# Seismic risk management of buildings with a focus on post-earthquake functionality

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Building Resilient Communities

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***Toronto – 20 February 2015***

# Outline

- Introduction
- Definitions and rationale for seismic risk management of OFCs in buildings
- Seismic vulnerability assessment of buildings designated as emergency shelters (public schools and community centers)
- Scrapbook of OFC damages in earthquakes
- Overview of CSA S832-14 *Seismic risk reduction of operational and functional components in buildings*
- Seismic functionality assessment of critical buildings (hospitals, schools, community centres, fire stations)
- Challenges and Opportunities
- Conclusions

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# Introduction

- Emergency response to natural or man-made disasters
- Natural hazards:

Source: ville.montreal.qc.ca/csc

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# Building Design Philosophy

A well designed and constructed building is expected to provide safety and comfort to its occupants when such a building is subjected to building occupant loads and other environmental loads such as wind, snow, rain, ice, earthquake etc.

A building is made up of various components that can be categorized into two groups:

**Structural components (SC)**

and

**Operational and Functional Components (OFC)**

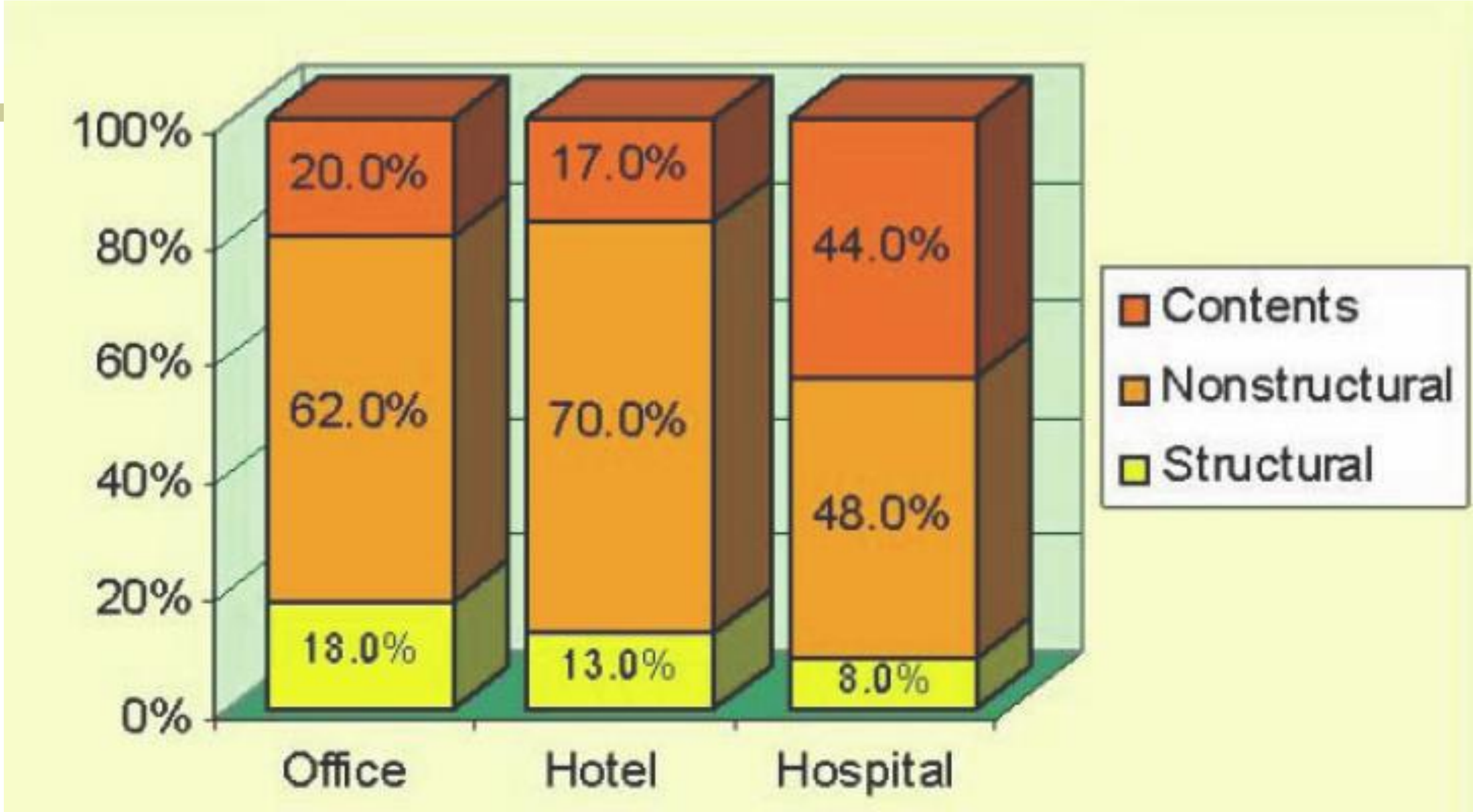
also known as **Non-structural components, (NSC)**.

OFCs are those components housed inside or attached to the building structure and that are required for the function and operation of buildings.

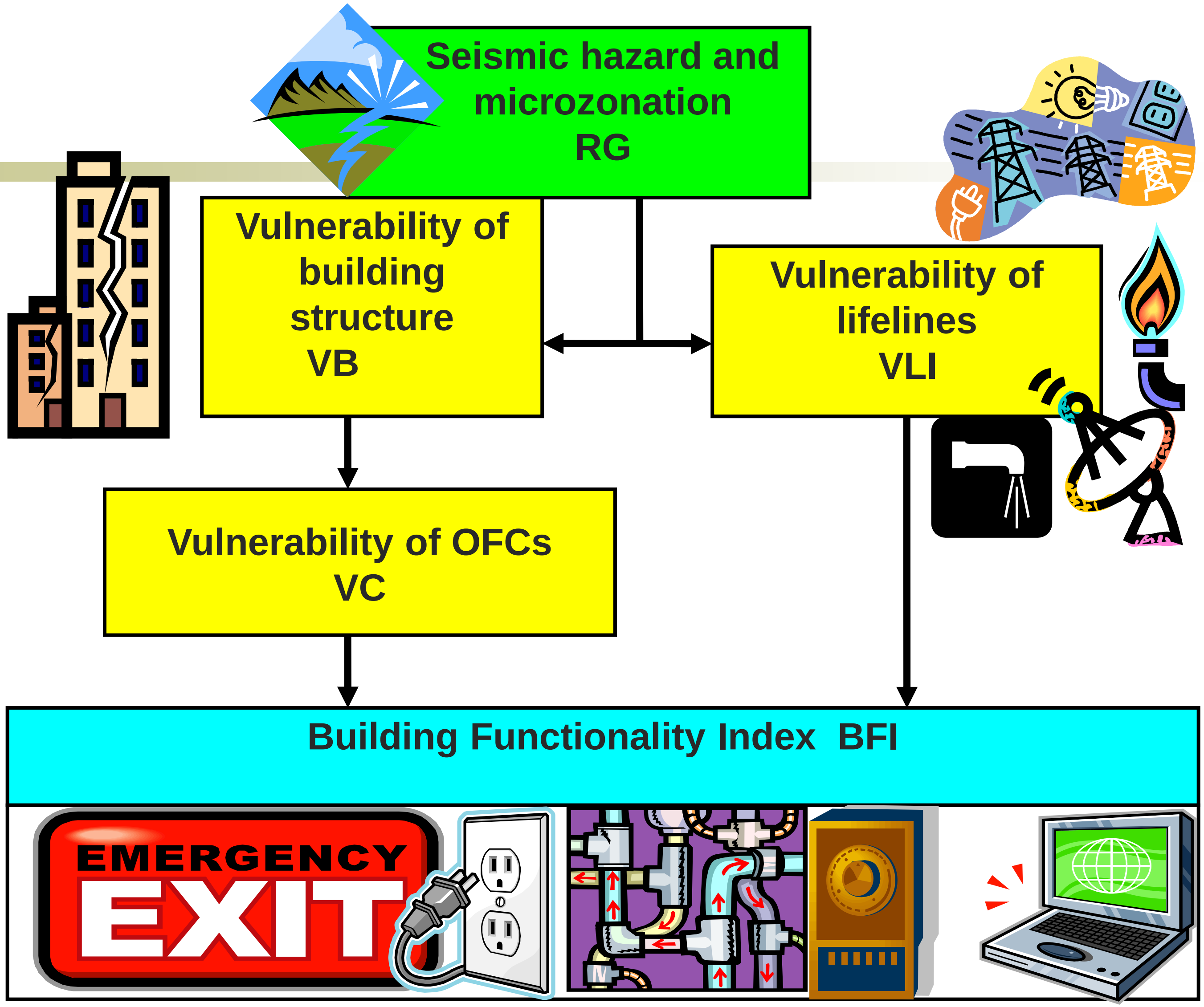
This is to acknowledge the close relationship that exists between the seismic behaviour of the structural system and the seismic performance of the other components in a building system.

OFCs (as per CSA S832-14) are further divided into:

Architectural (External & Internal),
Building Services (Mechanical, Plumbing, Electrical, Telecommunications)
and Building contents (Common & Specialized).




Relative dollar value of building components according to use and occupancy - Taghavi and Miranda (2003).

