A three-tier procedure for the seismic evaluation of school buildings in Eastern Canada

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SUMMARY:
In Eastern Canada the seismic hazard is generally moderate and large urban centres are faced with similar earthquake hazard levels. To date, earthquake mitigation of public infrastructure has remained scarce and no systematic vulnerability assessment program has been implemented on a large scale. This paper presents a three-tier procedure for the seismic vulnerability assessment of Québec school buildings. Tier-1 screening aims to classify school buildings within four priority groups, with a view to identify facilities that are not at risk and discard them from the pool to be screened at the next level. At Tier-2, seismic microzonation mapping information is used with general data on structural configuration to prioritize the more detailed evaluations. Tier-3 is a vulnerability assessment procedure that should identify which facilities will require a detailed seismic evaluation and eventual mitigation: it is designed as a tool for school board professionals and technical personnel.

Keywords: Seismic vulnerability, seismic screening, microzonation.

1. INTRODUCTION

In Eastern Canada the seismic hazard is generally moderate with the exception of the Charlevoix region with higher seismicity. Large urban centres like Montréal and Québec City are faced with similar earthquake hazard levels with typical peak ground acceleration of 0.33g and 0.30g and spectral acceleration at 0.2 second of 0.64g and 0.55g, respectively. This seismic hazard level, considered as moderate, is typical for the St. Laurence and Ottawa River valleys where more than 45% of Québec's population is concentrated (ISQ, 2011). It is worth noting that considering the size of its population, Montréal has the second highest estimated seismic risk in Canada.

Post-earthquake damage reconnaissance reports around the world have shown that buildings with poor seismic design detailing are prone to structural and non structural damage during moderate earthquakes (Dolce, 2006; Spence, 2004; EERI, 2001). The observed poor seismic performance of school buildings is partly explained by their age and their irregular structural features (ATC, 2004). In 1988, the 5.9 M_w Saguenay earthquake caused tens of millions of dollars in damage (Tinawi and Mitchell, 1990). Damages observed in school buildings were mostly caused by large inter-storey drifts in flexible frames, soft stories and soil amplification effects (Tinawi *et al.*, 1989; Tinawi and Mitchell, 1990). Most school buildings in Québec have been constructed prior to the introduction of modern seismic design codes and standards (pre-1970), a situation raising concern for their seismic safety. To date, earthquake mitigation of public infrastructure has remained scarce and no systematic vulnerability assessment program has been implemented on a large scale. In this context, provincial and local governments would greatly benefit from robust seismic risk assessment methods that are adapted to their facilities and local seismicity, to prioritize interventions and put in place efficient risk management programs.

In Québec, there are approximately 2700 schools (or school campuses) including all affectations (public and private, K-12, colleges, universities) for more than 4000 buildings. Approximately 87% of schools are part of the public network, under the jurisdiction of the Québec Ministry of Education (MÉLS), which includes 1750 public K-12 representing more than 2700 buildings. This large number of buildings requires a progressive approach to their seismic evaluation, such as the one proposed here.

This study presents the first part of a comprehensive research project that aims to develop seismic vulnerability assessment procedures for Québec school buildings. The proposed approach is a based on a three-step evaluation procedure. Each step of the procedure is performed at a different scale in terms of number of buildings and the nature of the information used. Tier-1 screening is carried out on 2714 public K-12 school buildings of the province and aims to classify buildings within four priority groups, and in this way eliminate facilities that are not at risk from future assessment. Tier-2 screening is performed at the school board level, regrouping 30 to 185 buildings in a localized area. Tier-2 aims to prioritize the buildings that will be required to undergo more detailed assessment at the next level. Finally, Tier-3 is a more detailed vulnerability assessment procedure (from inspection and study of structural drawings) that should identify which facilities will require a detailed seismic evaluation with analysis and eventual mitigation. Tier-3 screening is designed as a tool for school board professionals and technical personnel to establish a differential seismic risk rating for school buildings that were assigned a higher priority. To develop this three-tier procedure a thorough inventory of the province's school buildings was conducted to identify significant parameters to use in Tier-1 and Tier-2 screenings. The procedure is presented in the form of simple decision trees or logical matrices. To validate the procedure, Tier-2 and Tier-3 screenings are being performed on school buildings in Montreal Island and other regions.

