EARTHQUAKE ENGINEERING TECHNOLOGIES

State of Practice and Knowledge Gaps in Seismic Evaluation and Retrofit, and Performance Based Seismic Design of Existing Buildings

Proceedings of the NRC-MOST/NCREE Taiwan Workshop
7-8 October 2019
Ottawa, Ontario, Canada

Prepared by:
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National Research Council Canada
Conseil national de recherches Canada

NRC-MOST/NCREE Taiwan Workshop on Earthquake Engineering Technologies

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Sponsored by

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Edited by R. Fathi-Fazl, F. Fazileh, Z. Cai, and W.L. Cortés-Puentes

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Acknowledgements

On behalf of the National Research Council Canada (NRC), the organizing committee would like to thank all workshop participants for their contributions and suggestions, and for helping to identify future directions for research and development. We are especially grateful to all speakers for their informative and highly relevant presentations, and for agreeing to have them distributed.

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We extend our thanks to Dr. Shyh-Jiann Hwang and his delegation from Taiwan for sharing the latest advances in the areas of earthquake engineering research in Taiwan, including seismic evaluation and retrofit technologies, testing and simulation, health monitoring, and more.

And, finally, grateful acknowledgements are also extended to the NRC staff who supported and contributed to various phases of the workshop: Ms. Lorena Maciel, Mr. Alec King, and Mr. Colin Clarke from International Relations, and Ms. Johanne Lavictoire from Construction Research Center.

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Introduction

NRC-MOST/NCREE TAIWAN WORKSHOP ON EARTHQUAKE ENGINEERING TECHNOLOGIES
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100 Sussex Drive, NRC
Ottawa, Ontario, Canada

Observations of earthquake damage from previous major earthquakes around the world have shown that existing buildings are prone to experience severe damage or even collapse in the event of strong ground shaking. A variety of retrofitting techniques that utilize innovative technologies and materials have been proposed by researchers around the world to perform the seismic evaluation and retrofitting of existing buildings. In addition to retrofitting existing buildings, earthquake early warning systems have been developed and operated in some countries and regions (Mexico, Japan, Turkey, Romania, China, Italy, and Taiwan) and have successfully shown their importance and efficiency on minimizing the losses of human lives during strong earthquake ground motions. Furthermore, performance based seismic design, seismic resilience, and life cycle assessment have been increasing their popularity in the earthquake engineering community.

This workshop brought together national and international experts in structural and earthquake engineering, as well as stakeholders and managers of large public portfolios of existing buildings in Canada, including Public Services and Procurement Canada, Global Affairs Canada, and Department of National Defense. The objective of this workshop was to seek input and set direction in addressing the state of practice, knowledge gaps, and roadmap for seismic risk assessment and retrofit, and performance based seismic design of buildings. This workshop also explored the future joint research collaborations between Canada and Taiwan in the area of earthquake engineering.

The workshop was divided into Presentation Sessions and Discussion Sessions, and addressed the many challenges in earthquake engineering, including the following:

- Seismic risk assessment and retrofitting of existing buildings;
- Performance based seismic design of buildings; and
- Advanced research in earthquake engineering.

These proceedings provide an overview of the information that was presented at the workshop by the participating experts.

R. Fathi-Fazl, F. Fazileh, Z. Cai, and W. L. Cortés-Puentes

Keynote Speaker

Dr. A. Liel

Advancing seismic resilience: new directions for older non-ductile concrete buildings

ADVANCING SEISMIC RESILIENCE: NEW DIRECTIONS FOR OLDER NON-DUCTILE CONCRETE BUILDINGS

By Dr. A. Liel, University of Colorado Boulder

Abstract

Nonductile reinforced concrete buildings, or those built before about 1975 in the U.S. and Canada, are known to have elevated risk of earthquake-induced collapse compared to modern buildings, as well as higher vulnerability to earthquake-induced repairs and economic losses. This presentation will describe recent research assessing the seismic performance of these buildings, and explore the differences in performance due to ground shaking from subduction and crustal earthquake events. In the second part of the presentation, methods for identifying the most vulnerable buildings and retrofitting these buildings will be presented. In particular, the presentation will report on simulations of the improvements in seismic performance of these structures possible with retrofit, and the impact of this improved performance for individual buildings and for communities.

Keywords: nonductile reinforced concrete, collapse risk, economic losses, subduction zones.

Biography

Dr. Abbie Liel is an Associate Professor of Civil, Environmental and Architectural Engineering at the University of Colorado, Boulder. She earned undergraduate degrees in Civil Engineering, and the Woodrow Wilson School of Public Policy, at Princeton University. She began her graduate studies at University College London, where she received M.Sc.s in both Civil Engineering and Building and Urban Design and Development. She earned her Ph.D. at Stanford University, focusing on collapse risk of older nonductile concrete frame structures. Abbie has been the recipient of the Shah Family Innovation Prize from the Earthquake Engineering Research Institute, and recently received the University of Colorado College of Engineering's Teaching Award.

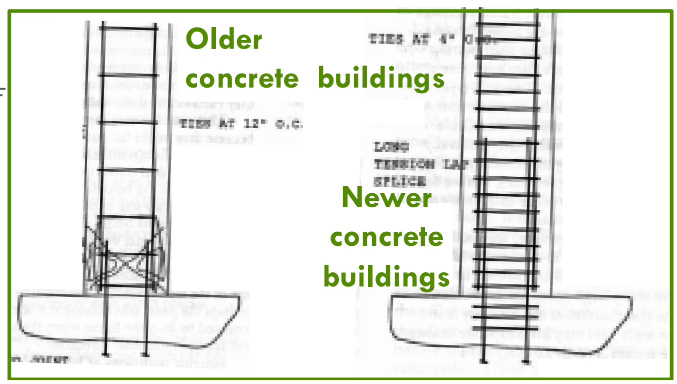
ADVANCING SEISMIC RESILIENCE: NEW DIRECTIONS FOR OLDER NON-DUCTILE CONCRETE BUILDINGS

ABBIE LIEL
ASSOCIATE PROFESSOR, CIVIL, ENVIRONMENTAL & ARCHITECTURAL ENGINEERING
UNIVERSITY OF COLORADO - BOULDER

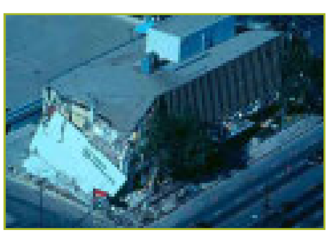
October 7, 2019

University of Colorado **Boulder**

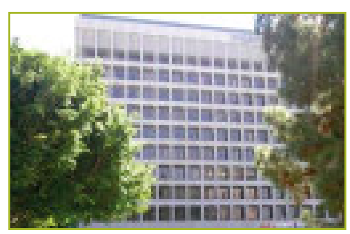
Motivation



(photos: Courtesy of PEER-NISEE, University of California, Berkeley)

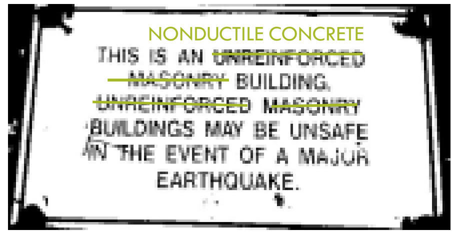


(photo: Anagnos et al.)



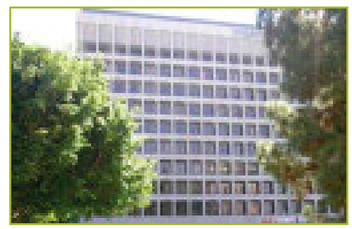
Motivation

How can we address the existing inventory of potentially vulnerable nonductile concrete buildings?



(photos: Courtesy of PEER-NISEE, University of California, Berkeley)

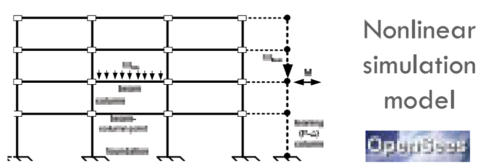
(photo: Anagnos et al.)



Performance-based earthquake engineering

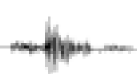
Photo Credit: Stanford Univ.

Structure of interest

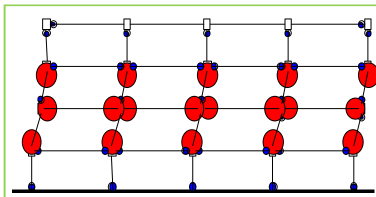


Nonlinear simulation model

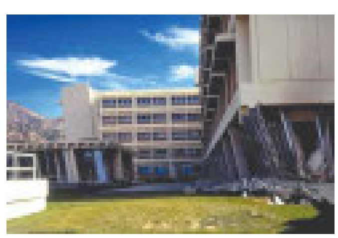
Input ground motion



Dynamic analysis



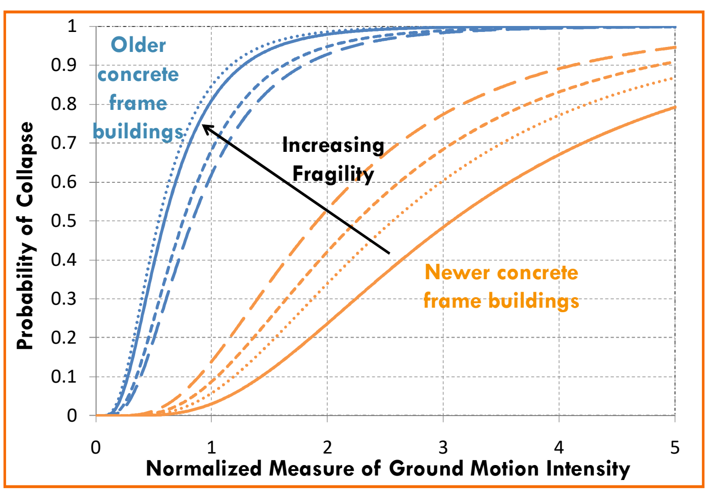
Structural response



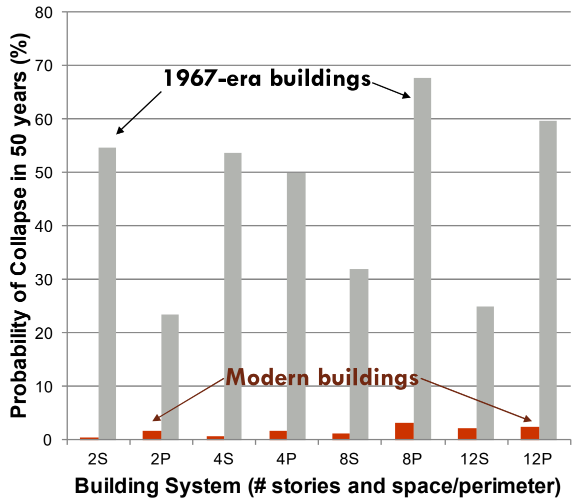
- Collapse & casualties
- Economic losses
- Repair time

How seismically vulnerable are older non-ductile reinforced concrete structures?

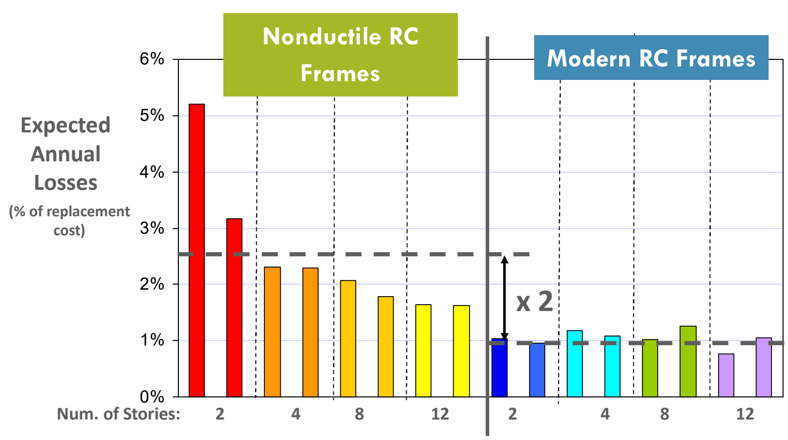
Collapse risk of older concrete buildings



Collapse risk of older concrete buildings

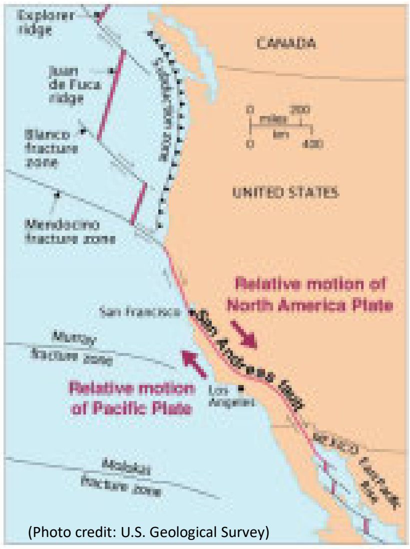


Estimated economic losses due to seismic repairs



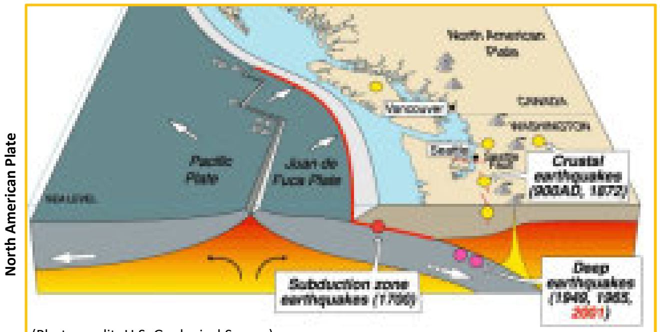
- Modern seismic codes have been less effective at reducing earthquake-induced economic losses than collapse