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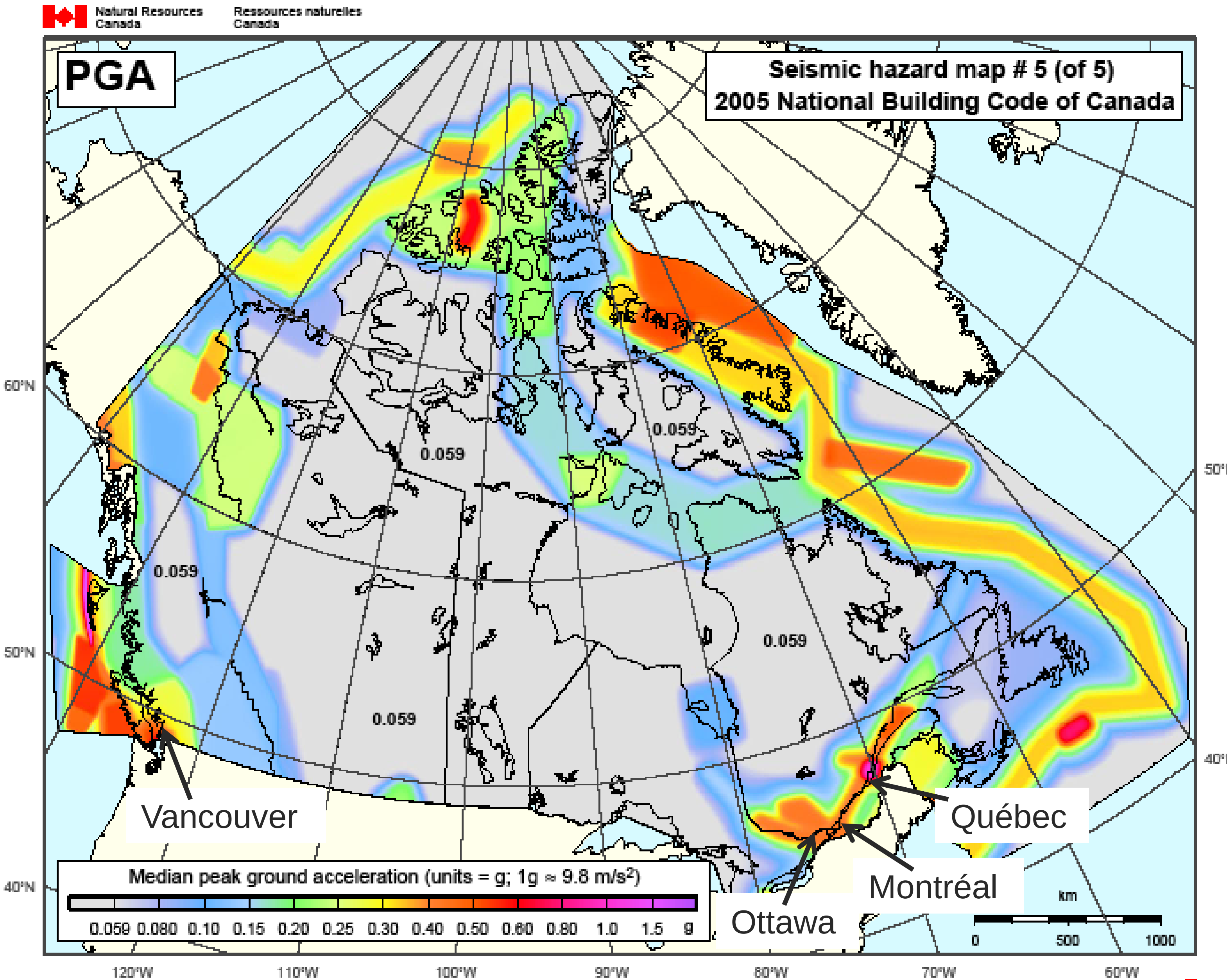
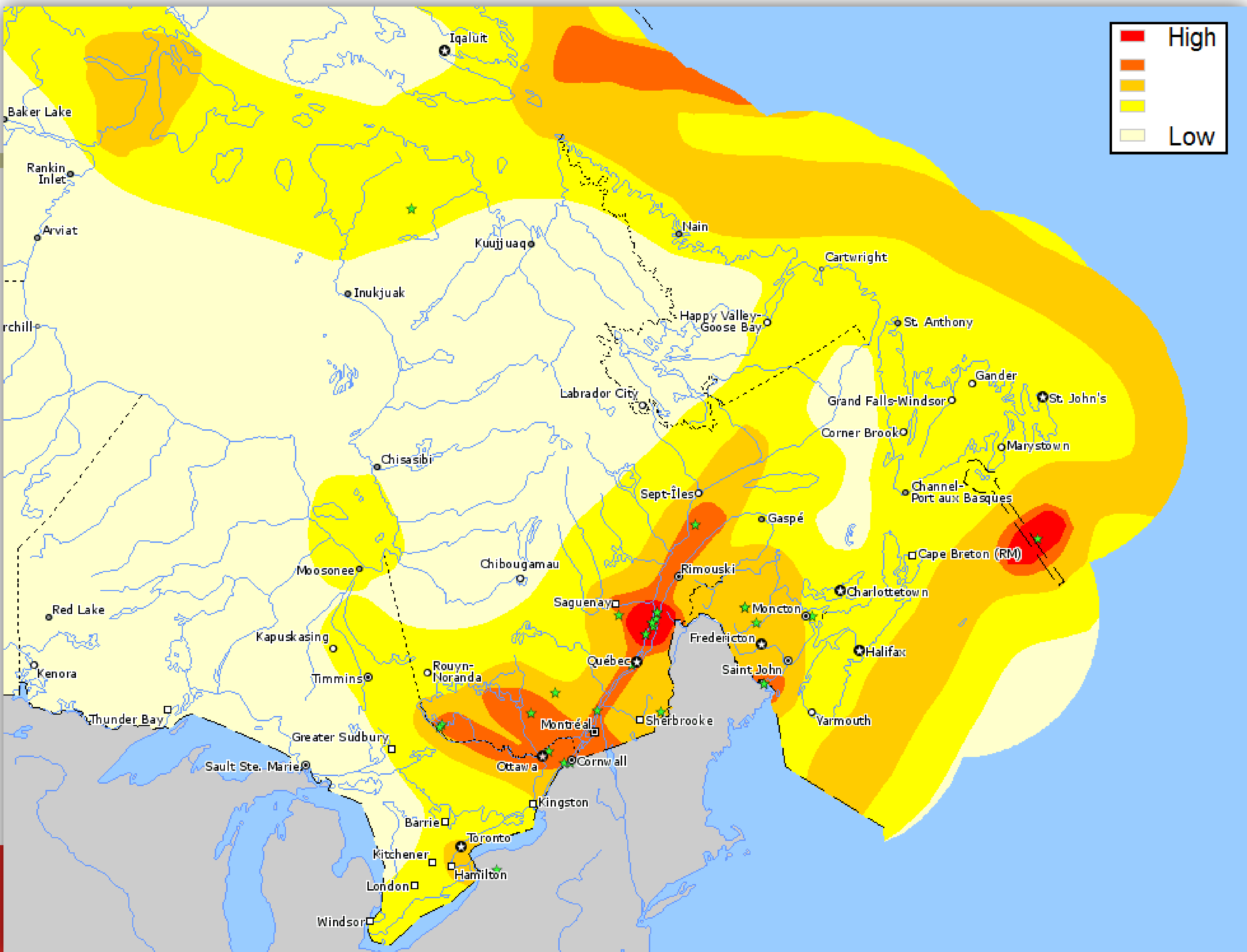



Peak ground acceleration at a probability of 2%/50 years for firm ground conditions (NBCC soil class C).

Canada

# ICLR Friday Forum 20 February 2015



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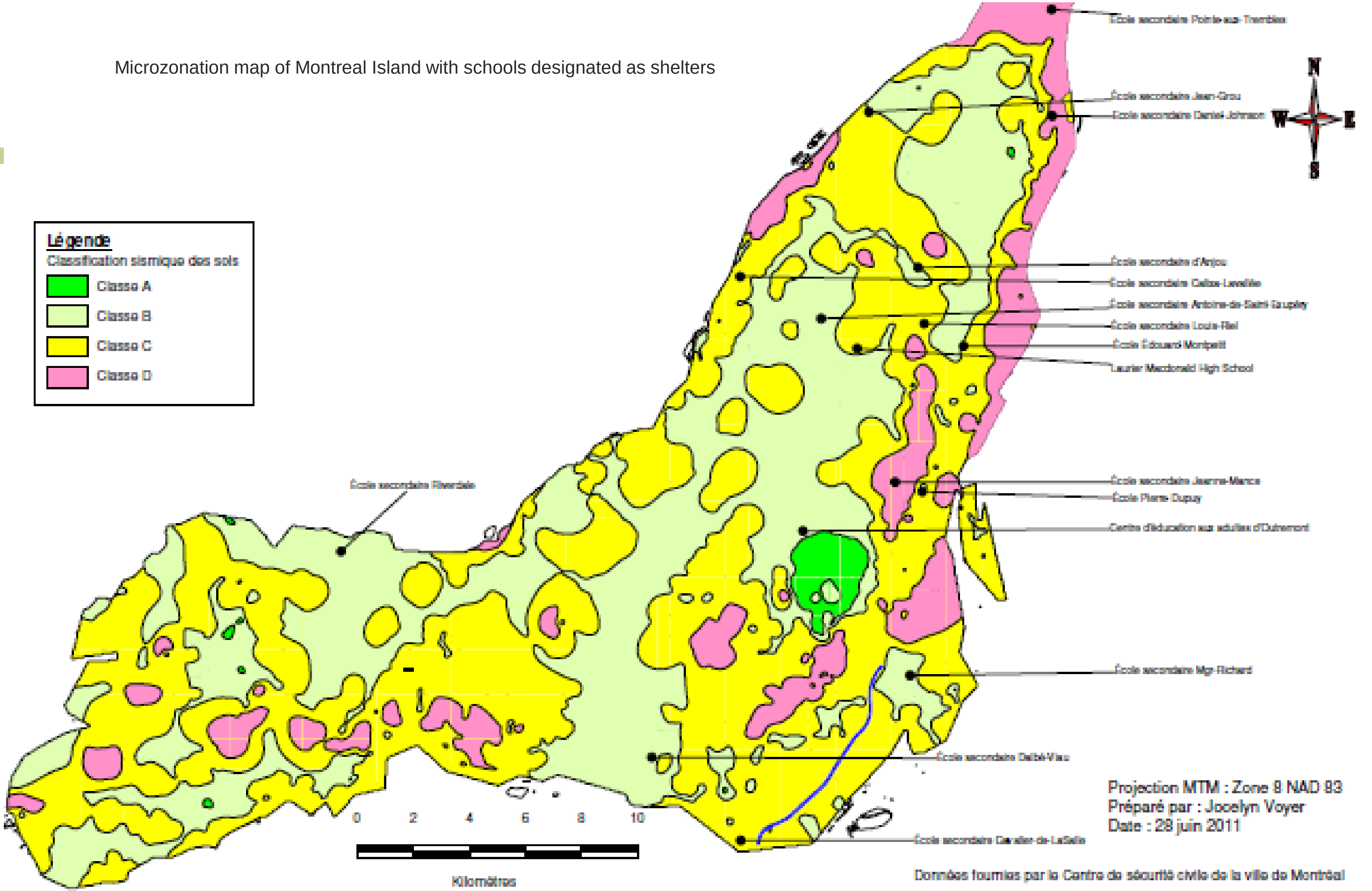
Microzonation map of Montreal Island with schools designated as shelters

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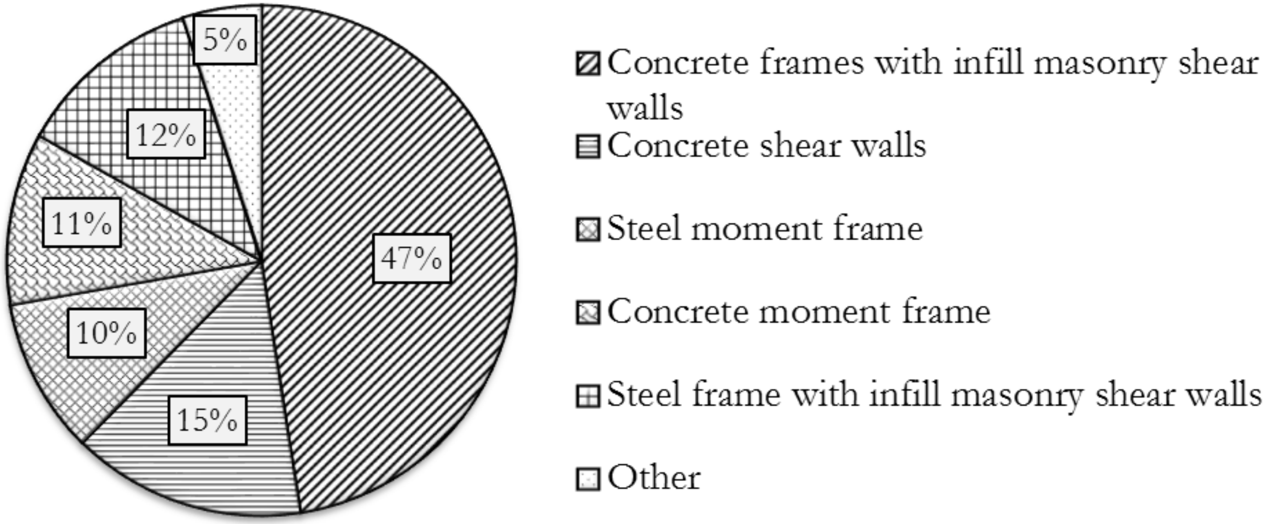
# Vulnerability assessment of school buildings designated as emergency shelters (2008-2011)