2. SCHOOL BUILDING EVALUATION PROCEDURE

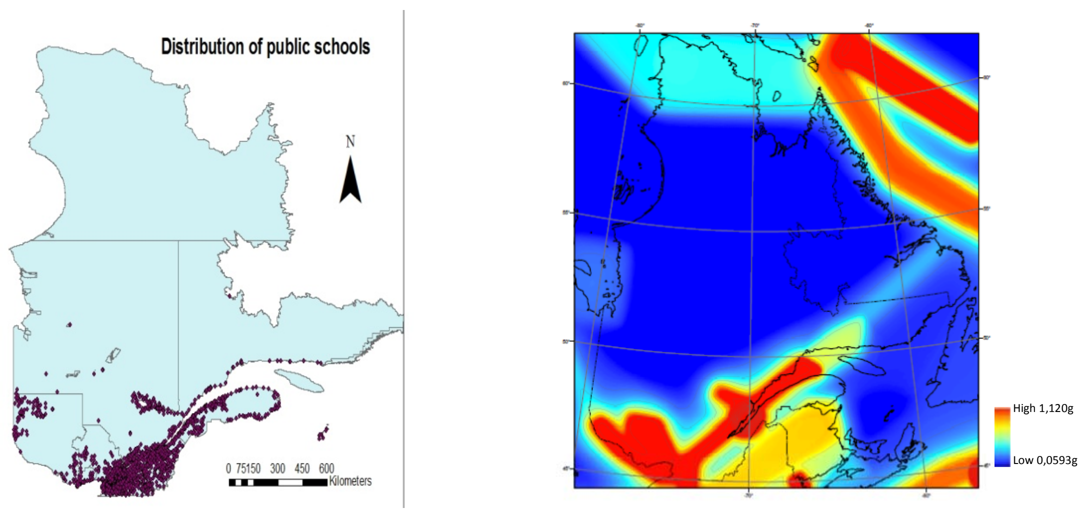
Most seismic risk mitigation programs for schools around the world use a screening procedure to prioritize detailed evaluation. The state of Oregon has undertaken the seismic screening of its school facilities using the FEMA 154 method, requiring information from inspection and structural drawings (McConnell, 2007; ATC, 2002). Local studies in Italy used a multi-level procedure similar to the one proposed here, with a focus on reinforced concrete and masonry structures (Dolce, 2006; Borzi *et al.,* 2011). The first level used basic data, already available to government agencies, to eliminate adequately designed buildings from following assessment levels.

These two examples of risk mitigation programs have in common the use of a Rapid Visual Screening (RVS) approach usually performed to identify seismically hazardous buildings by exposing structural deficiencies. Potential deficiencies and structural characteristics are correlated for different building classes using predefined sets of scores calibrated by experts or simplified analytical models. Buildings identified as more vulnerable from this scoring procedure must then be analyzed in greater detail. In the United States the publication of FEMA 154 and its companion FEMA 155 (ATC, 2002) described a score-based RVS developed from seismic hazard representations and building typologies. In Canada, the only screening procedure officially available for seismic evaluation is a score assignment procedure ranking buildings according to their seismic design load demand relative to the NBCC 1990 prescriptions (IRC, 1992). This procedure, known as IRC92, has been recently revised and integrated into software. (Saatcioglu *et al.* 2010). Karbassi and Nollet (2008) proposed an index assignment procedure compatible with the regional seismicity of Québec. Adapted from FEMA 154, it considers Eastern Canadian seismic hazard and spectral amplification factors defined according to the NBC 2005 soil classification (NRC-IRC, 2005). Tischer (2012) proposed an enhanced Tier-3 method, based on FEMA 154, which includes revised score modifiers for school buildings with specific consideration of the severity of structural irregularities (vertical and horizontal), potential for pounding due to insufficient separation and material deterioration. It was verified with the detailed assessment (using inspection, study of drawings and AVM) of a pool of 101 separate buildings on 16 high school campuses designated as emergency shelters on the Island of Montreal. The method proved more discriminating than FEMA 154 and IRC92. However, in spite of the recent availability of several improved methods, no systematic vulnerability assessment program has been implemented yet for schools in Québec.