Collapse risk in the Cascadia subduction zone



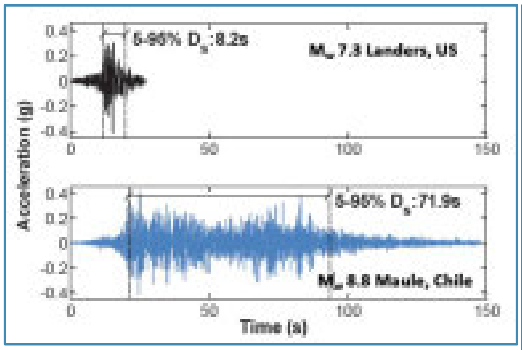
(Photo credit: U.S. Geological Survey)

Seismic environment of Pacific Northwest

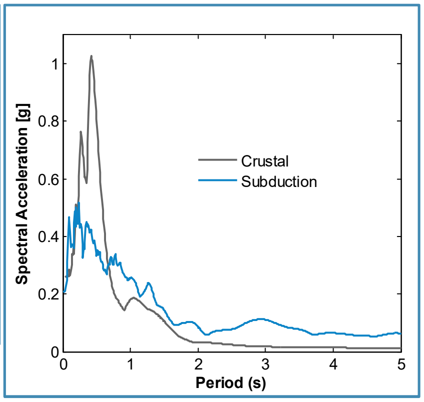


(Photo credit: U.S. Geological Survey)

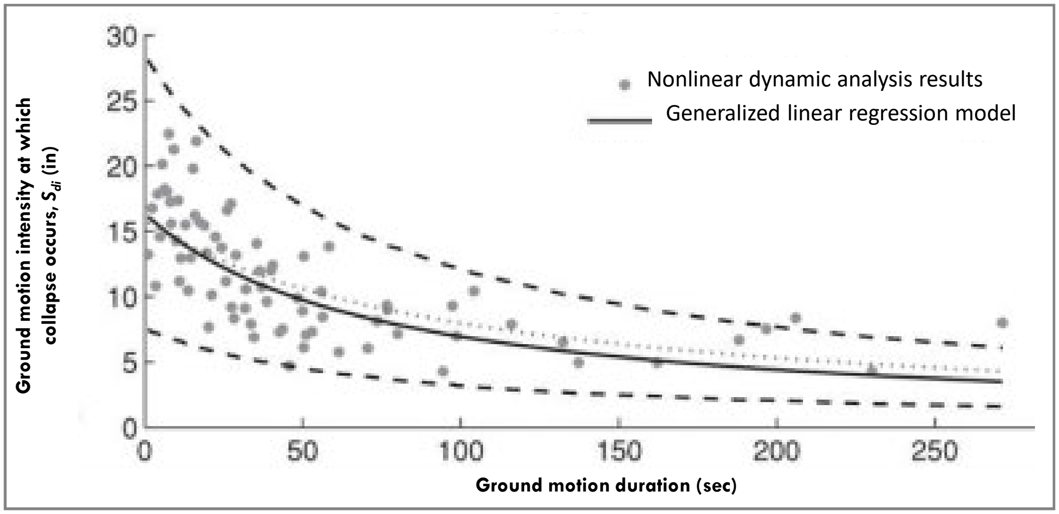
Collapse risk in the Cascadia subduction zone



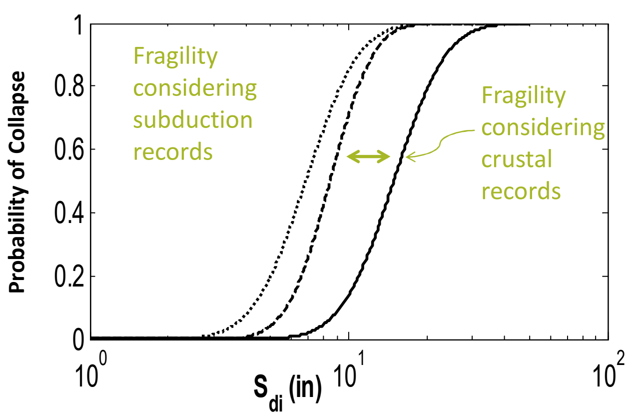
Subduction records differ from crustal records in terms of duration and frequency content



Increased ground motion duration reduces collapse capacity

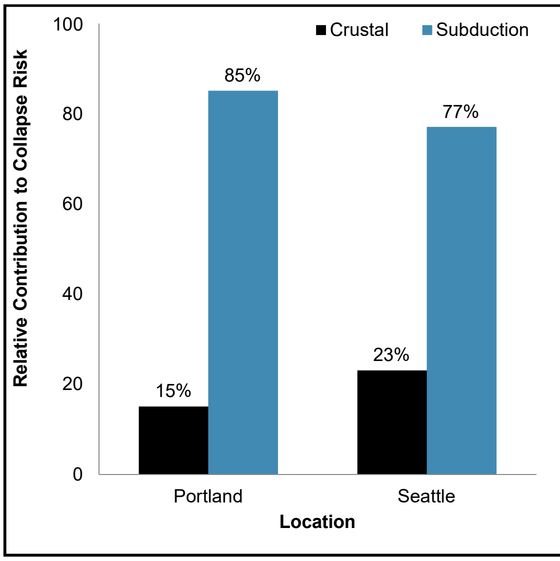


Collapse fragility is greater if subjected to subduction motions



For modern buildings, **about a 35% reduction in median collapse capacity** if subduction motions are considered

Subduction motions contribute substantially to collapse risk in Pacific Northwest



Deaggregation of collapse risk by earthquake source type for modern buildings in Portland and Seattle

How effective is retrofit at reducing seismic risk?

Performance of seismically retrofit buildings is uncertain

- Most studies of retrofit have focused on element improvements
- Limited observations of performance of retrofitted buildings after strong shaking
- Large variability in performance of retrofitted buildings
- US's ASCE 41 retrofit design standard is performance-based, but has not been "benchmarked"

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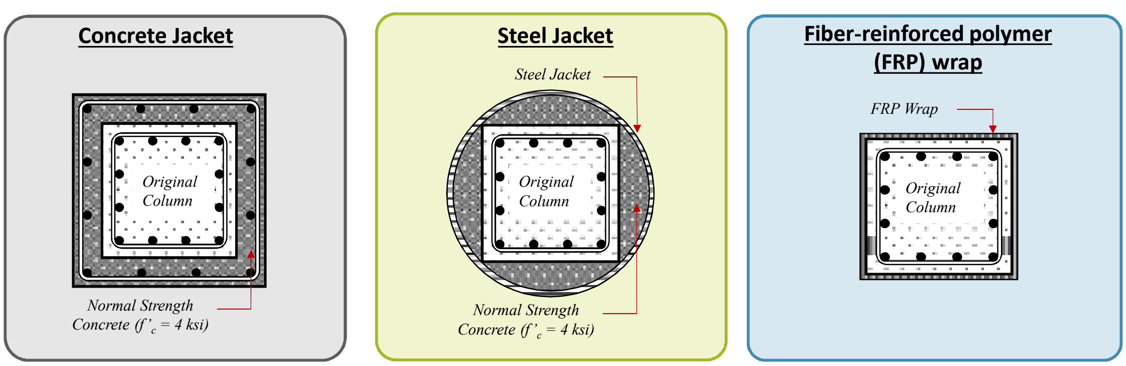
Analysis of "typical" older RC frame buildings retrofit with three different strategies



36 buildings retrofits considered

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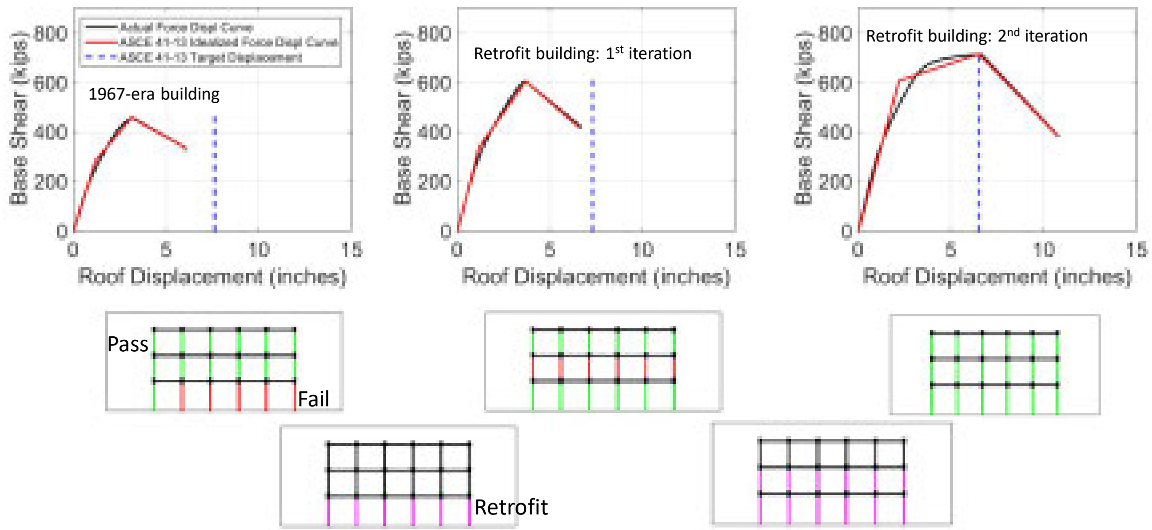
Based on three ASCE 41 performance objectives



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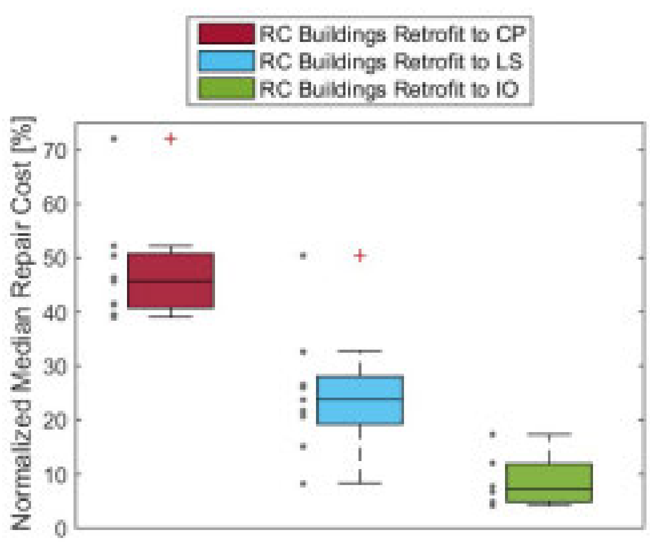
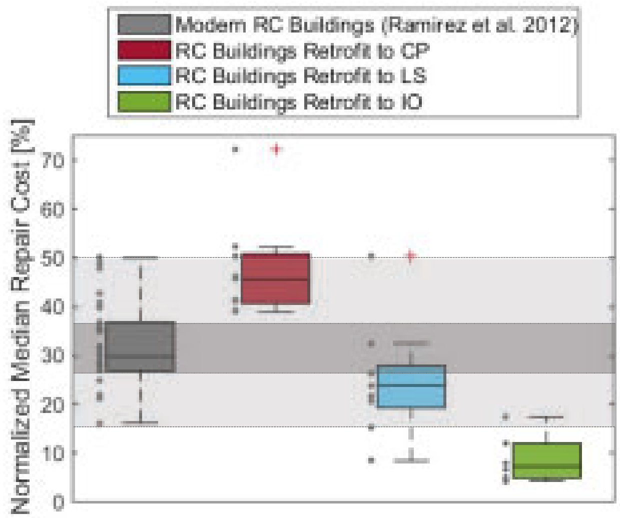
Performance during design level event



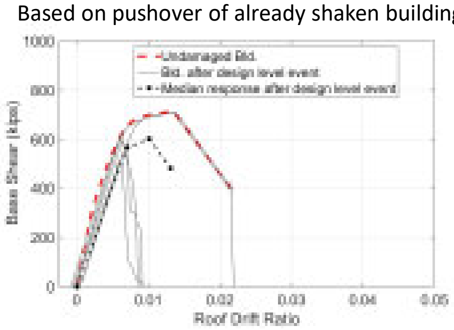
Performance during design level event



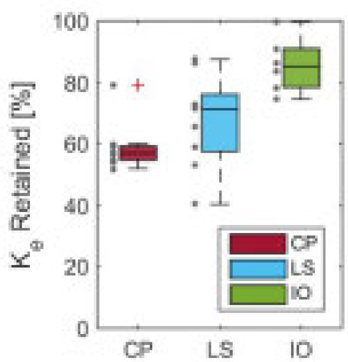
Performance of structural system

Simulated Damage & Observations

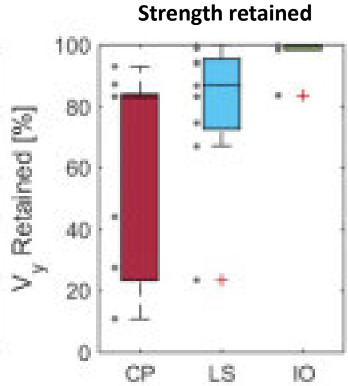
Based on pushover of already shaken building