- 16 public high school campuses comprising 101 buildings (isolated or with separation joints);
- Assessment of each building (drawings; inspection; AVM for structural identification; survey of URM walls)
- Types of lateral load resisting systems:



# Enhanced screening procedure (adapted from FEMA 154 and NZ practice) – work of Helene Tischer

- Indices vary between -2.1 and 7.2
- Used to establish priorities for more detailed evaluations; for CSC to select shelters than can serve after a damaging earthquake

| Seismic Vulnerability | Probability of collapse under maximum design earthquake (NBC 2010) | Index |
|---|---|---|
| Very high | 100% | ≤ 0.0 |
| High | 10% à 100% | 0.1 – 1.0 |
| Moderate | 1% à 10% | 1.1 – 2.0 |
| Low | Moins de 1% | > 2.0 |

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## *École secondaire (Name withheld)*

### DATA COLLECTION FORM

| | | | |
|---|---|---|---|
| School: École secondaire (Name withheld) | | Address: Withheld | |
| Latitude: Withheld | Longitude: Withheld | District: Withheld | |
| School board: Withheld | | Number of students: 1202 | Y |
| Building ID: B1 | Number of stories: 4 | Floor area: 2280 $m^2$ | In |

Satellite plan view


Picture

| Structural Type | | Choice | Certainty [%] |
|---|---|---|---|
| Wood | WLF | | |
| | WPB | | |
| Steel | SMF | | |
| | SBF | | |
| | SLF | | |
| | SCW | | |
| | SIW | | |
| Concrete | CMF | | |
| | CSW | | |
| | CIW | 1 | 80% |
| | PCF | 2 | 20% |
| | PCW | | |
| Masonry | RML | | |
| | RMC | | |
| | URM | | |

| Pounding | |
|---|---|
| Joint depth, d [cm]: | |
| Height of lower building, H [m]: | |
| Minimum story height, X [m]: | |
| Difference in story height y [m]: | |
| 20% Story height [m]: | |

| Soil type | |
|---|---|
| A | |
| B | |
| C | x |
| D | |
| E | |
| F | |
| Unknown | |

Comments

A small part of the

Only a small part o

the rest is 3 storie

Prefabricated slab

Concrete walls arc

| Structural Weakness | Low | Significant | Severe | Cert. |
|---|---|---|---|---|
| 1. Horizontal Irregularities | | | | |
| Re-entrant corners | | x | | 100% |
| Asymmetric stairways | | | | |
| Asymmetric partition walls | | | | |
| Torsion in LFRS | | | | |
| Diaphragm discontinuity | | | | |
| Out of plane offset | | | | |
| Other | | | | |

| Structural Weakness |
|---|
| 2. Vertical Irregularities |
| Steps in elevation view |
| Soft Story |
| Building on Hill |
| Change in structural type |
| Other |
| 3. Deterioration |
| 4. Short Concrete Columns |

## *École secondaire (Name withheld)* — *Building B1*

### SCORE CALCULATION FORM

| | | | |
|---|---|---|---|
| School: École secondaire (Name withheld) | | Address: Withheld | Postal Code: Withheld |
| Latitude: Withheld | Longitude: Withheld | District: Withheld | |
| School board: Withheld | | Number of students: 1202 | Year of construction: 1973 |
| Building ID: B1 | Number of stories: 4 | Floor area: 2280 $m^2$ | |

Satellite plan view


Picture

### CALCULATIONS

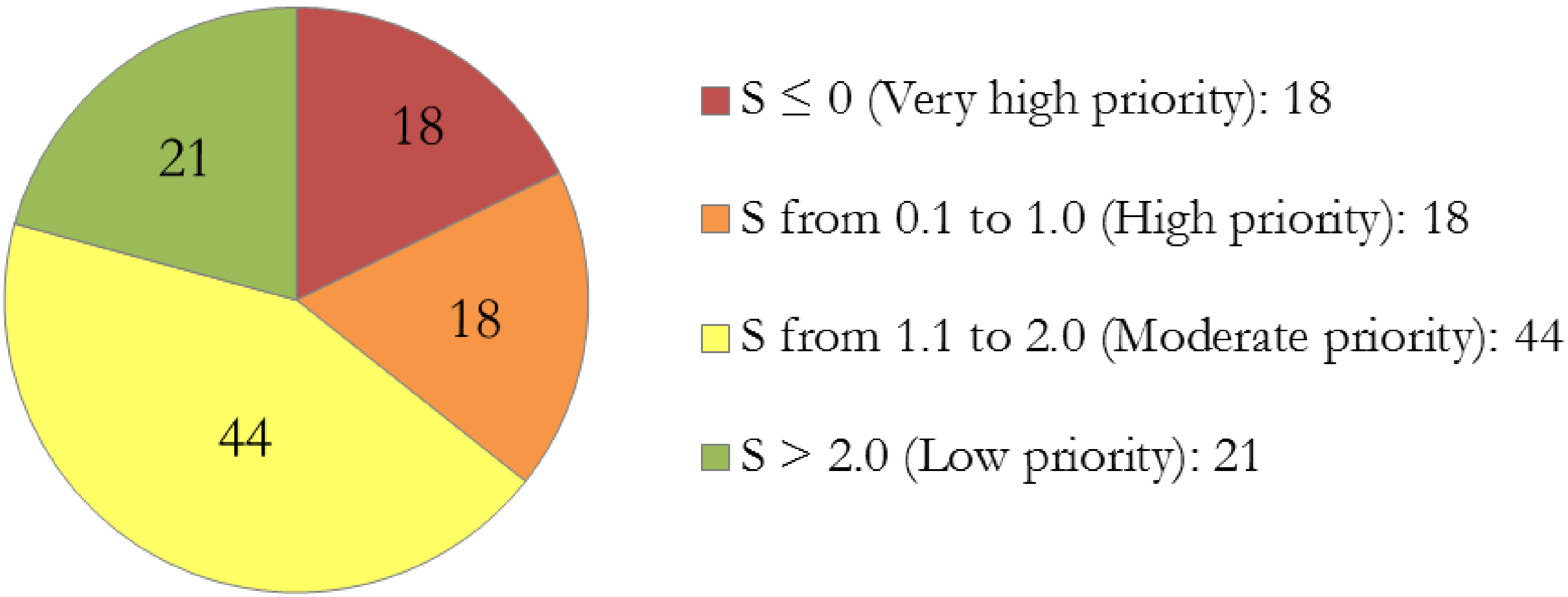
Seismicity: Moderate

| | Choice | | | Comments | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | | |
| Structural type | CIW | PCF | | | |
| Certainty | 80% | 20% | | | |
| Basic Structural Hazard Score | 3.1 | 3.2 | | | |
| Score Modifiers | | | | | |
| Pre-Code | 0.0 | 0.0 | | | |
| Post-Benchmark | 0.0 | 0.0 | | | |
| Mid Rise Buildings (4 to 7 stories) | 0.0 | 0.1 | | | |
| Soil Type | 0.0 | 0.0 | | Soil type: | C |
| Horizontal irregularities | -0.6 | -0.6 | | Effect (worst case): | Significant |
| Vertical irregularities | -0.6 | -0.6 | | Effect (worst case): | Significant |
| Deterioration | 0.0 | 0.0 | | Effect: | None |
| Short concrete columns | 0.0 | 0.0 | | Effect: | None |
| Pounding effects | | | | Effect: | Severe |
| Floor misalignment | -0.6 | -0.6 | | Vertical misalignment ≤ 20% of story height | |
| Total Score | 1.3 | 1.5 | | | |

### FINAL SCORE

| | |
|---|---|
| Structural type: | CIW |
| Final Score: | 1.3 |
| Probability of collapse: | ≥ 1% |
| Collapse potential: | Moderate |

# Summary of results (101 school buildings)




Priority of intervention = Seismic vulnerability level

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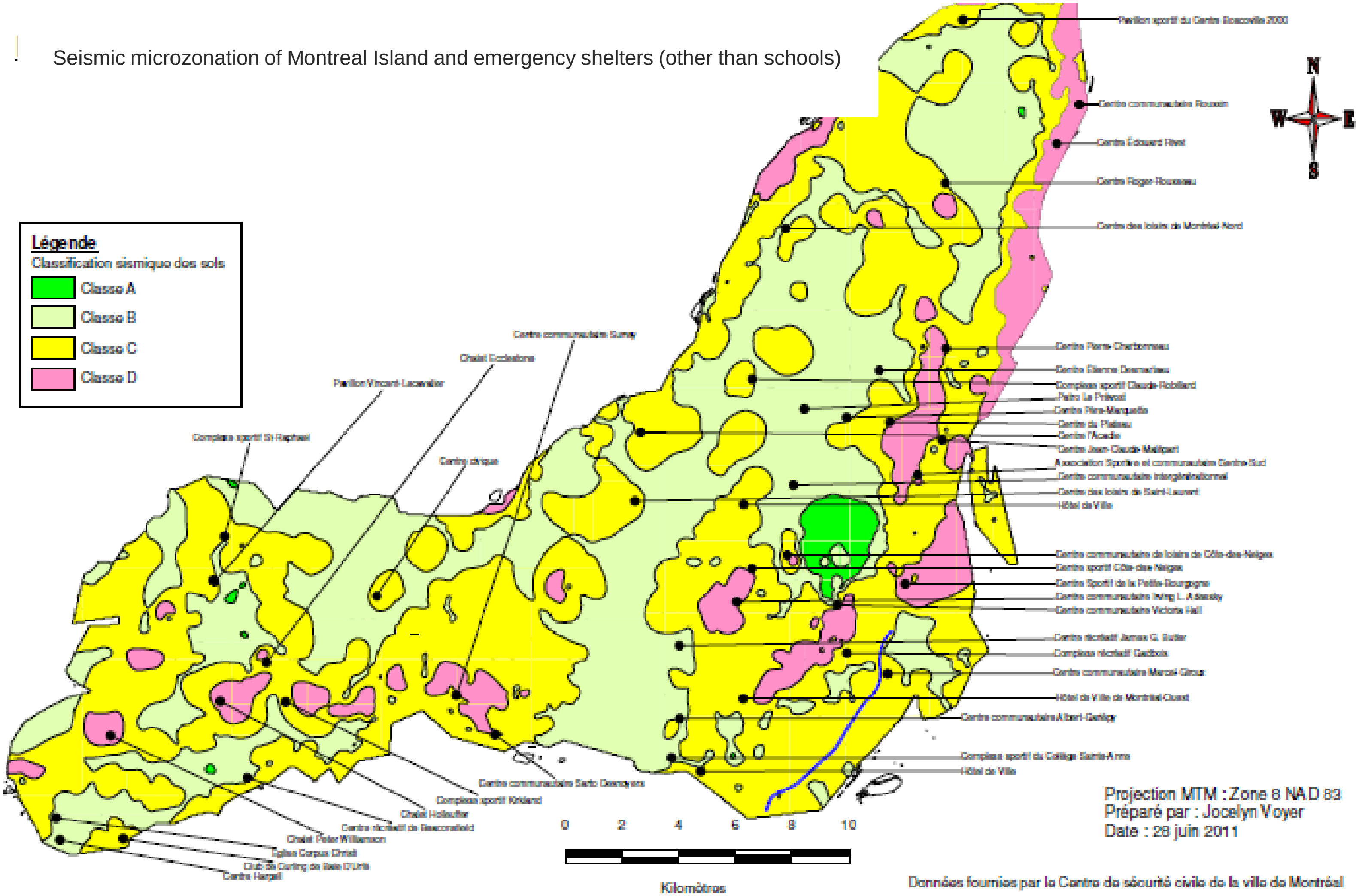
Seismic microzonation of Montreal Island and emergency shelters (other than schools)