In the province of British Columbia on the Pacific Coast, the earthquake hazard is higher than in Eastern Canada, and the Ministry of Education has committed to invest 1,5 G$ until 2025 to evaluate about 700 school buildings and upgrade them as necessary. These schools were identified among 850 schools from an assessment procedure with basic structural data obtained from inspection (Pandey and Ventura, 2010). Clearly, the issues take a different scale in the two parts of the country. In Québec, MÉLS and the various public school boards are responsible for the asset management of more than 3800 buildings, of which 426 are located on the Island of Montréal. Most of the Québec schools (83%) have been constructed before 1970, which is before earthquake-resistant design clauses were implemented in the National Building Code (NBC) and before Canadian seismic hazard levels were well understood and mapped. Therefore, even if several of the mitigation solutions used in schools projects in the West can eventually be applicable to some high-risk projects in the East, it is important that the assessment of building vulnerability address the specific characteristics and challenges of Eastern Canada.

3. QUEBEC SCHOOL BUILDINGS PORTFOLIO

The first step before embarking in the seismic vulnerability assessment procedure was to proceed with a general inventory to characterize the school buildings portfolio. Figure 3.1(a) shows the distribution of public schools in the Province, a territory covering more than 1 542 000 km^2. It can be observed that the large majority of the schools are located in the south of the Province and along the St. Laurence River valley, a moderate to high seismic hazard area as shown by the uniform hazard map of Figure 3.1(b) for reference stiff soil and a probability of exceedance of 2% in 50 years (NRCAN, 2010).



(a) Distribution of public schools in Québec

(b) Uniform hazard map for Québec, PGA for 2% probability of exceedance in 50 years

Figure 3.1. Distribution of public schools in Québec and seismic hazard

A previous study by Brayard (2008) addressed the structural characterization of Québec schools and identified five dominant structural types using correlation between year of construction (YC), use and floor area. Figure 3.2 shows the distribution of construction types according to year of construction. Prior to 1950, buildings were mostly constructed by religious institutions and steel moment resisting frames (SMF) were the dominant type for that period. The intensive school construction period that followed mostly used wood structures (WPB) for small schools and reinforced concrete moment resisting frames (CMF) and shear wall structures (CSW) for larger schools. Post-1980 buildings include all previous types as well as steel braced frames (SBF). Although the lateral load resisting system (LLRS) is a key parameter in seismic vulnerability assessment, this information was left for Tier-3 and not selected to be used in the pre-assessment procedure (Tier-1 and Tier-2) mainly because it cannot be confirmed without a building inspection or the study of structural drawings (assuming such drawings are available).