Stiffness retained



Strength retained



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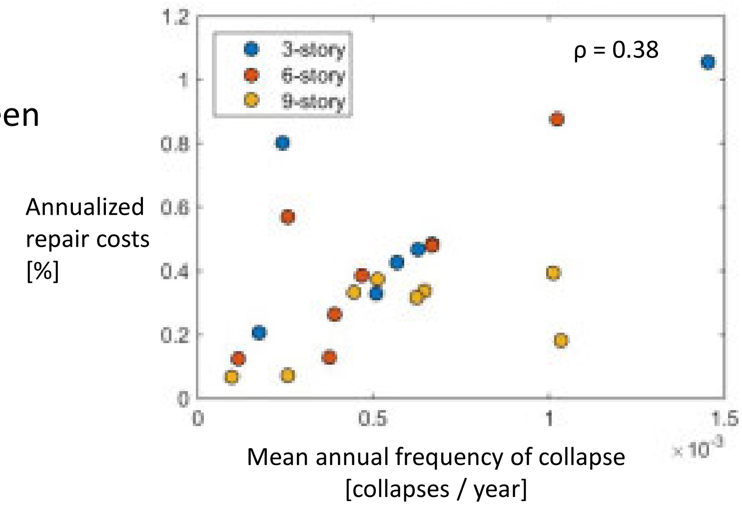
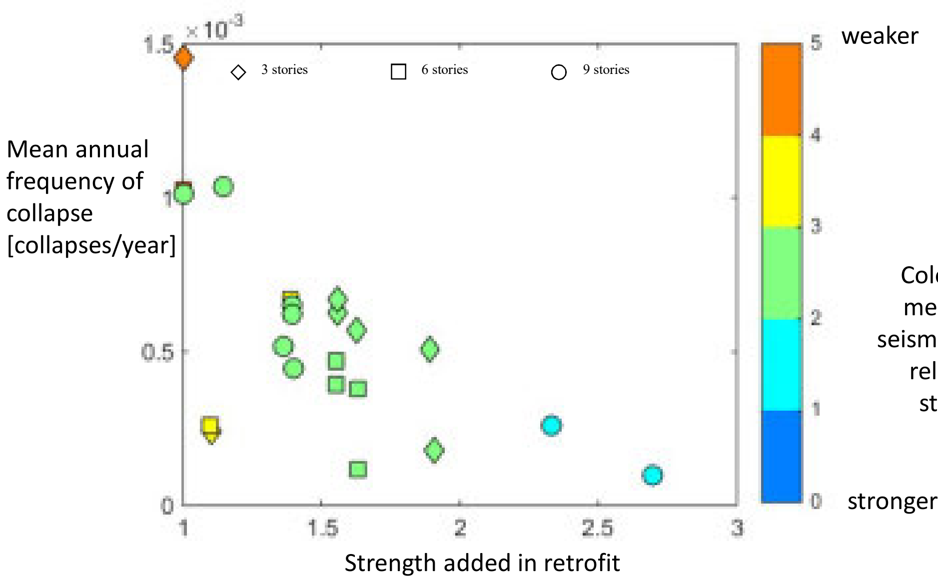
Assessment of retrofit structures depends on what we mean by "performance"

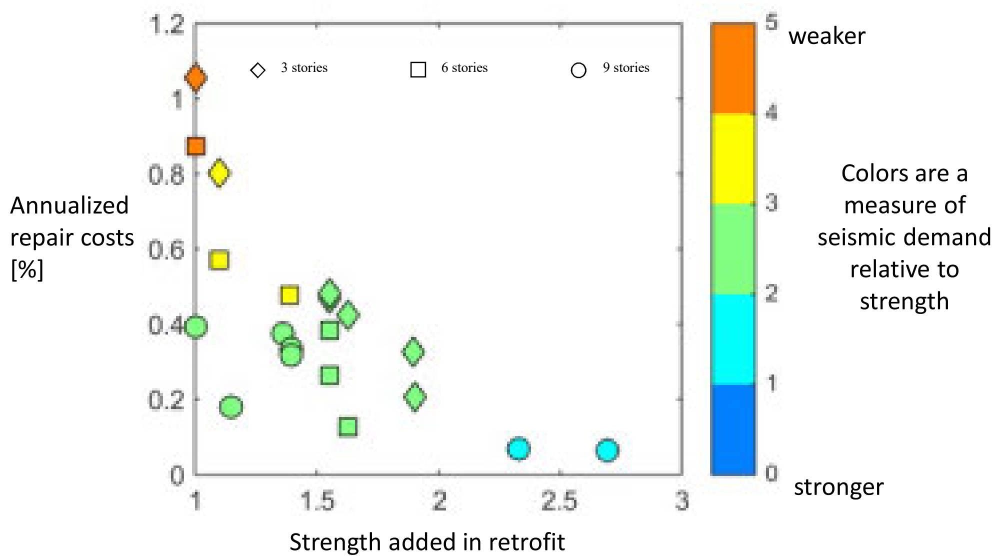
- Weak correlation between economic losses and collapse risk
- Designing for collapse resistance may not mitigate economic loss



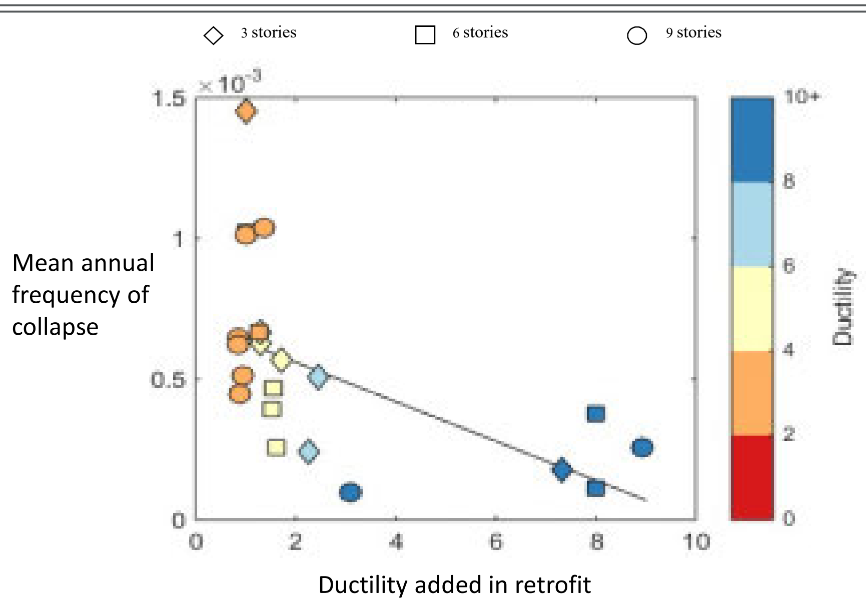
Retrofit performance indicators: strength



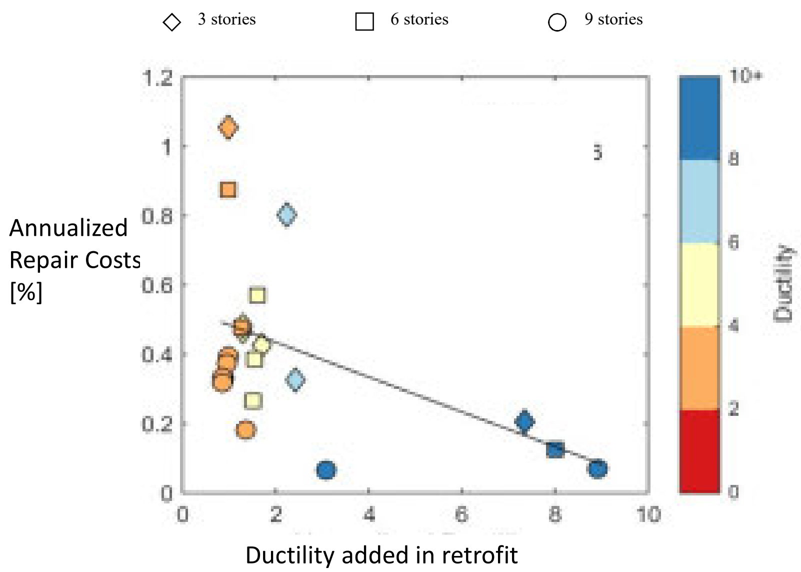
Retrofit performance indicators: strength



Retrofit performance indicators: deformation capacity



Retrofit performance indicators: deformation capacity



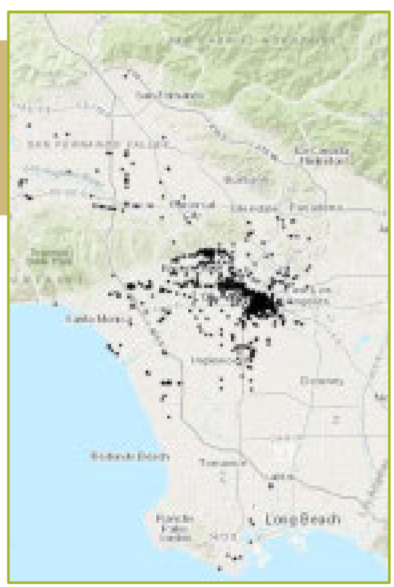
How does retrofitting improve seismic performance of a building?

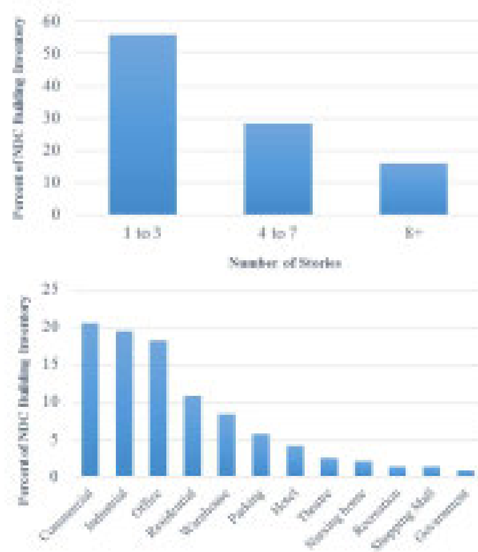
- Retrofit can improve performance of buildings to the level of modern code-designed buildings, or beyond
- But, large variability in performance of retrofitted buildings
- What you think about performance of the retrofitted building depends on whether you are concerned with collapse risk (life safety) or economic impacts or both
  - Collapse risk and economic losses are only weakly correlated
- Adding strength is effective at reducing both collapse risk and economic losses

How effective is retrofit at reducing seismic risk for communities?

Community risk from older reinforced concrete buildings

City of Los Angeles inventory of 1500 older concrete buildings





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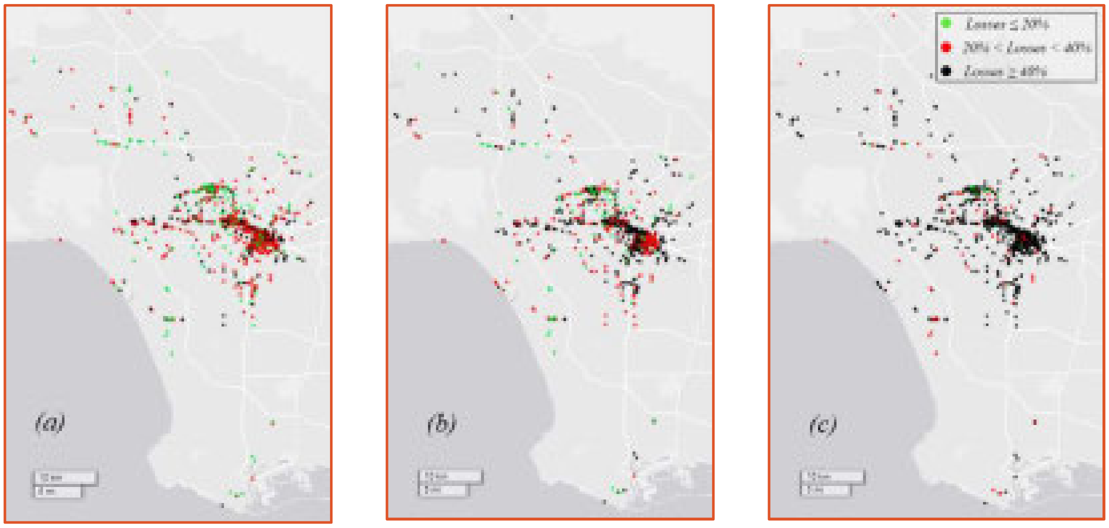
Losses to the unretrofit building inventory



Loss realization example for inventory at (a) 25th, (b) 50th and (b) 75th percentiles of regional loss

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Regional retrofit cases

% OF REGION RETROFIT:

10%

90%

BUILDINGS RETROFIT TO:

1) 100% Immediate Occupancy (IO)
2) 100% Life Safety (LS)
3) 100% Collapse Prevention (CP)
4) 33% IO 33% LS 33% CP
5) 10% IO 30% LS 60% CP
6) Also retrofit only mid-rise buildings and only residential buildings