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# Building Functionality Assessment

- 3 performance levels
  - Safety of occupants and safe egress
  - Immediate occupancy (fonctionality interrupted during earthquake, some damage is acceptable)
  - Full or partial functionality (in designated areas) – post-critical facilities and designated shelters

# Requirements for all civil protection buildings

- **Continuity of all essential services**
  - Fire protection system (alarms, emergency lighting, sprinkler system, fire extinguisher tanks);
  - Emergency electric power supply;
  - Supply of natural gas, water, sanitary systems; eau, systèmes sanitaires;
  - Communication systems;
  - HVAC

- Continuous functionality of interfaces with public utility services (water, electricity, telecommunications, natural gas, sanitary systems)

# Architectural Damage

Imposed deformations

Strong shaking

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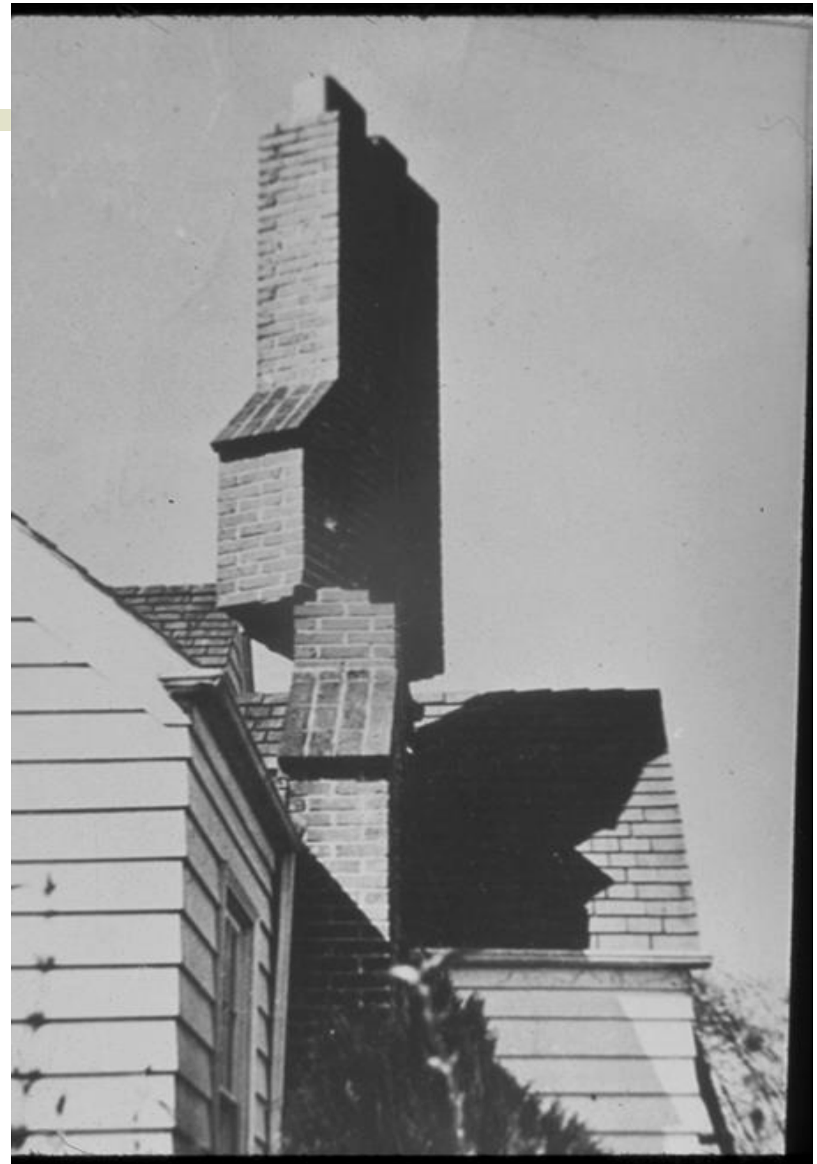
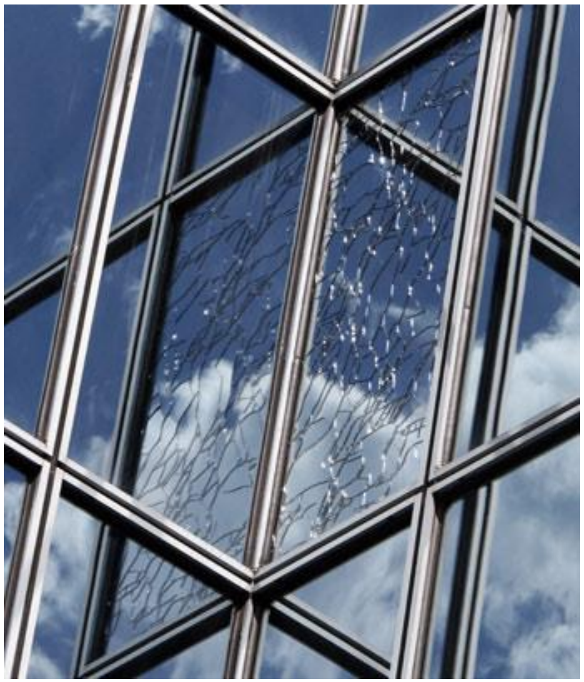
# URM & Brick Veneer Damage





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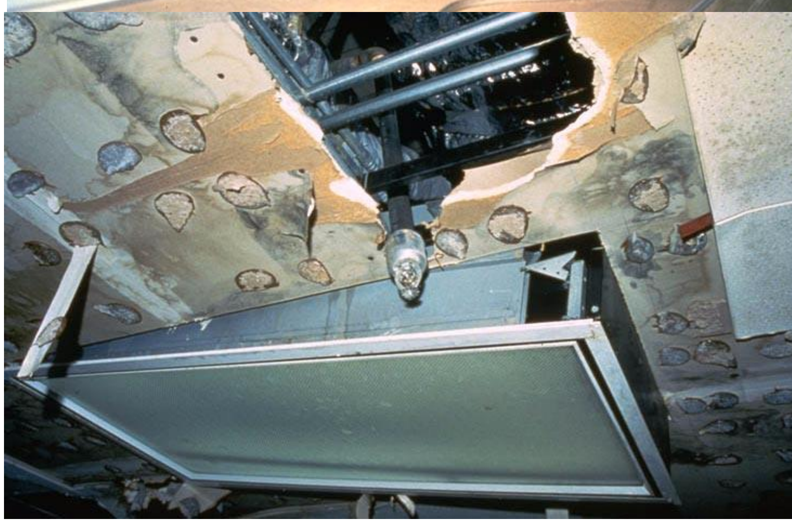

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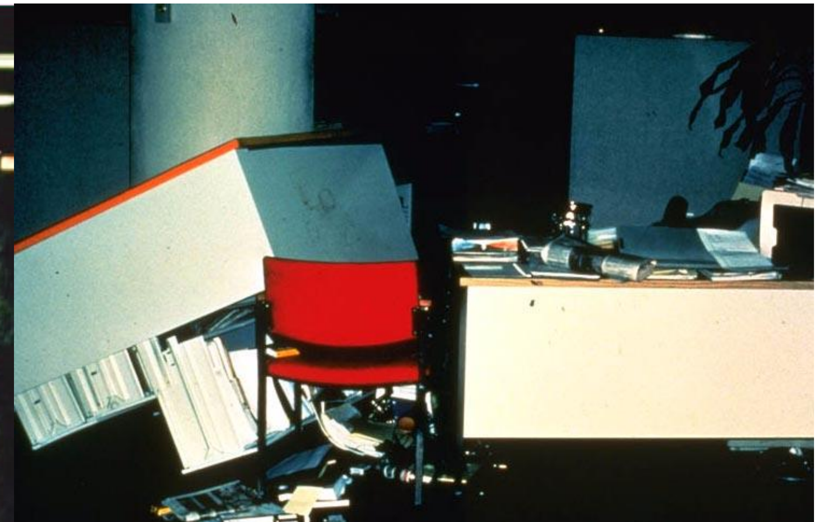