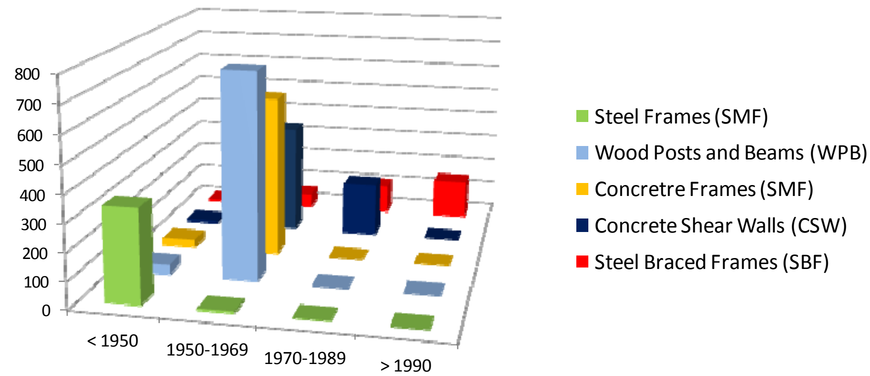


Figure 3.2. Distribution of public schools according to year of construction and LLRS type

4. GENERAL CONCEPT OF THE THREE-TIER PROCEDURE

The general concept of the proposed three-tier procedure encompasses the three components of the building's seismic risk R: Seismic hazard and geotechnical site effects (RG), Building structural vulnerability (RB) and, Consequences of structural dysfunction (RC). Each step of the procedure introduces a more detailed level of information to refine the seismic risk evaluation. This concept is mapped in Figure 4.1.

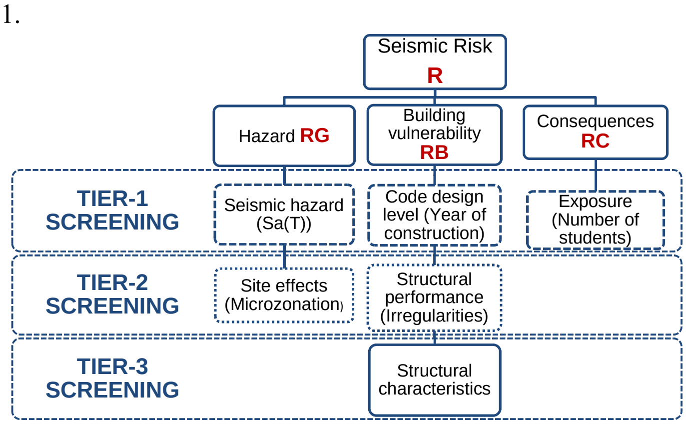


Figure 4.1. General concept map of the proposed three-tier evaluation procedure

In each screening step (or tier) the school buildings are assigned to one of four priority evaluation groups:

- Group G4: Low risk facilities identified in Tier-1 screening and that could be excluded from the priority list before Tier-2 screening is applied.
- Group G3: Low to Moderate priority facilities that must undergo Tier-2 screening to determine if a Tier-3 screening is required.

- Group G2: Moderate to High priority facilities that must undergo Tier-2 screening to determine if a Tier-3 screening is required.
- Group G1: High priority facilities that must undergo Tier-3 screening.

5. TIER-1 SCREENING

5.1 Definition of screening parameters criteria

Tier-1 screening must rely on basic information available in the MELS database. Three parameters are used to qualify each component of the seismic risk: (i) the seismic hazard (SH) as defined from mapping information prescribed in the 2010 National Building Code of Canada, (i) the year of construction (YC) that could be related to the code design level and structural vulnerability, and (iii) the number of students (NS) relating to the exposure (Figure 4.1). Buildings identified not at risk are assigned to group G4, while others will be assigned to groups G1, G2 or G3 depending on the three basic parameters (SH, YC and NS). To determine the priority group to be assigned to each building, the three selected parameters (SH, YC and NS) are divided into three relative risk categories (high, moderate and low) defined in Table 5.1.

Table 5.1. Relative seismic risk categories for Tier-1 screening.