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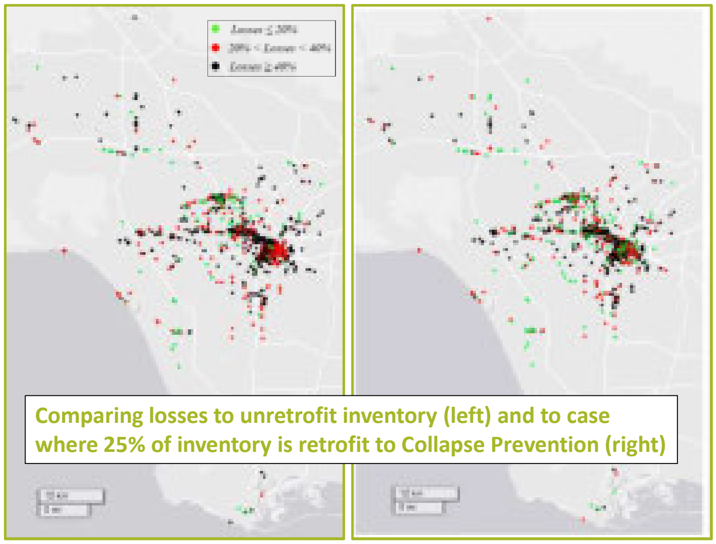
Losses to retrofit building inventory



Comparing losses to unretrofit inventory (left) and to case where 25% of inventory is retrofit to Collapse Prevention (right)

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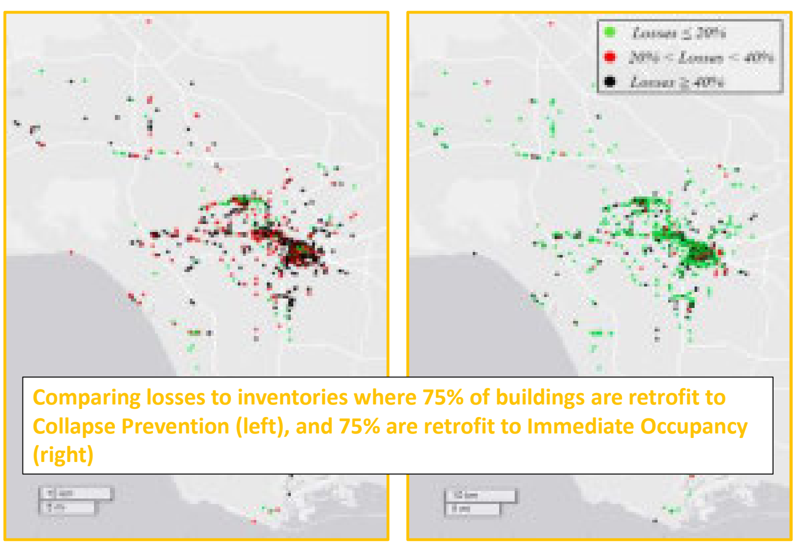
Losses to retrofit building inventory



Comparing losses to inventories where 75% of buildings are retrofit to Collapse Prevention (left), and 75% are retrofit to Immediate Occupancy (right)

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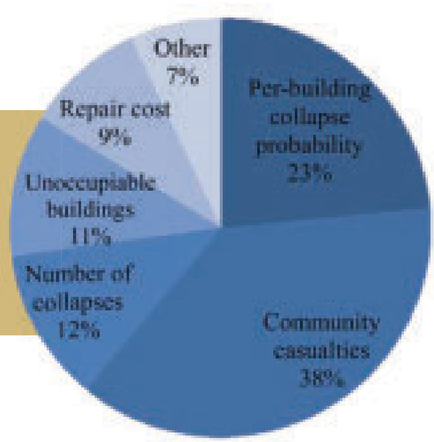
Can we tailor a retrofit program to achieved desired level of seismic resilience?

Public Expectations of Seismic Performance
What is the public's preferred measure of seismic performance?
Survey of 400+ California residents



(Davis & Porter, 2016)

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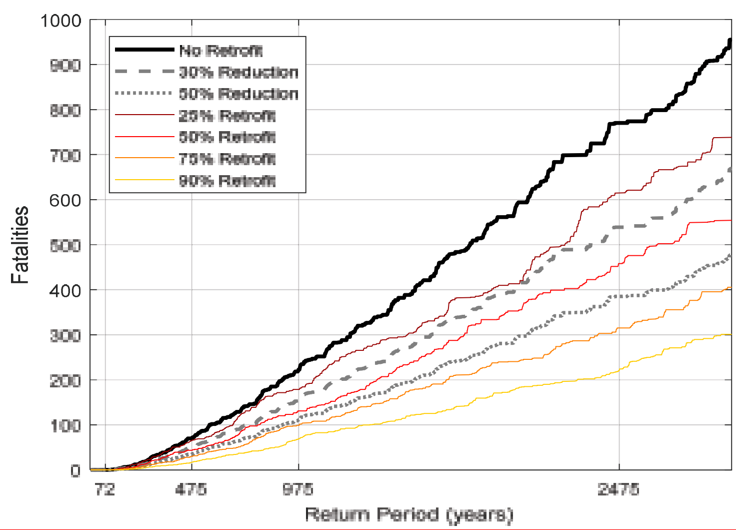
Retrofit effects: reducing community fatalities



Buildings retrofit to CP

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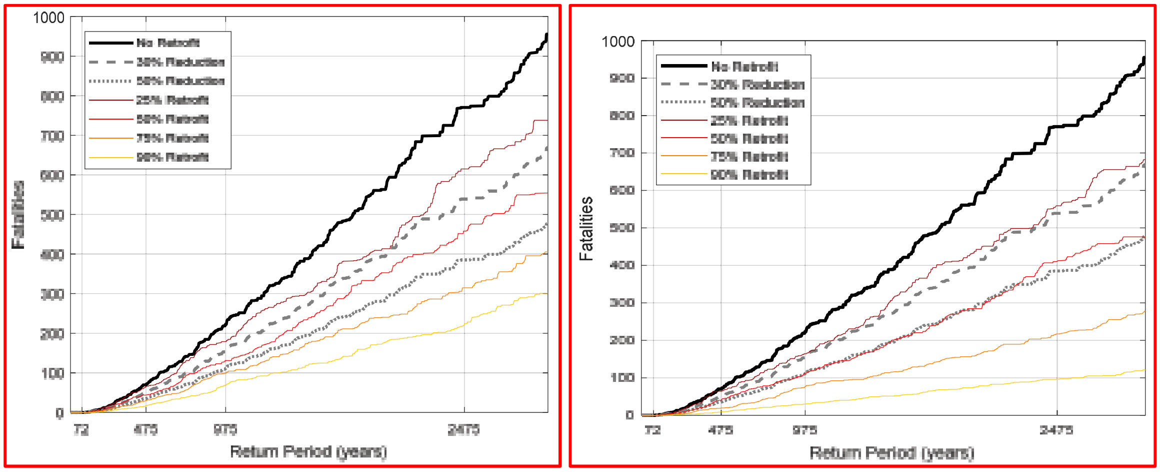
Retrofit effects: reducing community fatalities



Comparing fatalities in inventories retrofit to Collapse Prevention (left), and to Immediate Occupancy (right)

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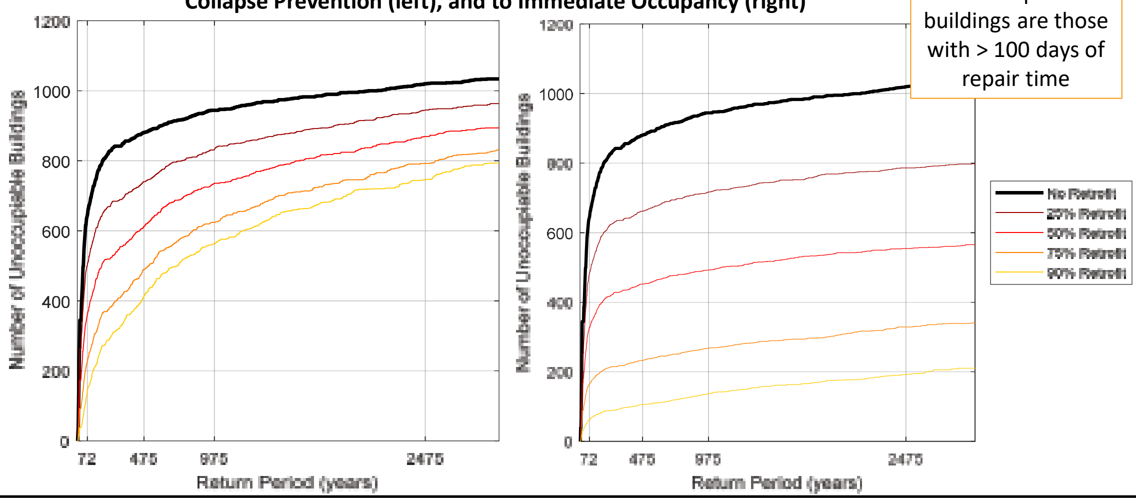
Retrofit effects: reducing unoccupiable buildings

Comparing numbers of unoccupiable buildings in inventories retrofit to Collapse Prevention (left), and to Immediate Occupancy (right)



Unoccupiable buildings are those with > 100 days of repair time

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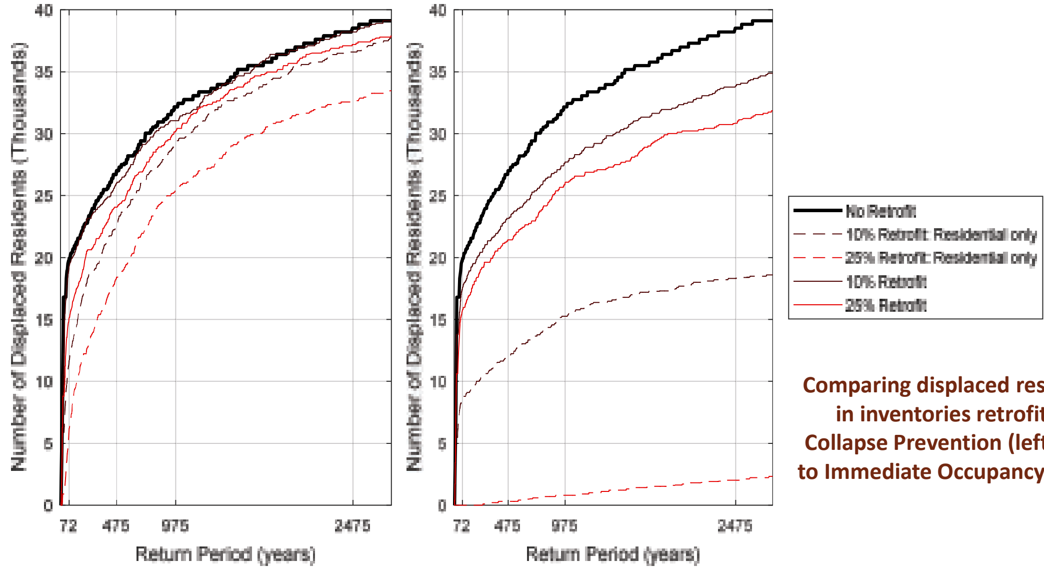
Retrofit effects: displaced residents



Comparing displaced residents in inventories retrofit to Collapse Prevention (left), and to Immediate Occupancy (right)

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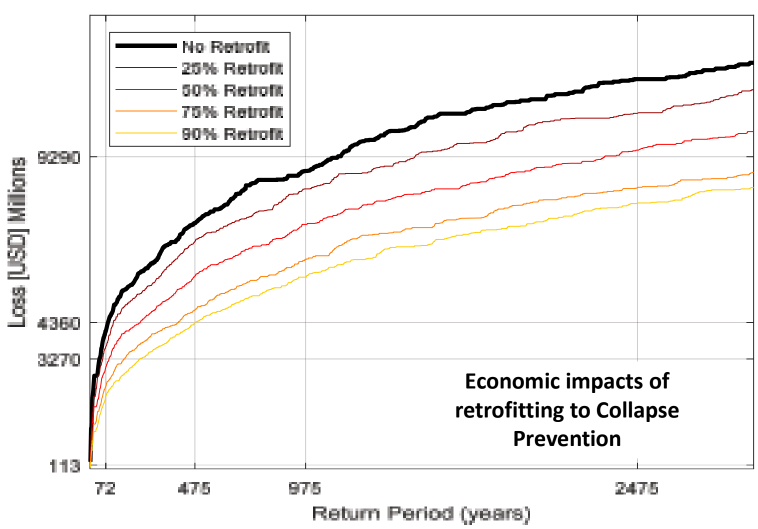
Retrofit effects: reducing costs of repair