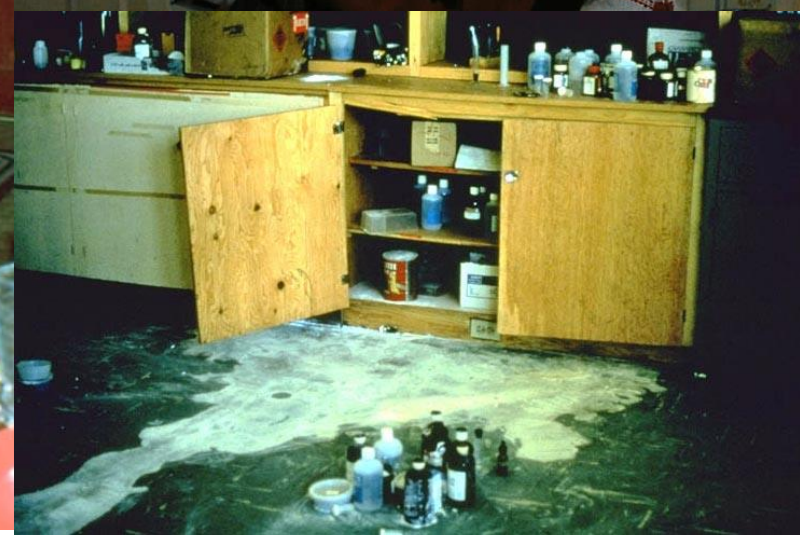

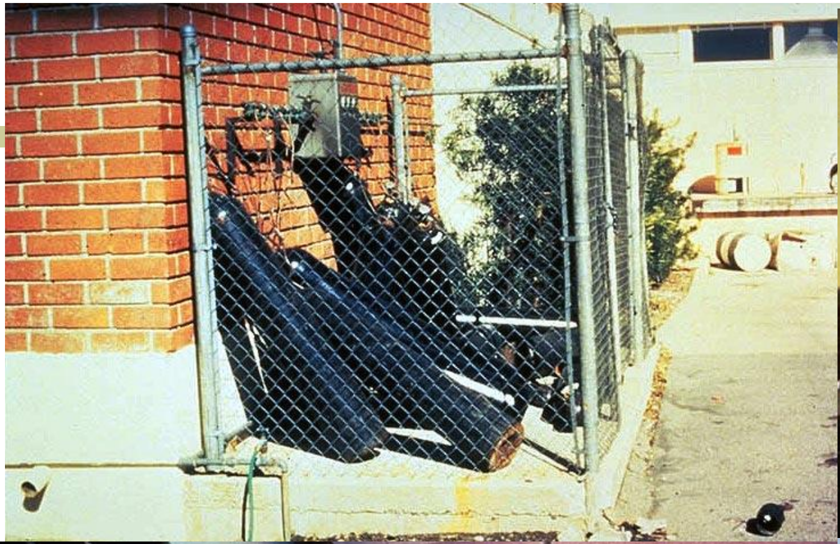

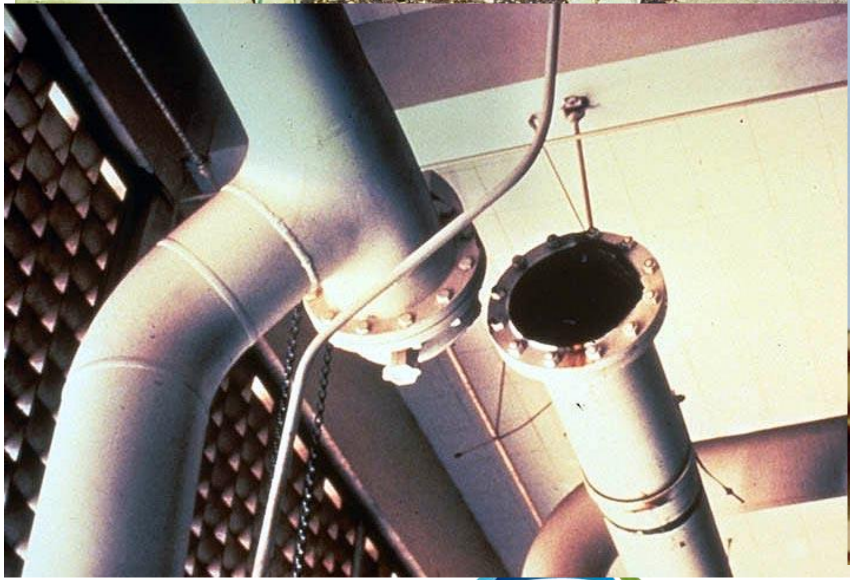

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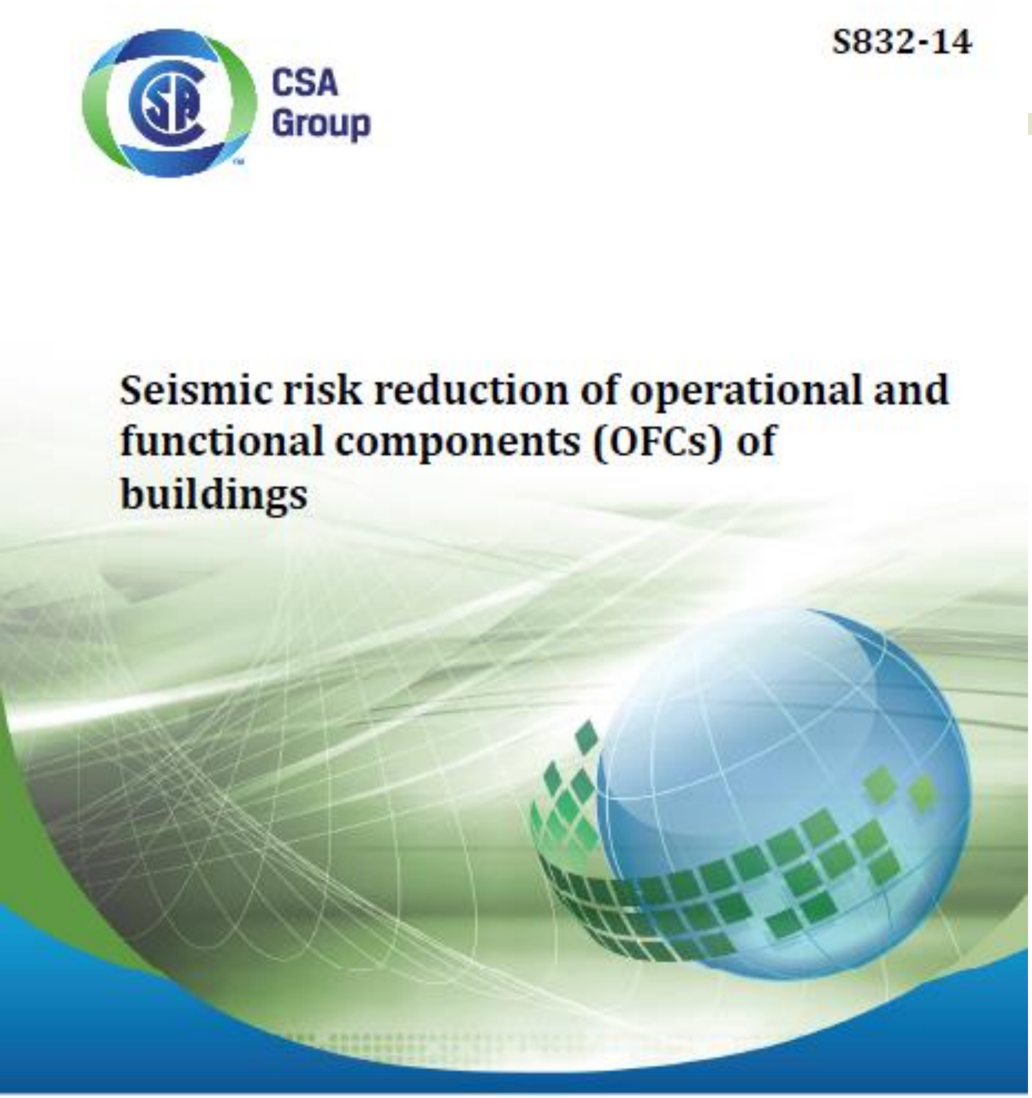


http://shop.csa.ca/en/canada/structures/s832-14/invt/27014872014

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# Design must protect against safety hazards

- **Direct hazard** – the possibility of casualties because of broken glass, light fixtures, appendages, etc.
- **Loss of critical function** – casualties caused by loss of power to hospital life support systems in bed panels, or functional loss to fire, police or emergency services facilities.
- **Release of hazardous materials** – casualties caused by release of toxic chemicals, drugs, or radioactive materials
- **Fire caused by non-structural damage** – damage to gas lines, electrical disruption, etc.

- **Economic Loss –** direct cost of repairing the damage
  - Experience in recent EQs indicates that aggregate loss is high
  - Combined effects of damage to NSC generally exceed those of direct structural damage in an earthquake
  - Mainly the result of small amount of damage to a large number of buildings
- **Loss of Building Function –** damage to components or systems necessary for useful function such as power and plumbing systems, or it may be due to disruption created by the repair of architectural or other OFCs
  - Prolonged loss of function may severely impact small business
- **Structural Response Modification**

# Main causes of OFC damage or loss of function

- Heavy structural damage
- Displacement incompatibility with structure
- Seismic force exceeding restraint capacity (or absence of restraint)

# 4 OFC performance objectives

**Table 1**
**OFC performance objective and performance level categories**
(See Clauses 4.2.1, 6.3, 7.5.3, and 9.2.)

| Performance objective | Performance level |
|---|---|
| Life safety (LS) | Mandatory |
| Limited functionality (LF) | Higher than mandatory |
| Full functionality (FF) | Highest |
| Property Protection (PP) | Optional, variable from higher than mandatory to highest |

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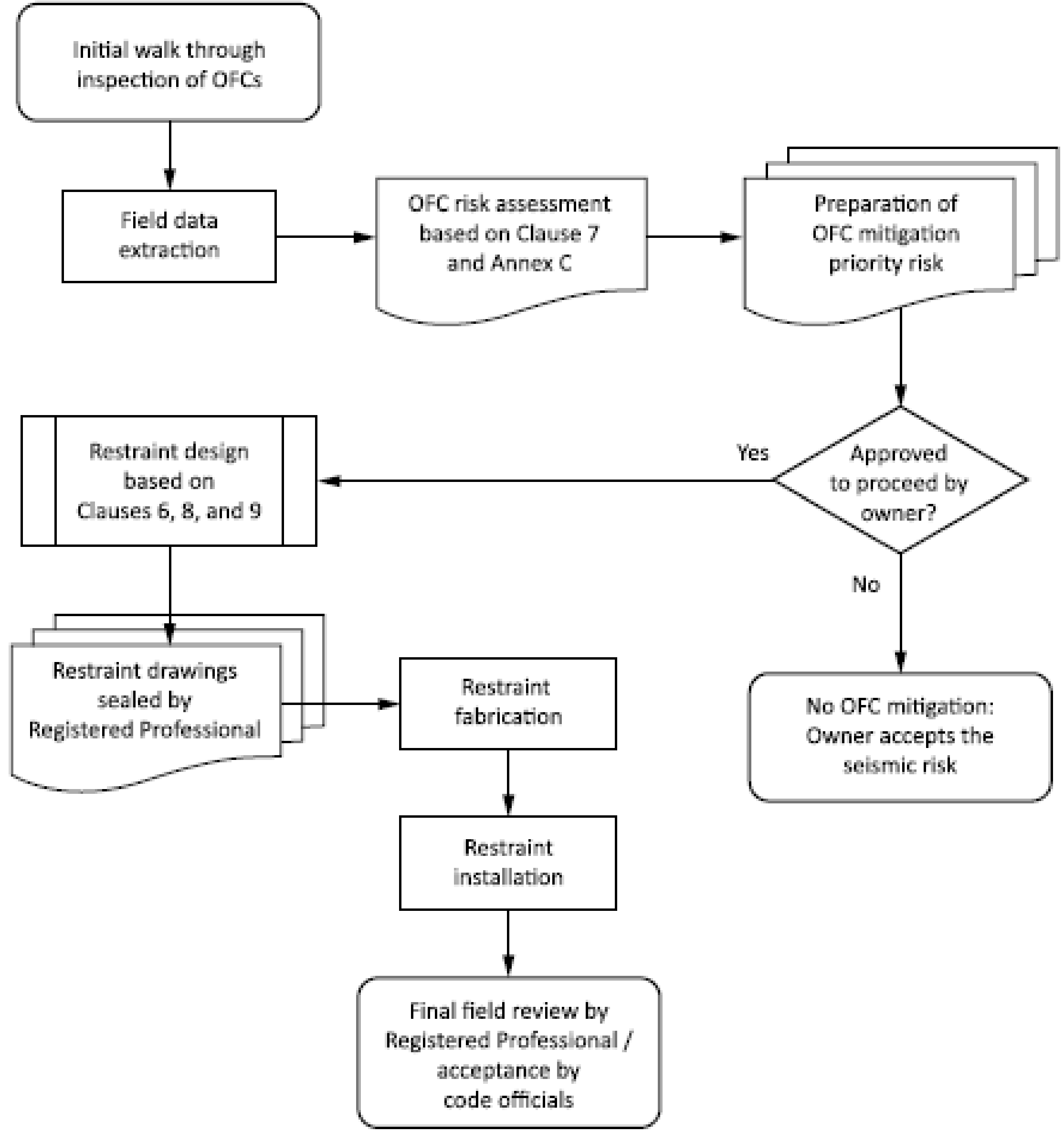
# Section 5 – Procedures for OFCs in new buildings