Relative risk category	Seismic hazard (SH)	Year of construction (YC)	Number of students (NS)
High	$Sa(0,2) \geq 0,65g$	$YC < 1970$	$NS \geq 1000$
Moderate	$0,50g \leq Sa(0,2) < 0,65g$	$1970 \leq YC < 1990$	$100 \leq NS < 1000$
Low	$Sa(0,2) < 0,50$ g	$YC \geq 1990$	$NS < 100$

Since 2005, seismic hazard in Canada is calculated in the form of uniform hazard spectra (UHS) at specific geographical locations (Adams and Atkinson, 2003) at a probability of exceedance of 2% in 50 years. This seismic hazard definition provides an improved, period-dependent representation of earthquake effects on structures, but it does not propose a relative seismic hazard classification. In view of assigning a relative seismic hazard level (high, moderate and low) to school buildings, the spectral acceleration value at 0,2 second at the school location was selected over spectral acceleration values at other periods. This choice was based on the approximate relation between the fundamental period (T in s) of the building and the number of stories (N), (T 0,1N). Using a sample of 1859 buildings out of the 2714, the number of stories was determined using Google™-Maps application. It was determined that 97% of buildings have three stories or less, or a period estimated to be smaller than 0,3s. The limits between the three seismic risk categories were established based on the distribution of the population and the schools according to the spectral acceleration values of the cities of the Province.

The year of construction (YC) was selected as the Tier-1 parameter for the structural vulnerability evaluation of the seismic risk. The three periods of construction were defined according to the evolution of the seismic performance requirements for buildings specified in the National Building Code (NRC-IRC, 2010) and design standards (CSA, 2010). Although seismic design provisions were first introduced in the 1941 NBC edition, they have evolved considerably over the years and most buildings constructed prior to 1970 are considered as pre-code buildings. The 1970 NBC edition introduced the first probabilistic zoning maps as well as a structural flexibility factor dependent on the fundamental period of the structure (Mitchell *et al.,* 2010). The 1990 NBC edition required that design and detailing be consistent with the ductility factors.

The number of students (NS) was selected as the Tier-1 parameter for the evaluation of the consequences. Statistical analysis of losses of life in past earthquakes has shown a clear correlation between the number of deaths and the number of damaged buildings (Coburn and Spence, 2002). To establish the limits between the three seismic risk categories in relation with the number of students, a statistical analysis of the recurrence of the number of students per schools was carried out. Furthermore, MELS identifies small town elementary schools (K-6) with less than 100 students while larger secondary schools have usually more than a thousand students.

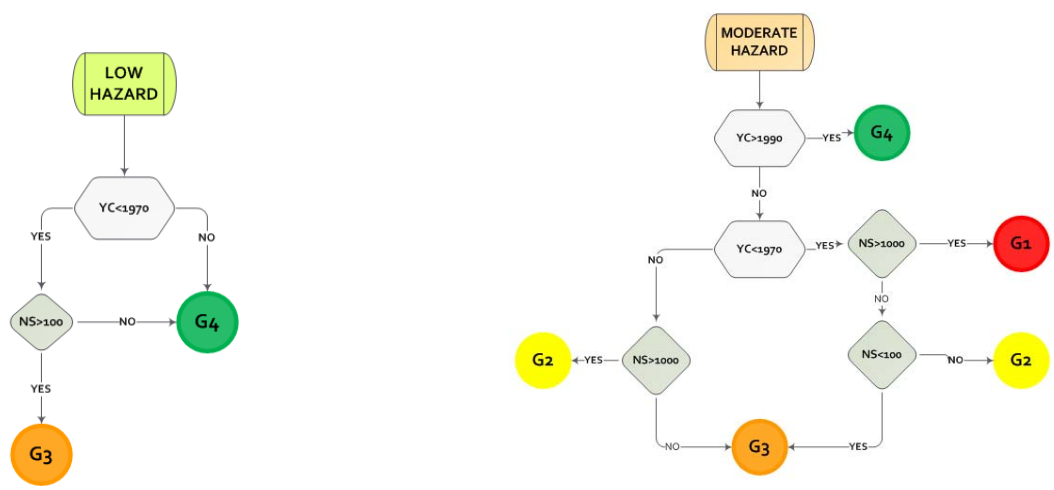
Table 5.2 presents the proportion of schools in each relative seismic risk category for the 2714 public K-12 schools. It can be observed that in terms of seismic hazard and exposure criteria (SH and NS), most schools might be considered in a moderate risk category, while in term of building vulnerability criteria (YC) a large number of schools (83%) might be considered in a high risk category.