City of LA Annual Budget

Estimated total damage in Northridge Earthquake

City of LA "Safe City" Budget

City of LA "Building and Safety" Budget

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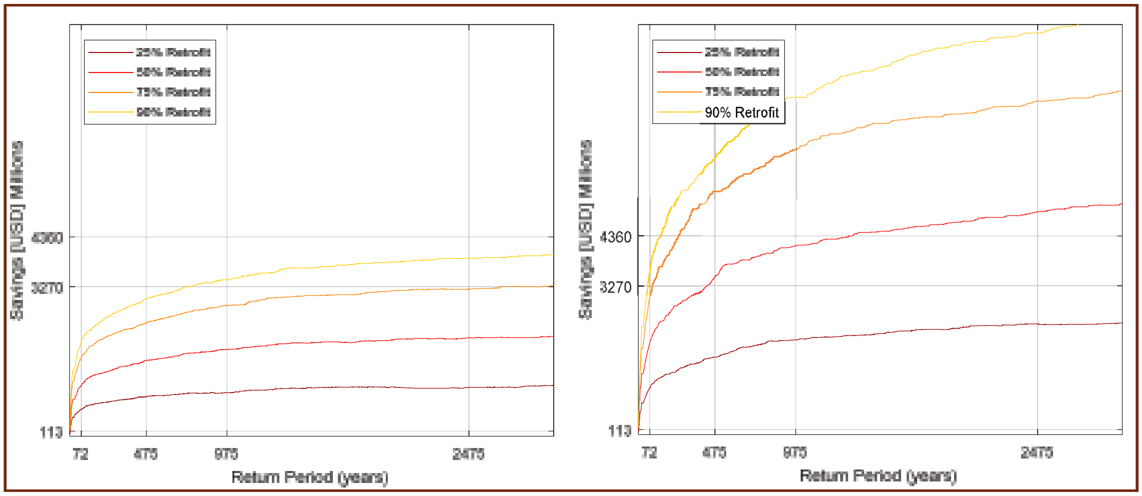
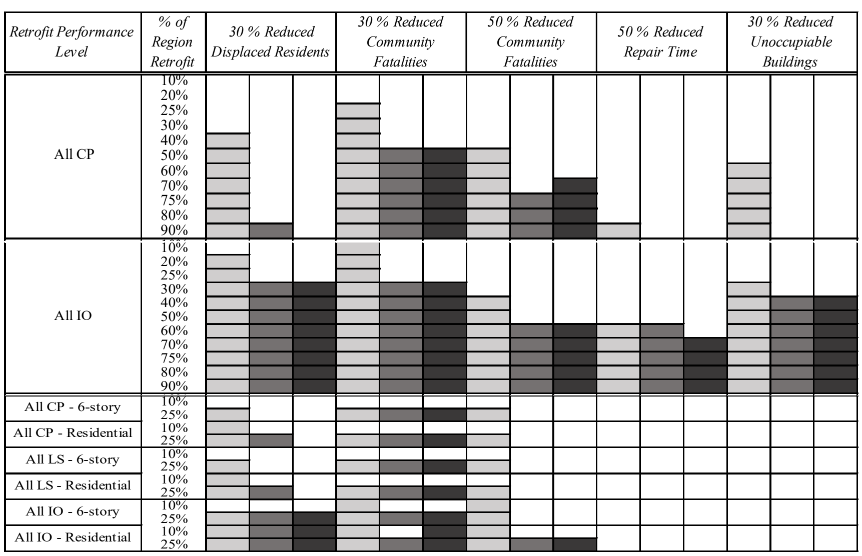
Retrofit effects: regional savings



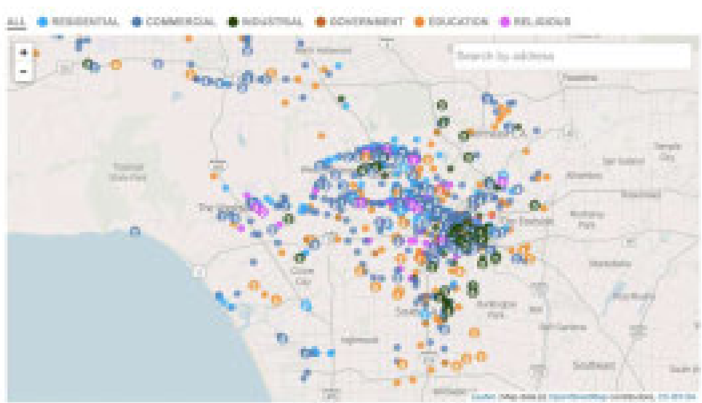
Comparing numbers of regional saving in inventories retrofit to Collapse Prevention (left), and to Immediate Occupancy (right)

Implications for policy making



How can we easily identify the most vulnerable older concrete buildings?

New FEMA methodology (P-2018) for identifying collapse potential of older concrete buildings



Methodology for identifying Exceptionally High Seismic Risk buildings

New FEMA methodology (P-2018) for identifying collapse potential of older concrete buildings

Simple

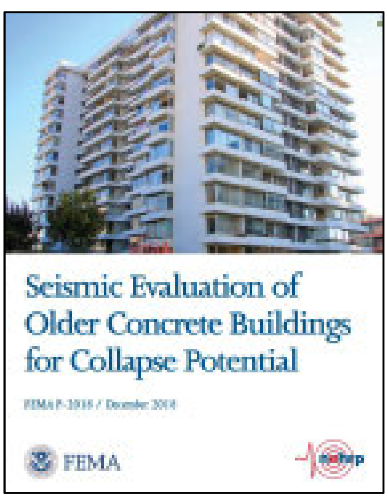
Repeatable

Cost-Effective

Avoid excessive conservatism

1) **Defensible through modern seismic performance assessment techniques**

Evaluation Methods

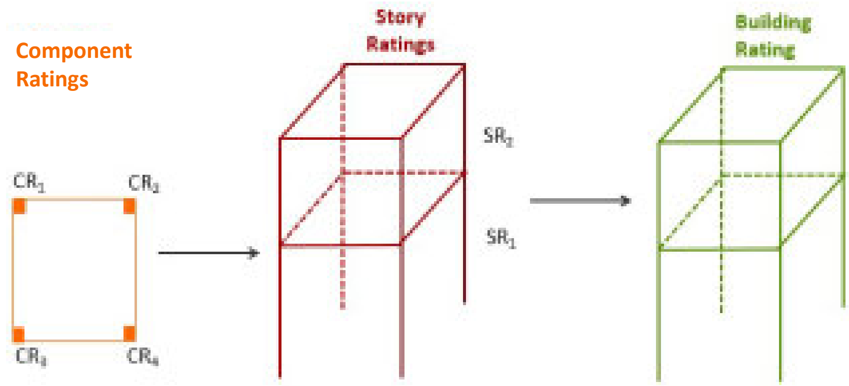


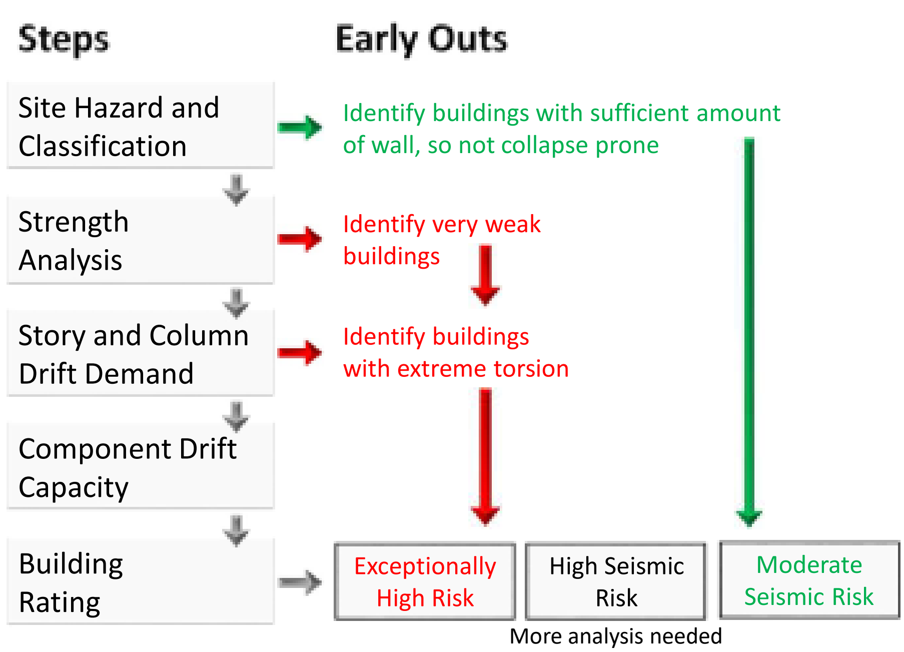
Site Hazard and Classification	Building Drawings Frame, Wall-Frame, or Wall
Strength Analysis	Determine Base Shear Strength using Mechanism Analysis
Story and Component Drift Demand	Modified SDOF Global Seismic Displacement Demand
Column or Wall Drift Capacity	Based on Component Test Data
Building Rating	Column/Wall Rating → Story Rating → Building Rating

Building rating provides ranking of buildings in inventory

Component, story and building ratings

- Column and wall ratings based on component drift capacities, which are related to story statistically, and depending on the gravity load carried.





Development supported by trial evaluations

- Conducted by engineers experienced in evaluation and retrofit
- Considered a group of concrete buildings; buildings had previously been evaluated using another procedure, but were not calibrated to earthquake damage
- Provided information about how the results compared to other methods; in many cases, good agreement; in others, ATC 78 method was less conservative (as expected)

Thank you!

Many thanks for the invaluable contributions of my former students, especially: Jared DeBock, Samantha Grey, Cody Harrington, Travis Marcilla, and Meera Raghunandan

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Session 1

Seismic Risk Assessment and Retrofitting of Existing Buildings

CURRENT SEISMIC RETROFITTING PROJECTS OF REINFORCED CONCRETE BUILDINGS IN TAIWAN

By Dr. S.-J. Hwang, National Taiwan University/ National Center for Research on Earthquake Engineering (NCREE)

Abstract

Prior to the introduction of modern seismic codes in the late 1990s for Taiwan, many reinforced concrete buildings were designed without adequate detailing and reinforcement for seismic protection. For these vulnerable buildings, enhancements to the seismic capacities through retrofitting are urgently needed. The objective of this presentation is to report the current seismic retrofitting projects of Taiwan. One is the school retrofitting project issued by the Ministry of Education 12 years ago. This school retrofitting project have upgraded the seismic capacities of approximately 8000 school buildings in Taiwan. The other is the seismic retrofitting project by phases issued by the Ministry of Interior Affairs. This project is aimed to remove the seismic deficiency of the soft first story as a first priority for the residential buildings. The strategy, technology and progress of these seismic projects will be introduced in this presentation.

Keywords: seismic retrofitting, seismic upgrading, reinforced concrete building, school building.

Biography

Dr. Shyh-Jiann Hwang is a Professor of Civil Engineering at the National Taiwan University, Taipei, Taiwan. He also serves as the Director of National Center for Research on Earthquake Engineering (NCREE) in Taiwan. He received his Master and Ph.D. form the University of California, Berkeley. He serves as a member of seismic code committee in Taiwan and is very active in Taiwan concrete society. His research interests include shear behavior of reinforced concrete members, and seismic design and retrofitting of reinforced concrete structures.

NRC-MOST/NCREE Taiwan Workshop
Earthquake Engineering Technologies

NARLabs
October 7, 2019

Current Seismic Retrofitting Projects of RC Buildings in Taiwan

Shyh-Jiann Hwang
Director
National Center for Research on Earthquake Engineering

Professor
National Taiwan University

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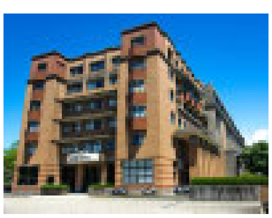
NARLabs

Introduction of NCREE

- Established at National Taiwan University in **1990**
- Mission:
  - Pre-quake preparation – Disaster prevention
  - Emergency response – Disaster reduction
  - Post-quake recovery – Disaster relief



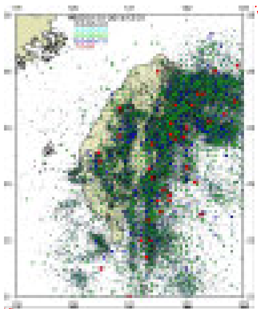
2

OUTLINES

- Introduction
- Evaluation and Retrofitting Technologies
- School Retrofitting Program
- Residential Building Program
- Conclusion

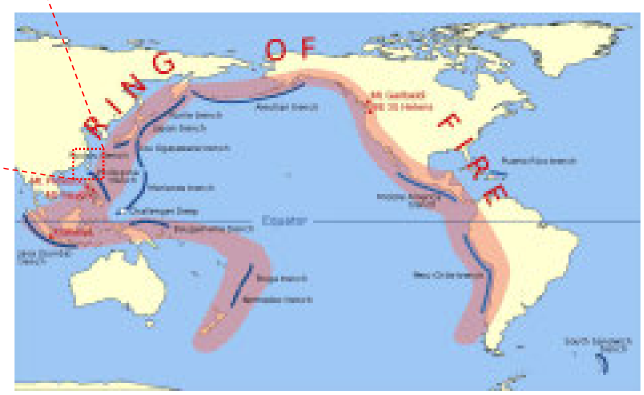
Introduction

Seismicity in Taiwan



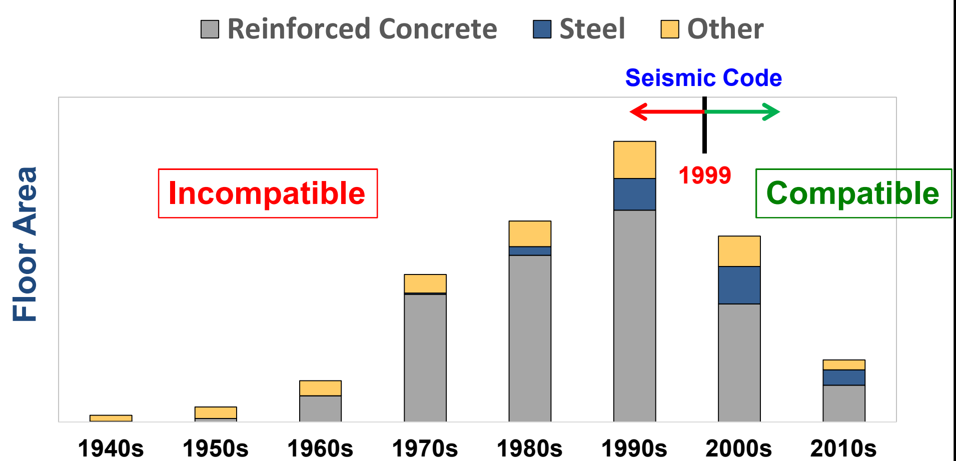
Earthquake Distribution of Taiwan (A.D.1900-2014)

