montreal.

The seismic vulnerability classes of school buildings according to the AHP developed equation were evaluated first without the coefficient of resonance, and then by considering it. The obtained results without the CR indicated the same seismic vulnerability class as in Tischer's adapted seismic screening method. An example of the structural vulnerability of a given school comprising eight buildings is shown in Table 9. The characteristics of these eight buildings are given in Table 8.

Table 8. Characteristics of the eight school buildings [8].

Building	LLRS	Year of Construction	Irregularities		Type of Soil	Height of building
			Plan irregularities	Vertical irregularities		
T	Concrete shear walls	1969	yes	yes	E	Mid rise
U	Concrete moment frame	1969	No	yes	E	Mid rise
V	Concrete shear walls	1969	No	No	E	Mid rise
W	Concrete shear walls	1969	No	No	E	Mid rise
X	Concrete shear walls	1969	yes	yes	E	Mid rise
Y	Concrete shear walls	1969	No	No	E	Low rise
Z	Concrete shear walls	1969	No	No	E	Low rise
S	Concrete shear walls	1974	yes	No	E	Low rise

Table 9. Comparison of Structural vulnerability index and class according to the AHP-based method and Tischer's adapted screening method without the coefficient of resonance.

Building	Analytical equation results (AHP)	Vulnerability Class	Adapted screening method	Vulnerability Class
T	0.2	very high	-0.1	very high
U	0.11	very high	-0.1	very high
V	0.79	low	2.4	low
W	0.79	low	2.4	low
X	0.21	very high	-0.1	very high
Y	0.77	low	2	low
Z	0.77	low	2	low
S	0.84	low	3.1	low

The results from the investigation of the effect of soil-building resonance indicate that the vulnerability class has changed considerably, especially for buildings that can be affected by a potential soil-structure resonance. Table 10 presents the vulnerability index from Eq. (6) using the same buildings presented in Table 9. For example, building V has a coefficient of resonance equal to 1.08 and the vulnerability index from Eq. (6) dropped from 0.79 to 0.33, which means that the vulnerability class has increased from low to high. For buildings Y and S, the vulnerability class did not change since their coefficient of resonance is far from 1. Moreover, many school buildings had a very high vulnerability class and they are in the range of resonance. In this case, a more detailed investigation of the structural and soil properties should be undertaken to confirm the resulting high vulnerability classes.

Table 10. Comparison of Structural vulnerability index and class according to the AHP-based method and Tischer's adapted screening method with the coefficient of resonance.

Building	Coefficient of resonance	Analytical equation results (AHP)	Vulnerability Class	Adapted screening method	Vulnerability Class
T	1.04	-0.14	very high	-0.1	very high
U	1.1	-0.16	very high	-0.1	very high
V	1.08	0.34	high	2.4	low
W	1.08	0.34	high	2.4	low
X	1.04	-0.14	very high	-0.1	very high
Y	0.56	0.77	low	2	low
Z	1	0.31	high	2	low
S	0.82	0.84	low	3.1	low

CONCLUSIONS

The paper has summarized the results of a study concerning the structural vulnerability of 101 school buildings and the effect of soil-building resonance on the seismic structural vulnerability of a subset of 69 of them, all located on the Island of Montreal. A new scoring procedure is introduced based on the Analytical Hierarchy Process (AHP) that allows a more systematic weighting of parameters than the method previously developed by Tischer at McGill University, using the same database of building and soil characteristics. When the coefficient of soil-building resonance is not taken into consideration, the vulnerability indices are similar in both methods, which validates the proposed new method. An additional parameter is introduced in the new method to account for the influence of possible soil-building resonance during ground shaking. The addition of this parameter has a very significant effect on the vulnerability classes. Based on the results available for 69 buildings, it was found that 28% are in the range of resonance. Furthermore, the use of the AHP method has shown that the coefficient of soil-building resonance contributes by 24% to the overall vulnerability index. The study underlines the importance of considering this parameter during the evaluation of the seismic vulnerability of buildings. Screening results indicating high vulnerability should normally be followed by a more detailed on-site investigation of the risk of soil-building resonance.

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