Table 5.2. Proportion of schools in each relative seismic risk category

Relative seismic risk level	Seismic hazard criterion (SH)	Year of construction criterion (YC)	Number of students criterion (NS)
High	2,7%	83,0%	5,7%
Moderate	72,3%	11,9%	73,9%
Low	25,0%	5,2%	20,4%

5.2 Decision tree

The Tier-1 screening procedure is conceptualized by a decision tree (Figures 5.1 and 5.2) for the three levels of seismic hazard. As shown in Figure 5.2, for high seismic hazard, this concept is also illustrated by a logical matrix a representation more suitable to implement the procedure in a database.



(a) Decision tree for low seismic hazard (b) Decision tree for moderate seismic hazard

Figure 5.1. Schematic of Tier-1 screening procedure for low and moderate seismic hazard

In low seismic hazard regions ($Sa(0,2) < 0,50$ g), only older schools (built before 1970) with more than 100 students are kept for Tier-2 screening (group G3). All remaining schools are considered at low risk and therefore excluded from subsequent evaluation (group G4). In moderate seismic hazard regions ($0,50g \leq Sa(0,2) < 0,65g$), school buildings built after 1990 are systematically assigned to group G4 and excluded from subsequent evaluation. Larger and older schools, with more than 1000 students and built before 1970, are assigned to group G1 and will undergo Tier-3 screening, a detailed vulnerability assessment requiring an inspection and study of structural drawings. All other schools are assigned to groups G2 or G3 and will undergo a Tier-2 intermediate screening. In high seismicity hazard regions ($Sa(0,2) \geq 0,65g$), school buildings built after 1990 are systematically assigned to group G4 and excluded from subsequent evaluation. Larger or older schools, with more than 1000 students or built before 1970, are assigned to group G1 and will undergo Tier-3 screening. All other schools are assigned to groups G2 or G3 and will undergo a Tier-2 intermediate screening.

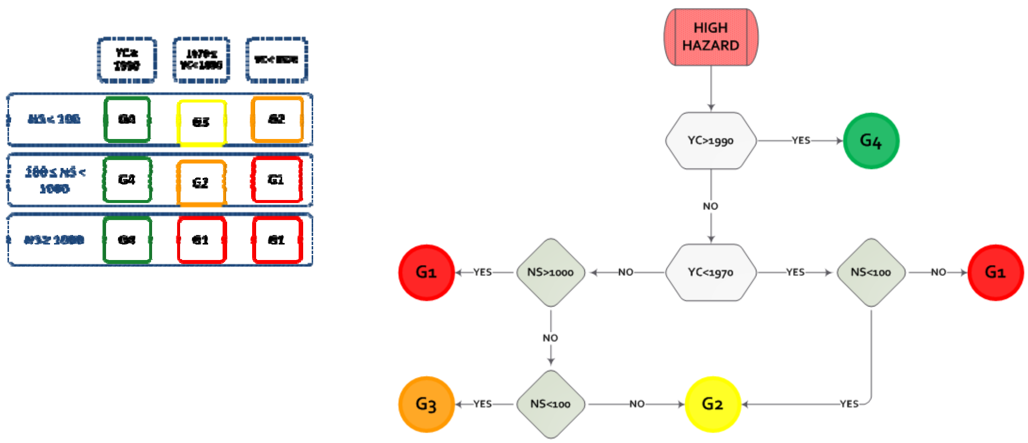


Figure 5.2. Schematic of Tier-1 screening procedure for high seismic hazard

5.4 Results

Results of Tier-1 screening of the 2714 K-12 public school buildings are summarized in Table 5.3. It is seen that 16% of school buildings are at low risk and do not require a seismic evaluation. At the opposite, 4% of school buildings are classified as high priority for seismic evaluation and should go directly through Tier-3 screening (bypassing Tier-2). The remaining school buildings are considered to have a moderate priority for seismic evaluation. Considering, the minimum information used to obtain this classification, Tier-2 screening must be performed on school buildings in groups G2 and G3 to ascertain their priority and determine whether adverse site conditions and / or structural irregularities are present, which should promote them to a higher priority group (G1 or G2).