Taiwan



RC Buildings in Taiwan

- **Reinforced Concrete Building: 74%**
- **Older RC Building: 58%**



Total: **1.75 billions m²**

Evaluation and Retrofitting Technologies

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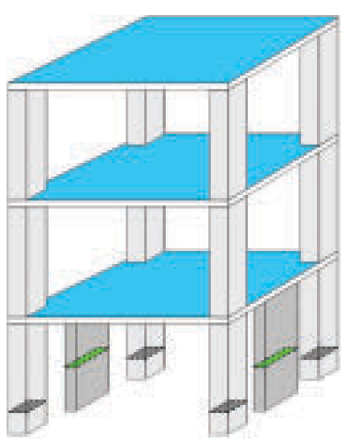
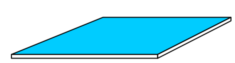
Preliminary Evaluation

Seismic Index: $$\frac{Capacity}{Demand} = \frac{\tau_C A_C + \tau_W A_W}{a_g \times w \times \Sigma A_f}$$



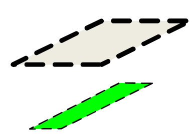
ΣA_f



Total Floor Area above 1st Floor

A_C

A_W

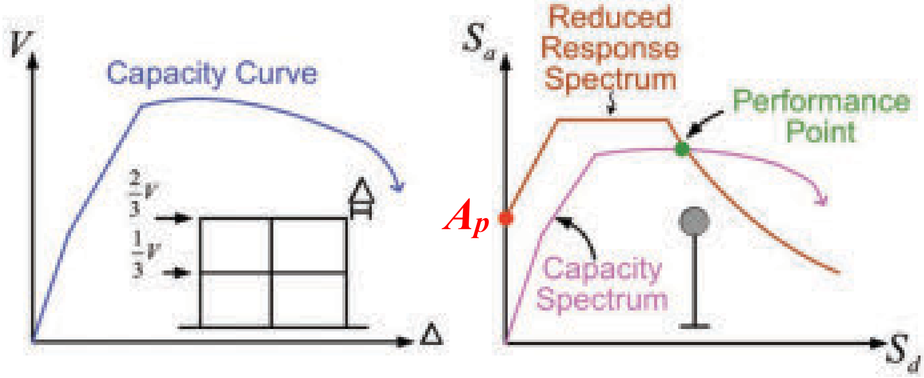


1st Floor Capacity

8

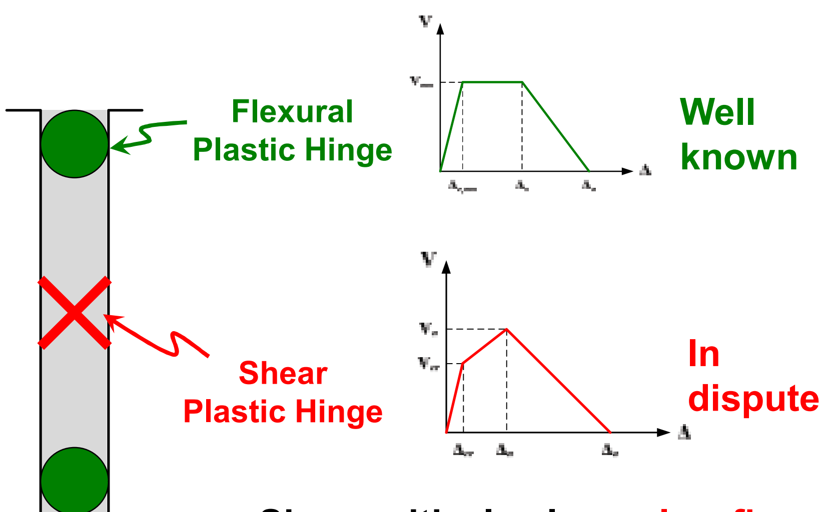
Detailed Evaluation

Pushover Analysis → **Capacity Spectrum Analysis**

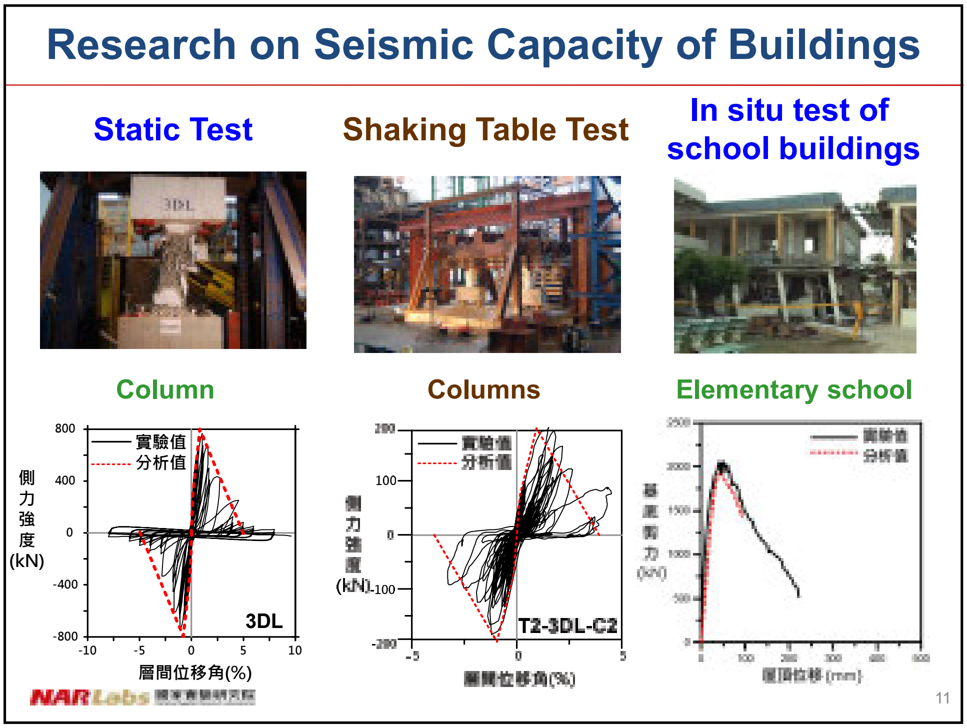


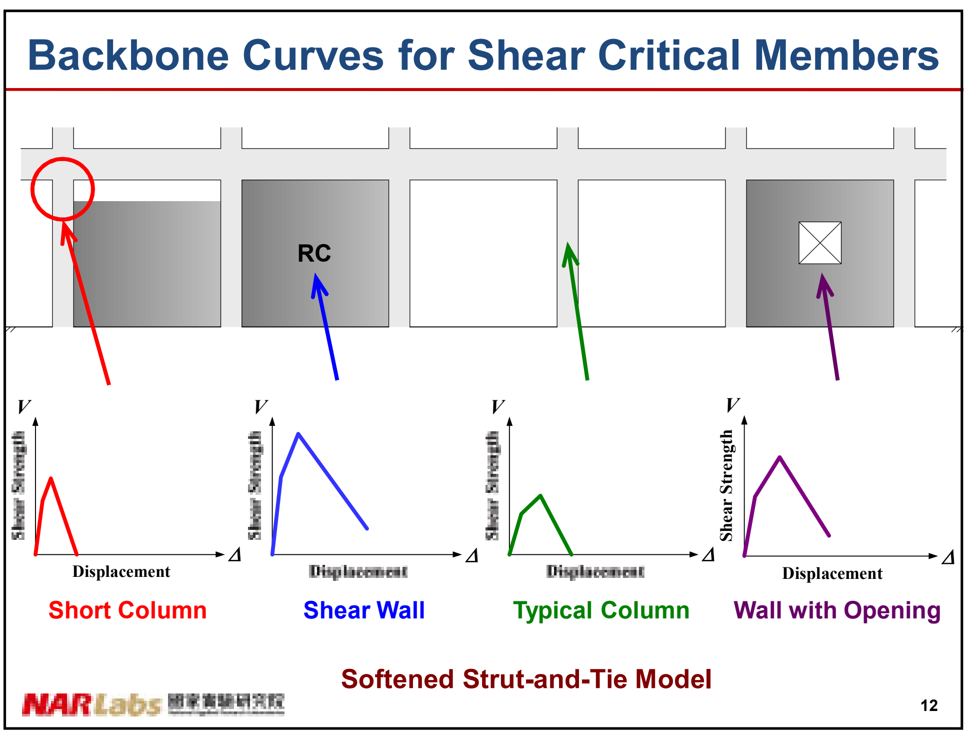
Performance-Target Ground Acceleration A_p

Column Modeling



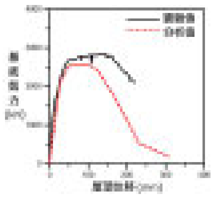
Shear critical column: low f'c, less transverse reinforcement


Research on Seismic Capacity of Buildings
Static Test
Shaking Table Test
In situ test of school buildings
Column
Columns
Elementary school
側力強度 (kN)
實驗值
分析值
3DL
層間位移角(%)
T2-3DL-C2
11

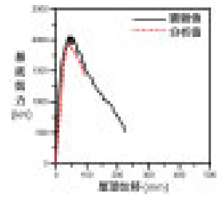

Backbone Curves for Shear Critical Members
RC
V
Shear Strength
Displacement
Δ
Short Column
Shear Wall
Typical Column
Wall with Opening
Softened Strut-and-Tie Model
12

In-Situ Tests of School Buildings: Verification of Pushover Analysis

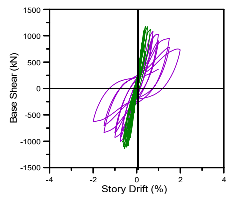
Hua-Lien (2005)



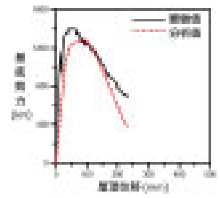
Yun-Lin (2005)



Tao-Yuan (2006)



Tainan (2007)



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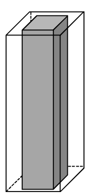
Test Video of Monotonic Loading

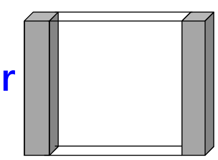
Pseudo Dynamic Test (# 3), Courtesy of Dr. Min-Lang Lin

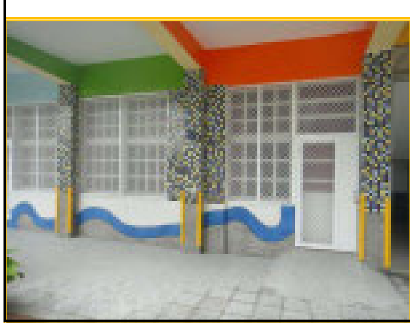
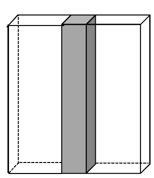
Common Retrofitting Techniques




Jacketed column

Shear wall



Wing wall

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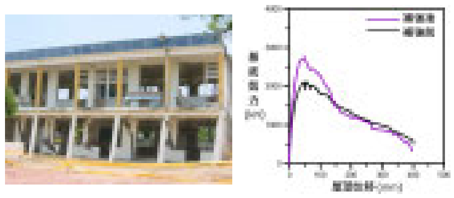
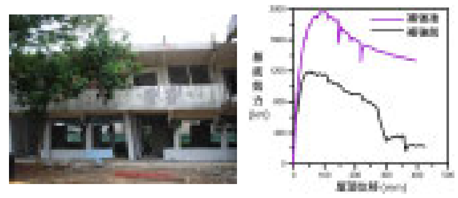
In-Situ Tests of School Buildings: Verification of Retrofitting Methods

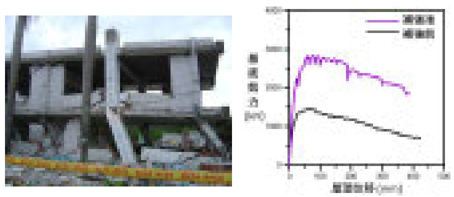
RC Wing Wall (2005)



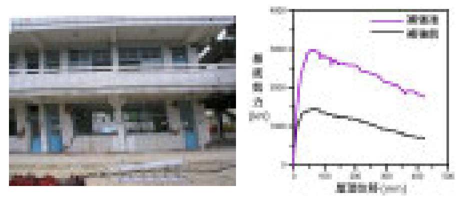
Composite Column (2006)



RC Jacketing (2007)



Steel Jacketing (2007)



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Chi-Chi Earthquake Damage Database of School Buildings in Taiwan

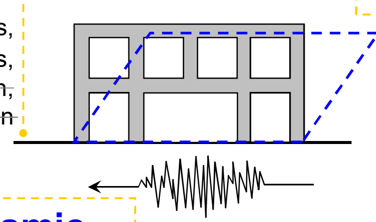
- **Basic Methodology from ATC-13**

Structural Properties

Plan, Dimensions,
Section details,
Material strength,
Soil condition

Damaged Conditions

Damage records,
Definition of
"damage"



Seismic Magnitude

Site PGA,
Longitudinal PGA for individual building

NCREE-07-023
Tu et al.