- 5.1 Application: design, construction and review of OFCs installed in new buildings.
- 5.2 Responsibilities: owner or delegate, design team, constructor, field reviewer
- 5.3 Analysis and design requirements: force effects and displacement effects (covered by NBCC Article 4.1.8.18. with CSA S832 enhancements in Annexes D and F)
- 5.4 Field review requirements

# 6- Procedures for OFCs in existing buildings

- 6.1 Seismic assessment team
- 6.2 Requirements
- 6.3 Procedures

# Figure 4 OFC seismic mitigation in existing buildings



# 7. Seismic risk assessment

- 7.1 General
- 7.2 OFC Inventory
- 7.3 Preliminary assessment
- 7.4 OFC with insignificant hazards – $S(0.2) \leq 0.12$
- 7.5 Determination of seismic risk index, $R = V \times C$

## Figure 5
## OFC seismic risk assessment
(See Clause 7.1.)

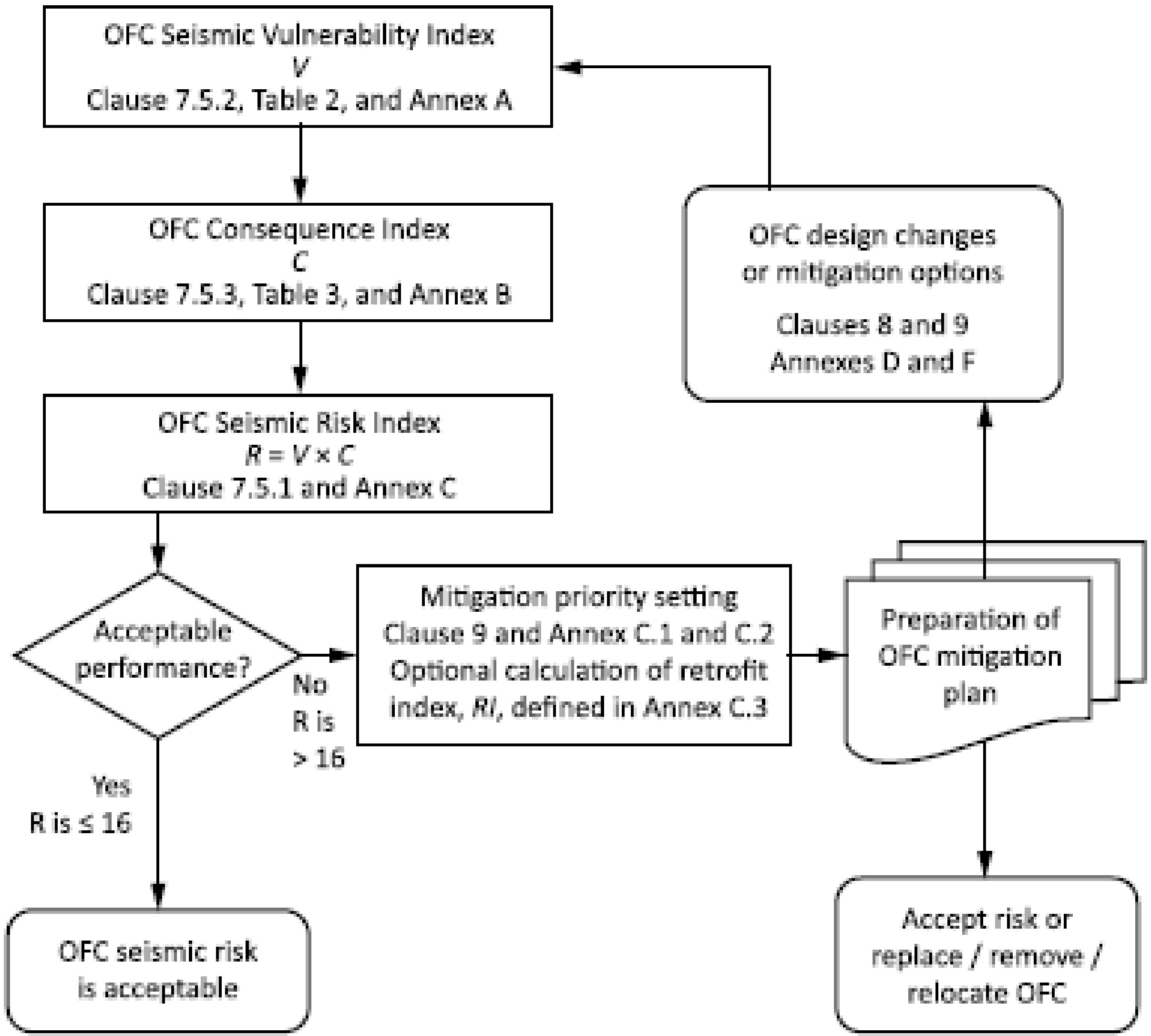


**Table 2**
**Determination of seismic vulnerability index, *V**, for OFCs**
(See Clauses 3.1, 3.2, 7.5.1, 7.5.2, A.1, A.4, C.3, E.1, and E.2 and Figure 5.)

| Vulnerability parameters | Parameter range | Rating score (*RS*) | Weight factor (*WF*) |
|---|---|---|---|
| OFC restraint (*RS1*)<br>(see Annex E for explanatory notes on restraint) | Full restraint | 1 | 4 |
| | Partial restraint or questionable restraint | 5 | 4 |
| | No restraint | 10 | 4 |
| Impact/pounding (*RS2*) | Gap adequate | 1 | 3 |
| | Gap questionable or gap inadequate | 10 | 3 |

Impact, pounding, and/or displacement-sensitive OFC

| | | | |
|---|---|---|---|
| OFC overturning (*RS3*)<br><br>*h* = distance from support or restraint to centre of gravity or top of the OFC<br><br>*d* = horizontal distance between OFC supports<br><br>$F_a$ = acceleration-based site coefficient<br><br>$S_a$ = spectral response acceleration value | OFC fully restrained against overturning or $h/d \leq 1/(1.2F_aS_a(0.2))$ | 1 | 2 |
| | $h/d > 1/(1.2F_aS_a(0.2))$ | 10 | 2 |
| OFC flexibility and location in building (*RS4*)† | Stiff or flexible OFC on or below ground floor | 1 | 1 |
| | Stiff OFC above ground floor | 5 | 1 |
| | Flexible OFC above ground floor | 10 | 1 |

*(Continued)*

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## Table 2 (Concluded)

| Vulnerability parameters | Parameter range | Rating score (*RS*) | Weight factor (*WF*) |
|---|---|---|---|
| OFC characteristics | $VE = \Sigma_{i=1,4} (RS_i \times WF_i)$‡ | | |
| Ground characteristics<br><br>*VG*§ = characteristic of ground motion and soil condition, expressed as the product of the spectral response acceleration value for a period of 0.2 s, $S_a(0.2)$, and the acceleration- based site coefficient, $F_a$, as defined in Article 4.1.8.4 of the *NBCC* | $VG = F_a S_a(0.2)/1.25$ | Not applicable | |
| Building characteristics<br><br>*VB*** is based on the predominant type of lateral-force-resisting system of the building structure | Various types of structures | See Table 4 | |

* *Seismic vulnerability index is calculated using V = VG × VB × VE/10.*

## Building characteristics, *VB*

(See Clauses 3.2, 7.5.2, and A.4.4 and Table 2.)

| | Estimated fundamental period of the building ($T$), s | | | |
|---|---|---|---|---|
| | $0 < T \le 0.2$ | $0.2 < T \le 0.5$ | $0.5 < T$ | **Seismic force resisting system** |
| Number of storeys | 1–2 | 3–4 | ≥ 5 | Steel moment resistant frame |
| | 1–2 | 3–5 | ≥ 6 | Reinforced concrete moment resistant frame |
| | 1–2 | 3–7 | ≥ 8 | Concrete shear wall |
| | 1 | 2–4 | ≥ 5 | Braced frame |
| Site Class A Hard rock | 1.0 | 1.1 | 1.2 | |
| Site Class B Rock | 1.0 | 1.2 | 1.3 | |
| Site Class C Very dense soils and soft rock | 1.1 | 1.2 | 1.3 | |
| Site Class D Stiff soil | 1.2 | 1.3 | 1.4 | |
| Site Class E Soft soil | 1.3 | 1.4 | 1.5 | |
| Site Class F | 1.5 | 1.5 | 1.5 | |

**Note:** *Site Classes are defined in Article 4.1.8.4 of the* NBCC.

## Table 3
## Determination of consequence index, $C^*$, for OFCs
(See Clauses 3.1, 7.5.1, 7.5.3, B.3 to B.5, and H.1 and Figure 5.)

| Consequence parameters | Parameter range | Rating score ($RS$) |
|---|---|---|
| Life safety (LS)<br><br>Impact on life safety from malfunction or failure of OFC during and immediately after the earthquake (e.g., items falling on or crushing people, blocking of egress, potential for fire or explosion, loss of life-support systems in hospitals, or release of toxic materials) | Threat to very few ($N \leq 1$)† | 1 |
| | Threat to few ($1 < N < 10$)† | 5 |
| | Threat to many ($N \geq 10$)† | 10 |
| Limited Functionality (LF)<br><br>OFC is required for immediate austere building occupancy or occupancy with minor repairs following the earthquake | Not applicable or OFC breakdown greater than one week is tolerable | 0 |
| | OFC breakdown up to 1 week is tolerable | 1 |
| | OFC in high importance category building according to the *NBCC* ($I_E = 1.3$) and that is not required to be fully functional | 3 |
| | OFC in post-disaster facility according to the *NBCC* ($I_E = 1.5$) and that is not required to be fully functional | 5 |

| | | |
|---|---|---|
| Full Functionality (F) | Not applicable<br>OFC required to be fully functional | 0<br>10 |
| OFC is required for post-disaster functions or for uninterrupted functionality during or immediately after the earthquake | | |
| Property protection (PP) (Optional) | Score may vary from 0 to 10 as determined by the owner/operator | 0–10 |
| OFC damage can result in financial losses related to asset damage, replacement, and business interruption due to non-operational components | | |

** Consequence index is calculated using C = Σ(RS), with a minimum value of 1 and a maximum value of 20.*
*† N = area × occupancy density × duration factor.*

where

| | |
|---|---|
| N | = occupancy factor as defined in Table L-5, Commentary L of *User's Guide — NBCC Structural Commentaries (Part 4)* |
| area | = occupied area exposed to risk, $m^2$ |
| occupancy density | = per $m^2$ as defined in Table L-6, Commentary L of *User's Guide — NBCC Structural Commentaries (Part 4)* |
| duration factor | = average weekly hours of human occupancy/100 ≤ 1.0 |

**Note:** *When doing the summation of the rating scores, it will be LF, FF, or PP scores, added to the LS rating score, as relevant depending on the OFC performance objective. PP is optional.*

## Table C.1
## Suggested mitigation priority thresholds
(See Clauses 9.3, C.2, and H.3 and Tables H.2 and H.4.)

| Risk Index | Seismic risk level | Mitigation priority |
|---|---|---|
| $R \leq 16$ | negligible | not required |
| $16 < R \leq 32$ | low | low |
| $32 < R \leq 64$ | moderate | medium |
| $64 < R \leq 128$ | high | high |
| $R > 128$ | very high | very high |

# 8. Methods for determining OFC seismic adequacy

- 8.1 General
- 8.2 Prescriptive method (selected industry guidelines cf. Table 9)
- 8.3 Analytical Method (simplified and refined)
- 8.4 Special requirements (H+V; drift ratios, relative displacements)
- 8.5 Evaluation/analysis criteria (F D F/D)