Table 5.3. Distribution of K-12 public school buildings after Tier-1 screening

Priority evaluation group	Number of buildings	Percentage
G1 High priority	112	4%
G2 Moderate to High priority	1318	48%
G3 Moderate to Low priority	860	32%
G4 Low priority	424	16%

6. TIER-2 SCREENING

6.1 General

Tier-2 screening is performed on facilities initially assigned to groups G2 or G3, and essentially serves to prioritize the more detailed screening evaluations that are required at the next level. Seismic microzonation mapping information is used along with data on building configuration to identify facilities with structural irregularities. As such Tier-2 does not require a detailed inspection of the facilities unless to ascertain technical data that appears doubtful.

6.2 Microzonation

Microzonation maps are available for the two largest urban centers in Québec: Montreal Island (hazard data obtained from CSRN[1]) and Québec City (LeBoeuf *et al.*, 2011). These maps identify seismic geotechnical site classes as proposed by Finn and Wightman (2003) and introduced in NBC 2005 (NRC-IRC, 2005). Five site classes (A, B, C, D and E) are associated to site amplification factors that reflect local soil conditions; these classes are defined by standard geotechnical parameters (shear wave velocity in the top 30 m soil layer, undrained shear strength or Standard Penetration Test blow-count). An additional class (F) refers to potentially vulnerable sites for which a specific soil dynamic evaluation is required; as such, site class F is not identified on microzonation maps. Amplification effects on site classes D and E are considered in Tier-2 screening, leading to a higher priority group for buildings on these sites. Site classes A or B are associated to rock or hard rock and amplification factors are smaller than unity (Class C is the reference).

6.3. Horizontal plane irregularities

Structural configuration irregularities include plan and vertical irregularities, short columns, soft story and pounding potential due to insufficient separation between adjacent buildings. They are generally recognized to increase seismic vulnerability. Tischer (2012) and Brayard (2008) have pointed out that plan irregularities associated with re-entrant corner are frequent in Québec school buildings, and this was selected as a parameter in Tier-2 screening. According to ASCE/SEI 7-10 (ASCE, 2010) a re-entrant corner irregularity is defined where both plan projections of the structure beyond a re-entrant corner are greater than 15% of the plan dimension of the structure in the given direction. Tischer (2012) proposed an additional criterion to classify the irregularity as severe when a re-entrant corner is greater than 30% of the plan dimension. These two conditions are used to qualify the in-plane irregularity as moderate or severe.

Table 6.1 presents the logical matrix used to determine the priority group assigned at the conclusion of Tier-2 screening, for low, moderate and high seismic hazard. It considers soil site class and the severity of the in-plane irregularity and it is used to determine if the priority group assigned by Tier-1 screening should remain the same (G2 or G3), be automatically assigned to a specific category or promoted to the next higher priority group. It should be noted that buildings on soils of site classes A or B with no or moderate plane irregularity are all assigned to priority group G3.