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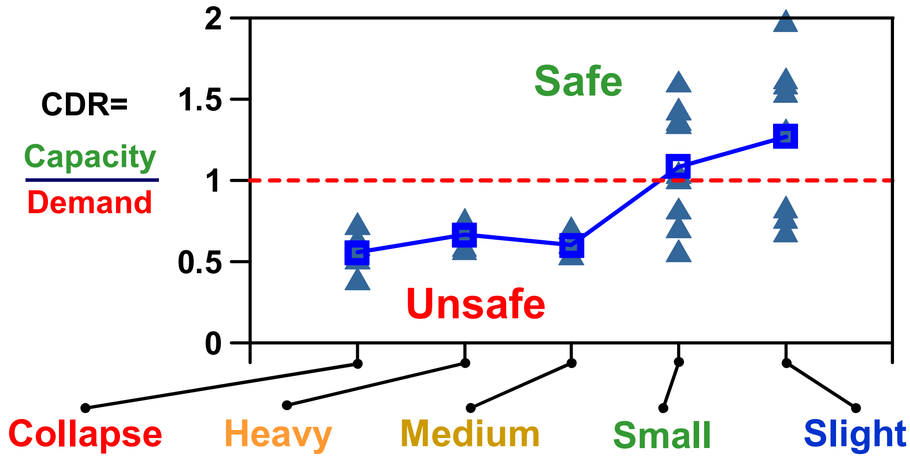
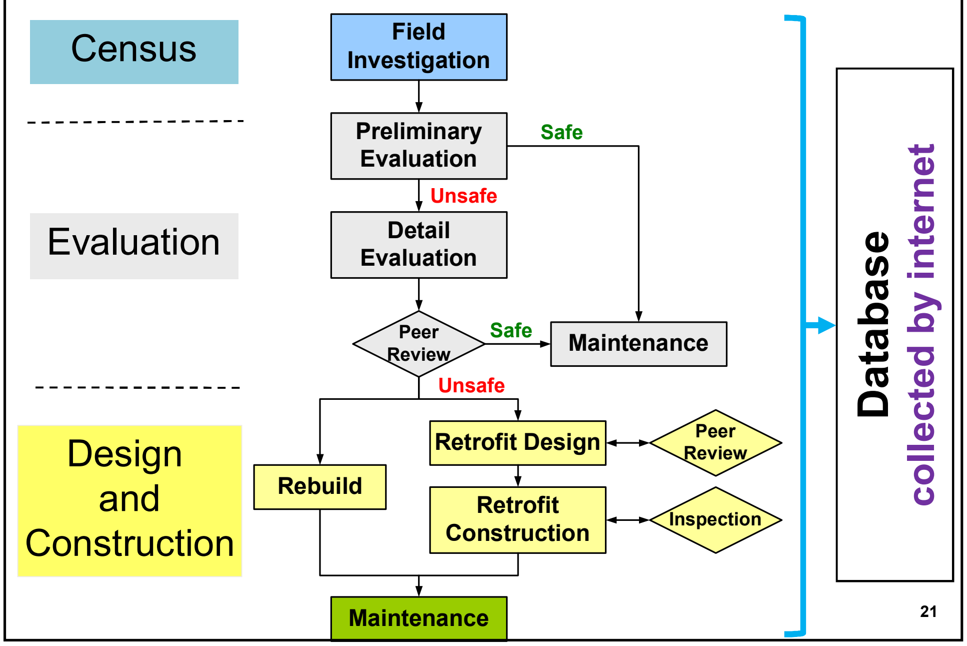
Verification of Acceptance Criteria (35 Buildings)



School Retrofitting Program

Strategy for School Upgrading in Taiwan



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Unification of Process

- Complex Parties: governmental official, school teacher, engineer, constructor, student, parent
- Tight Schedule: annual budget, short construction period
- Unification Document: operation specification, contract document, design manual

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Budget Control - Service Payment

New Construction	Seismic Retrofitting
Design Payment = Rate × Construction Fee	Design Payment = Rate × Floor Area
Payment per Quantity	Innovation for Quality

23

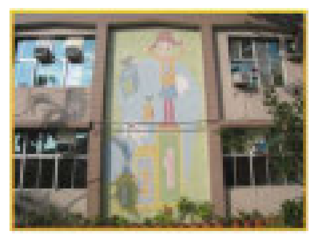
Budget Control - Economic Methods

Traditional Retrofitting Method ⇨ Encouraged

RC Column Jacketing

RC Wing Wall

RC Shear Wall



Seismic Devices with Patents ⇨ Prohibited

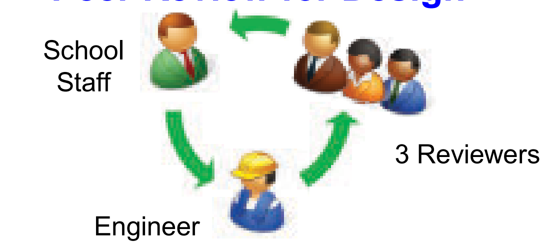
Isolated Device

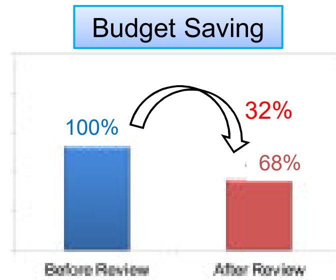
Damper

24

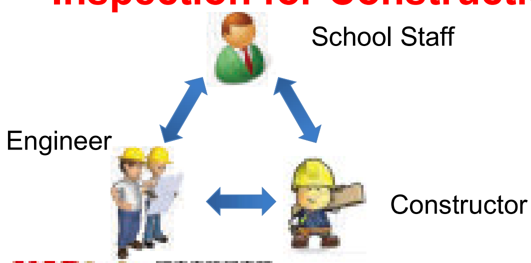
Quality Control - Review and Inspection

- **Peer Review for Design**





- **Inspection for Construction**



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Quality Control - Workshops

- Workshops for Engineers, School Administrators, Educational Officials

- Case Study

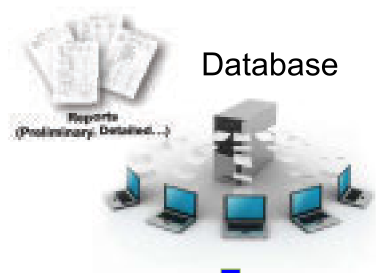
Number of Participants: 8,987

NAR

Website and Database

https://school.ncree.org.tw

Browsing No.: over 5,520,000



- Data Collecting
- News Announcement
- Download Service
- Exchange of Information

- Process monitoring
- Decision making

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Retrofitting Effectiveness

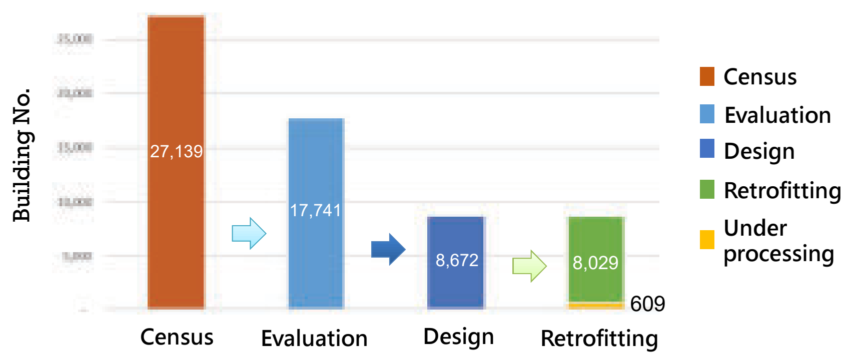
Kaohsiung Jia-Xian EQ

M_L = 6.4, March 4, 2010

28

School Buildings Upgrading Projects

- Project span from 2009 to 2019
- Upgrading rate by construction up to 32%



Data deadline： 2019.6.30

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Residential Building Program

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Characteristics of Damaged Buildings

- Older RC building

- Soft and weak first story

Source : DEGENKOLB RECONNAISANCE TEAM
2016 MEINONG TAIWAN EARTHQUAKE DEBRIEF

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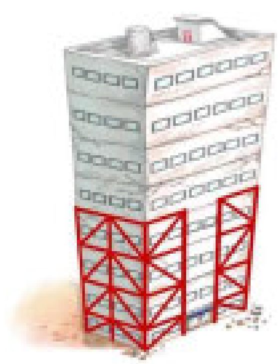
Interim Seismic Retrofit



Building with soft first story

Removal of seismic deficiency

Prevent Building Collapse Immediately during Earthquake

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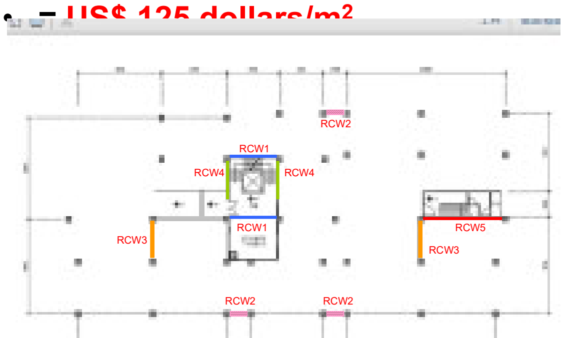
Interim Retrofitting Case - 1F Parking Space

- Story： 6F/B1
- Floor area：4900 m^2
- Construction Floor：1F (690 m^2)
- Interim retrofitting
- Budget: US$ 85,000/690
- = US$ 125 dollars/m^2



Street map view from Google Maps

Conclusion

Conclusions

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- Disaster reduction of earthquake needs constant efforts.
- Canada and Taiwan share the same earthquake threats.
- Collaboration between Canada and Taiwan is highly expected.

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國家地震工程研究中心

Thank you for your attention

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SEISMIC HAZARD ESTIMATES FOR CANADA, 1953-2020 – SOME IMPLICATIONS FOR FUTURE RISK MITIGATION THROUGH DESIGN AND RETROFIT

By Dr. J. Adams, National Resources Canada

Abstract

Canada covers the entire range of seismic conditions, from magnitude 9 subduction earthquakes off its west coast to moderate and to extremely-low seismicity in eastern Canada. The National Building Code of Canada (NBC) has used 6 generations of seismic hazard map since 1953 to assign the level of anti-seismic design needed. The 65-year history of seismic hazard estimates shows the impact of increased knowledge and has implications for the level of retrofit needed. The 6th generation map for the NBC 2020 has increased the estimated hazard in southwestern British Columbia through the addition of 4 greater subduction earthquakes into the paleoseismic record. The hazard in eastern Canada has increased through the introduction of the NGA-East ground motion model. The NBC 2020 will also introduce performance-based design. The marginal cost of the NBC 2020 seismic hazard increases and engineering improvements for new buildings is about +1% of the total national building cost.

Keywords: earthquake, seismic hazard, history, National Building Code of Canada.

Biography

Dr. John Adams is a Research Scientist in the Canadian Hazards Information Service at Natural Resources Canada. John graduated with a Ph.D. in Geology from New Zealand in 1978. His 39-year career at Natural Resources Canada has involved all aspects of the earthquake program, from running field aftershock surveys to managing the program, and from creating national seismic hazard maps to participating in post-earthquake engineering reconnaissance visits. Since 1985 John has led production of the seismic hazard maps for the NBC, including those for the NBC 2020.