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## Table 9
## Typical OFC problems and mitigation techniques

(See Clauses 8.2, 9.1, and B.2.6.)

| Typical problems noted or anticipated | Suggested mitigation techniques | Mitigation effects on structure or on other OFCs | References |
|---|---|---|---|
| 1. Architectural components — External | | | |
| Appendages (cornices, parapets, spandrels, ornamentation, signs, canopies, marquees) | | | |
| Cornices, parapets, spandrels, and other architectural appendages that have insufficient anchorage capacity or are slender can collapse or topple, creating the possibility of falling debris. | For heavy and ornate cornice work, remove the cornice or reconstruct it with adequate anchorage and/or new lighter materials.<br><br>Reduce parapet height to reduce likelihood of overturning; limit height-to-thickness ratio of unreinforced masonry parapets to<br><br>4 if $(S_a(0.2)F_a \leq 0.2)$<br><br>2.5 if $(0.2 < S_a(0.2)F_a \leq 0.35)$<br><br>1.5 if $(0.35 < S_a(0.2)F_a \leq 0.55)$<br><br>1.0 if $(S_a(0.2)F_a > 0.55)$ | Changes made to the existing appendages or their connections should be such that the total structural integrity, including foundations, is ensured for the safe resistance of seismic and other load effects. | Appendix A of NRCC *Guidelines for Seismic Evaluation of Existing Buildings*<br><br>FEMA E-74 and FEMA 547 |

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Ceilings

| | | | |
|---|---|---|---|
| Unbraced suspended ceilings can swing independently of the supporting floor, resulting in damage to the ceiling, particularly at the perimeters. | Provide four-way diagonal wire bracing with a compression strut between the ceiling and supporting floor.<br><br>For lay-in ceilings, stiffen splices and connections of T-bar sections with new metal clips and self-tapping screws.<br><br>Provide a gap between edge of ceiling and enclosing walls on at least two perpendicular sides.<br><br>Discontinue ceiling across any seismic joint. | Caution should be exercised not to alter or affect the performance of assembled systems. | ASTM E580<br>CISCA 1990 *Guidelines for Seismic Restraint for Direct-Hung Suspended Ceiling Assemblies* (zones 3–4)<br>CISCA 1991 (zones 0–2)<br>ASTM C635/C635M |
| Unbraced suspended integrated ceilings can cause grid distortion and loss of panels. | This is not a problem with light weight panels (less than 10 $kg/m^2$). | | |
| Ceiling finishes such as plaster can fall due to failure of adhesives or spalling, creating a falling hazard and possibly impairing egress | Replace ceiling in egress routes and large assembly areas. | Consideration should be given to fire-rated assemblies. | |
| | Replace ceiling tiles housing fire suppression sprinkler's heads. | | |

*(Continued)*

# 9.OFC problems and risk mitigation procedures

- 9.1 General
- 9.2 Mitigation strategies
- 9.3 Mitigation priority setting
- 9.4 OFC attachments and restraints

# List of Annexes

- A Seismic Vulnerability of OFCs
- B Consequences of OFC failures
- C Seismic risk assessment and mitigation
- D Drift-related effects on OFCs
- E Explanatory notes on OFC restraints
- F Methods of selecting and sizing OFC restraints

# Annexes (cont'd)

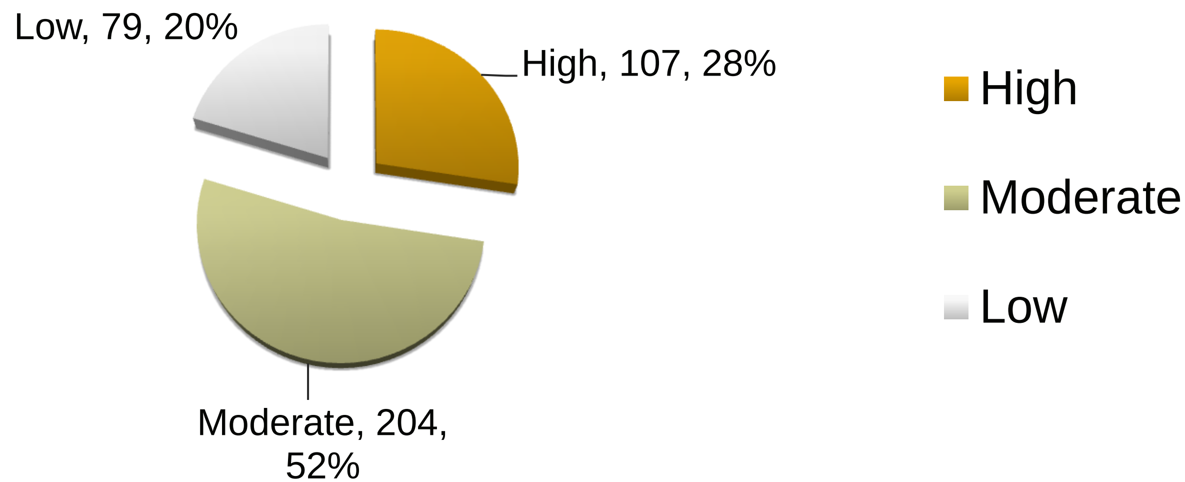
- G Additional considerations for special occupancies and systems (13 types)
- H Sample application of seismic risk assessment methodology
- I Sample calculations for determining seismic adequacy

# Seismic functionality assessment using CSA S832 procedure

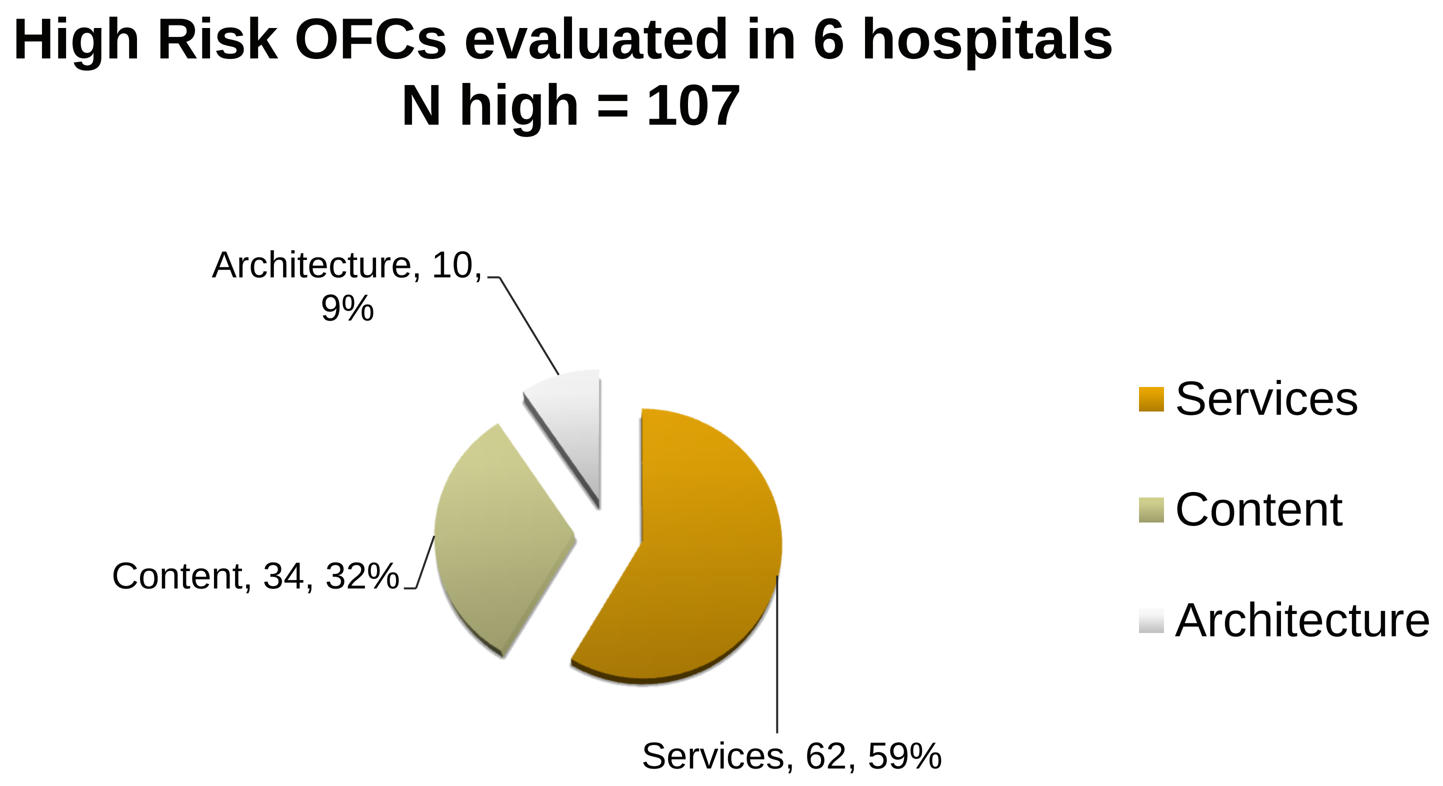
- 101 school buildings for schools designated as emergency shelters
- 15+ community centres designated as emergency shelters
- 6 hospitals (35 buildings) and 2 ongoing for more detailed studies of subsystems
- 14 fire stations