Table 6.1. Criteria to promote priority groups based on in-plane irregularities

	Low Seismic Hazard Sa(0,2) < 0,50 g			**Moderate and High Seismic Hazard Sa(0,2) ≥ 0,50 g**		
Soil site class	**Insignificant irregularity**	**Moderate irregularity**	**Severe irregularity**	**Insignificant irregularity**	**Moderate irregularity**	**Severe irregularity**
A, B	G3	G3	G3	G3	G3	G2 or G3
C	G3	G2 or G3	G2 or G3	G3	G2 or G3	G2 or G3
D	G2 or G3	G2 or G3	G2	G2 or G3	G2 or G3	G1
E	Promote	Promote	Promote	G2	G1	G1

6.4 Results

Tier-2 screening was applied to 283 school buildings of Montreal Island, administered by five different school boards, using microzonation information and geometrical configuration. To identify the presence of plan irregularities in school buildings without having access to the building layouts, a simple relation is found between the area of the building footprint available from a GIS database and its surface envelope area. Figure 6.1 presents the distribution of buildings between the four priority

[1]CRSN : Canadian Seismic Research Network linking 26 researchers from 8 universities across Canada (http://csrn.mcgill.ca/main.htm)

groups after Tier-1 and Tier-2 screening. It should be noted that site class E has not been inventoried from the microzonation, while 30 buildings were located on site class D and 131 on site class C. After Tier-2 screening, the number of buildings in priority group G1 increased from 10 to 35. Most of the buildings promoted to priority group G1 were on site class D with severe irregularities. .

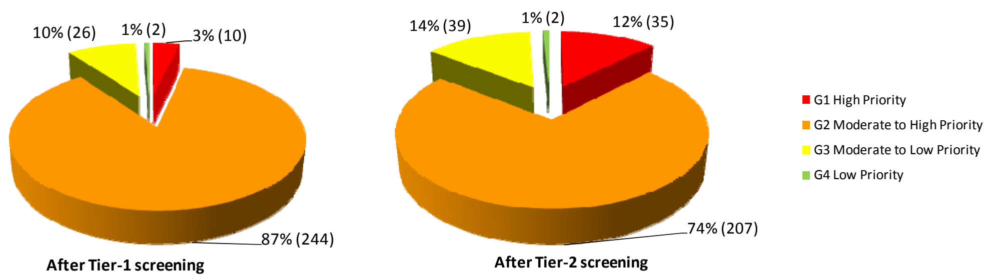


Figure 6.1. Results of Tier-1 and Tier-2 screening of public school buildings on Montreal Island

7. TIER-3 SCREENING

Using information from inspection and structural drawings, Tier-3 is a detailed vulnerability assessment procedure to identify the facilities that will require a detailed seismic evaluation and eventual mitigation. The Tier-3 screening procedure is still under development. It is based on Tischer's work (2012) and will be adapted for the most frequent school building types. Details considered in Tier-3 screening are structural type, structural weaknesses (horizontal and vertical irregularities, deterioration and short columns), potential for pounding and local soil conditions. This procedure will be calibrated using ambient vibration measurements (AVM) in several school buildings to extract their dominant dynamic characteristics and estimate their seismic demand level.

7. CONCLUSION

This paper has presented a three-tier procedure for the seismic evaluation of school buildings in Eastern Canada, in the province of Québec. As such, this procedure is a preliminary assessment programme that aims at its first level (Tier-1) to identify buildings that are considered at low risk and can therefore be excluded from subsequent evaluation, and at its second level (Tier-2) to identify buildings that should undergo a detailed vulnerability assessment requiring inspection and study of structural drawings. Tier-1 screening uses seismic hazard mapping information as prescribed in the 2010 National Building Code of Canada and basic information such as the year of construction and number of students, and is used on 2714 K-12 public school buildings under the jurisdiction of the Québec Ministry of Education. Tier-2 uses microzonation information and geometrical configuration data obtained using a GIS database. At the conclusion of Tier-2 screening, the seismic vulnerability of buildings that are assigned a higher priority is evaluated through a score assessment procedure for detailed seismic evaluation and eventual mitigation. To validate the complete three-tier procedure, Tier-2 and Tier-3 screening is currently being carried out on school buildings on the Island of Montreal. The complete procedure will be implemented in a computer interface for its application by school board professionals and technical personnel.

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