# Risk Ratings for OFCs in Hospitals

**OFCs evaluated in 6 hospitals    N = 380**

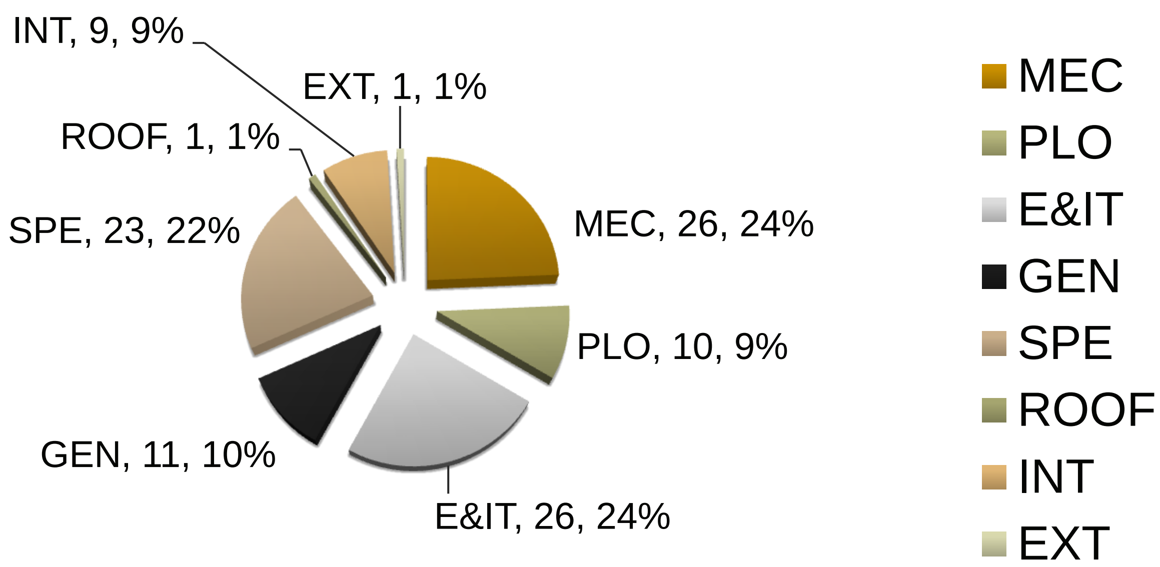


# Risk Ratings for OFCs in Hospitals



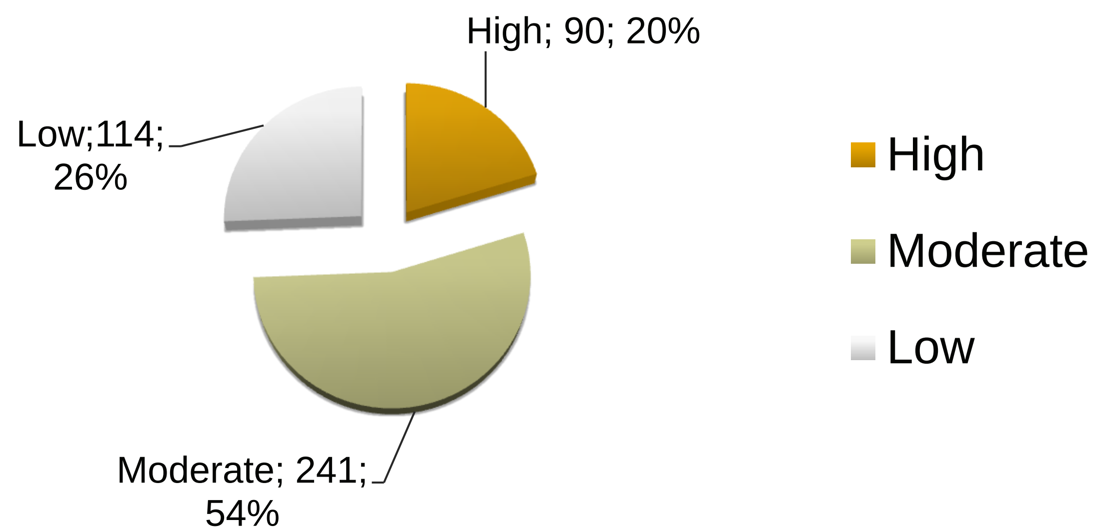
# Risk Ratings for OFCs in Hospitals

**High Risk OFCs in 6 hospitals**
**N high = 107**



# Risk Ratings for OFCs in Schools

## OFC evaluated in public high schools designated as emergency shelters
## N = 445

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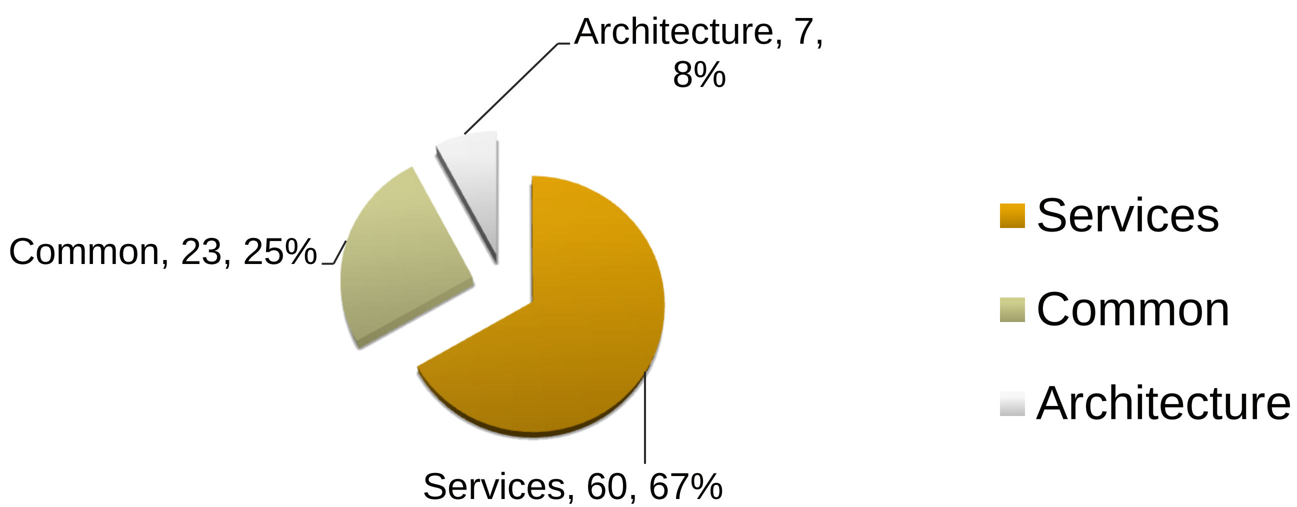
# Risk Ratings for OFCs in Schools

## High risk OFCs in schools
## N high = 90

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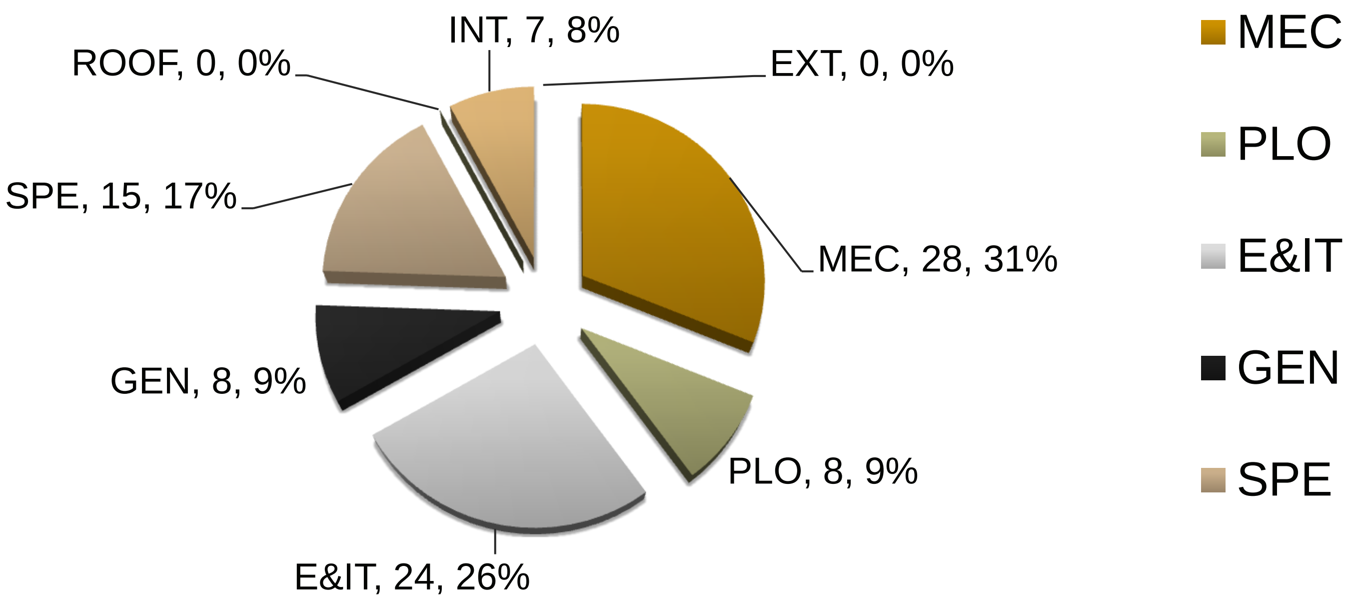
# Risk Ratings for OFCs in Schools

**High risk OFCs in 12 community schools identified as post-critical sheleters in the Island of Montreal**
**N high = 90**



# High risk OFCs

- Electric power emergency generators improperly anchored (or free standing) on floors; unrestrained batteries;
- Slender control panels unrestrained;
- Unbraced suspended piping;
- Classical suspended ceilings (unbraced)

# SUSPENDED CEILINGS & PIPES

Single solid round rod can bend; Missing supports

T-bar light framing supported by wires with no lateral bracing

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# TALL ELECTRICAL COMPONENTS

No base restraint (raised floor with no lateral support) nor intermediate or top restraint to prevent overturning of slender units.

# BOOKSHELVES & MEDICAL ARCHIVES

**UNRESTRAINED** – Shelves and content

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# Lack of adequate base support

# INSTALLATION INCOMPLETE

MISSING BOLTS OR BOLTS AT IMPROPER LOCATIONS

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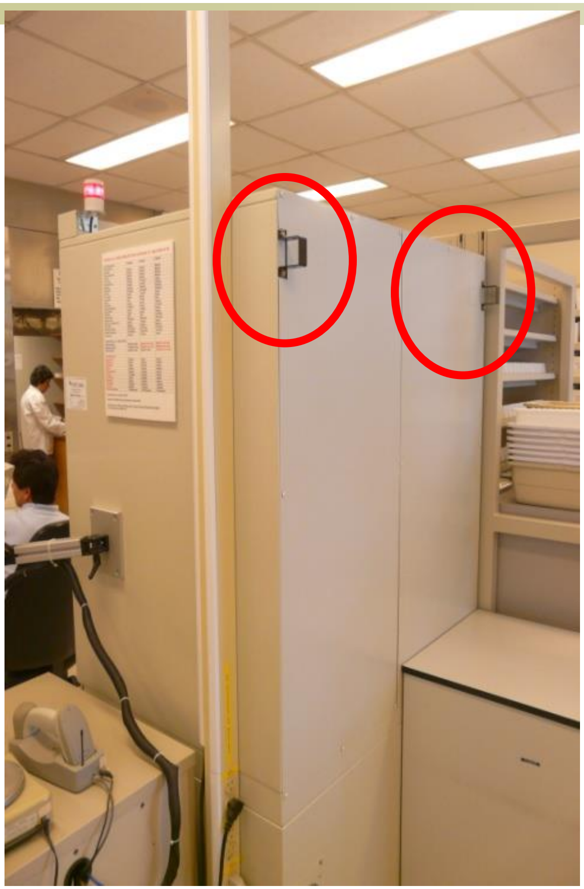
# INSTALLATION INCOMPLETE



EQUIPMENT DESIGNED TO BE RESTRAINED

# Summary of observations

- Approximately 20% of components for Schools and 27% for Hospitals are considered High Risk;
- Majority of components are Moderate Risk ;
- Mitigation is often very simple to provide: lack of restraint to floor is the most common deficiency;
- The staff/users should be informed of the risks to prevent hazardous situations.

# Challenges and Opportunities

- Raise awareness to seismic risk;
- Ensure preparedness and encourage mitigation;
- Mitigation on a large scale cannot be afforded;
- Moderate seismic hazard brings focus on functionality rather than collapse prevention;
- Strictly enforce functionality performance requirements in new constructions.

# Conclusions

- Much progress has been made towards understanding the seismic behaviour of OFCs;
- Simplified and highly sophisticated methods of analysis and design are available;
- Building standards and specifications still do not reflect our level of understanding and have not yet incorporated many of the rational procedures that have been developed over the last 50 years (e.g. floor response spectra)
- CSA S832-14 is a step forward with many improvements over previous editions
- Stakeholders need to become "better" informed of the relevant issues: Building Owner, Architect/Engineer, Contractor/Trades Worker, Specialty Inspector, Building Department and Insurer

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# THANK YOU

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**And CSA S832-14 standard!**