Seismic Hazard Estimates for Canada, 1953-2020

Some Implications for Future Risk Mitigation Through Design and Retrofit

John Adams john.adams@canada.ca

on behalf of M. Kolaj, S. Halchuk, T. Allen and others

20191007

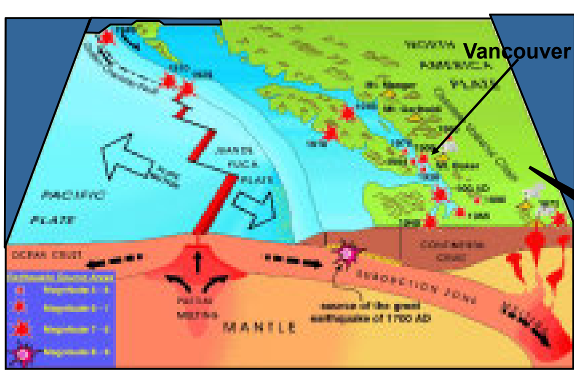
Outline

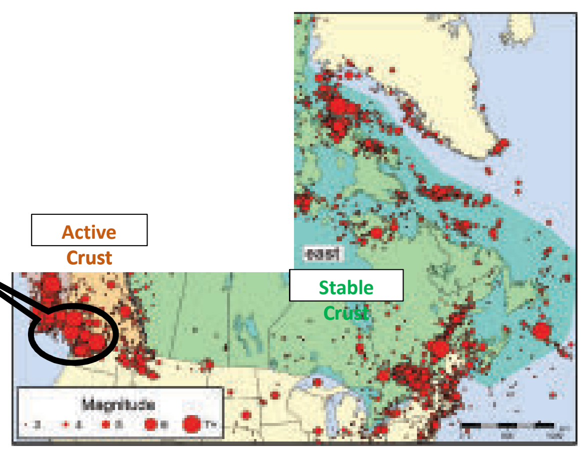
1. Seismicity of Canada
2. History of seismic hazard estimates for Canada
3. Updated 2020 seismic hazard estimates
4. Updated 2020 code: performance-based design
5. Marginal cost of seismic hazard improvements (2015 →2020) for new buildings
6. Global assessment of seismic hazard

Canada

Seismicity of Canada

Western Canada - high seismicity, plate-boundary

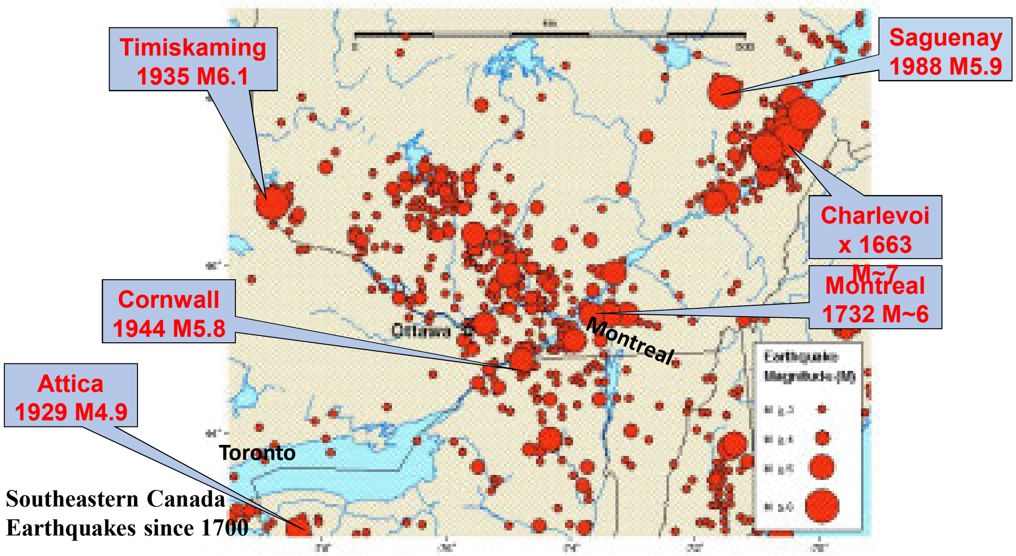




Crustal 0-25 km M7+ (1949 M8.1 strike-slip)
Interface – great earthquakes (1700 M~9 thrust)
Inslab 50-65 km (1949 M7 normal)

Central Canada – low seismicity
Southeast Canada & Arctic – moderate seismicity

Moderate seismicity in southeastern Canada

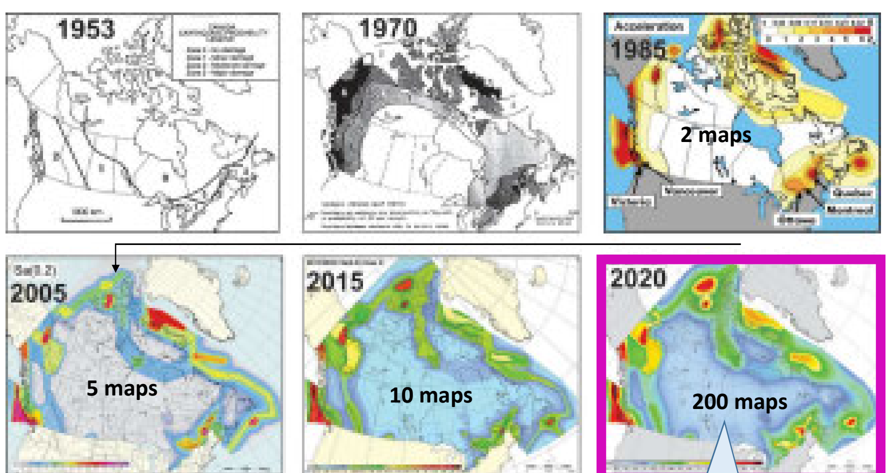


Six Generations of seismic hazard maps for NBCC

Progressed from qualitative → quantitative

High probability → lower probability

PGA supplanted by alternative shaking measures

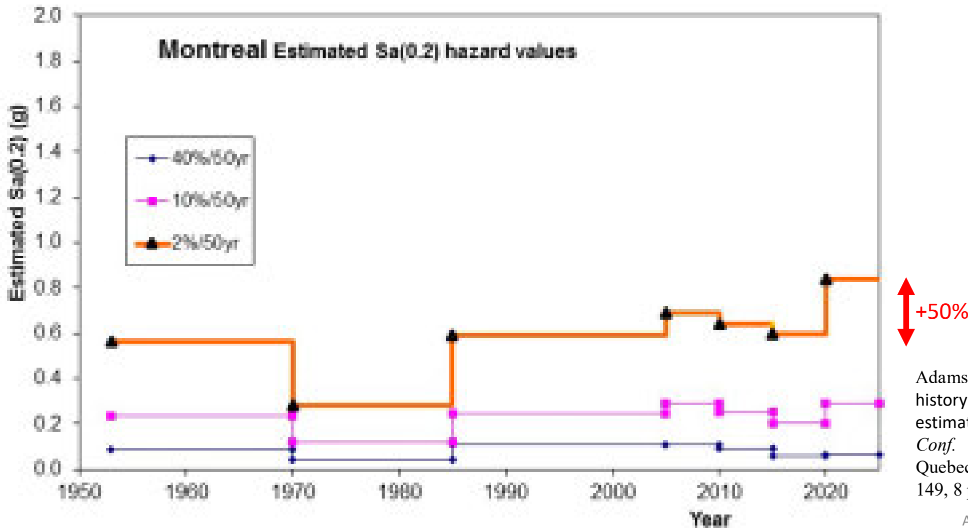


6th Generation being proposed for NBCC2020

NBCC2020 will be issued for Public Comment in late January 2020
Expected to be implemented - end of 2020

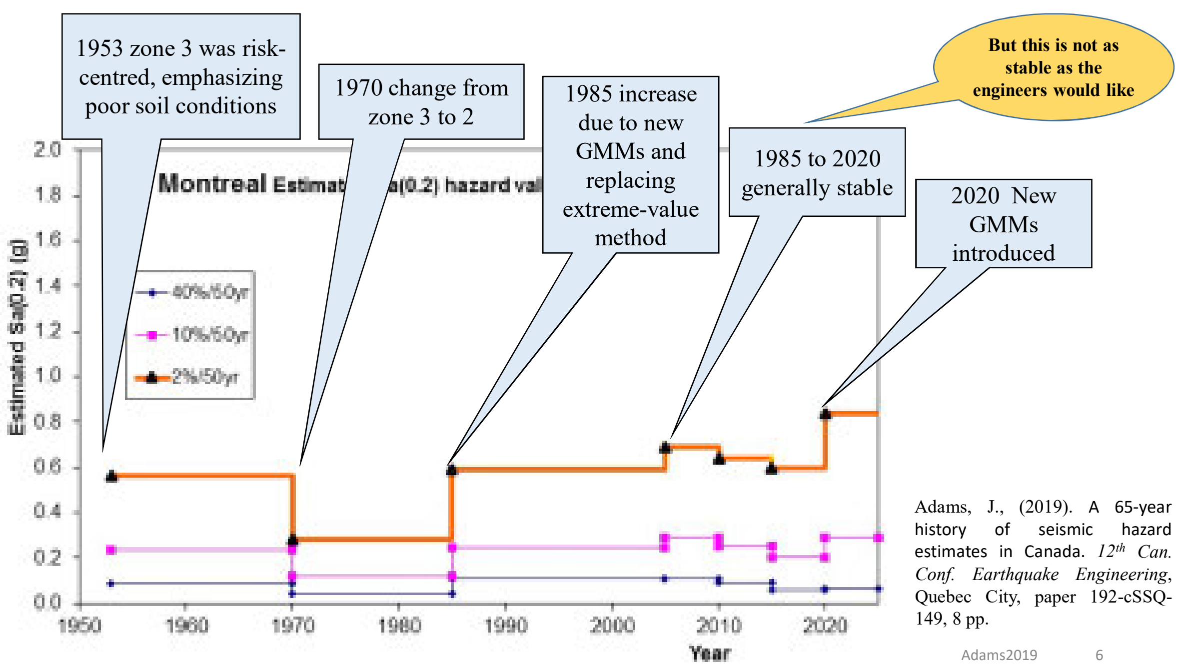
Change in estimated hazard through time - Montreal

(this is change in the estimate, actual hazard is probably constant or very slowly changing)



Adams, J., (2019). A 65-year history of seismic hazard estimates in Canada. *12th Can. Conf. Earthquake Engineering*, Quebec City, paper 192-cSSQ-149, 8 pp.

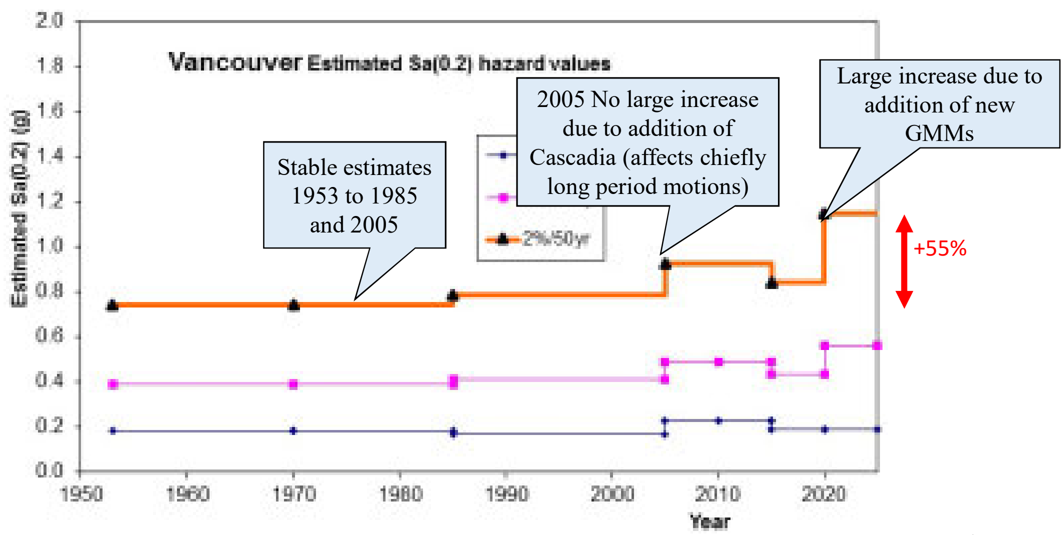
Adams2019 5



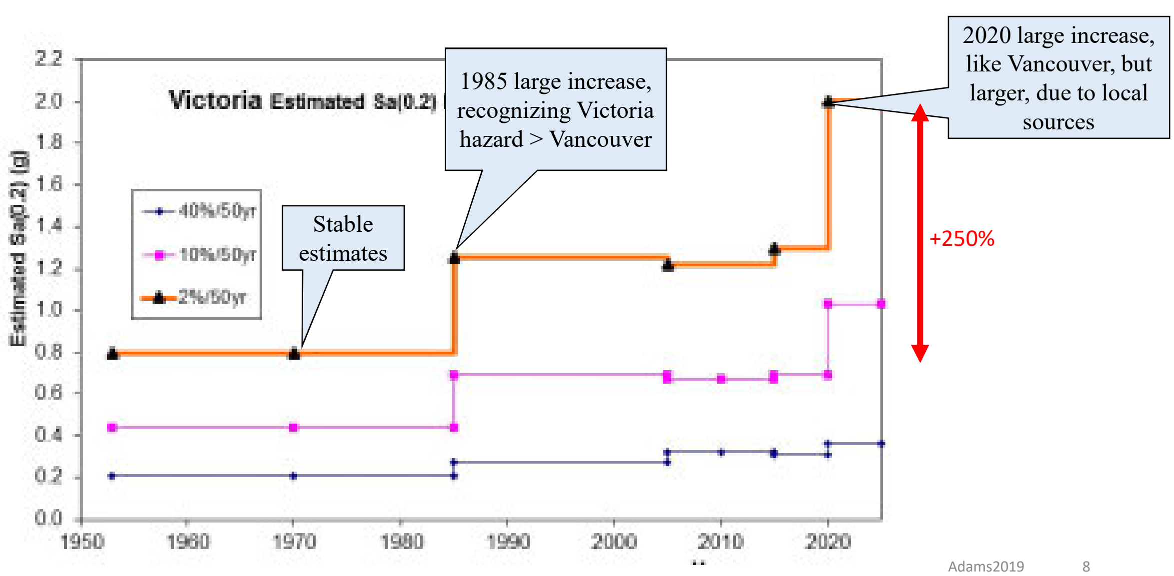
Adams, J., (2019). A 65-year history of seismic hazard estimates in Canada. *12th Can. Conf. Earthquake Engineering*, Quebec City, paper 192-cSSQ-149, 8 pp.

Adams2019 6

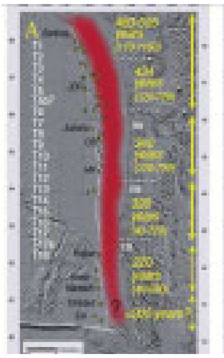
Change in estimated hazard through time - Vancouver



Change in estimated hazard - Victoria



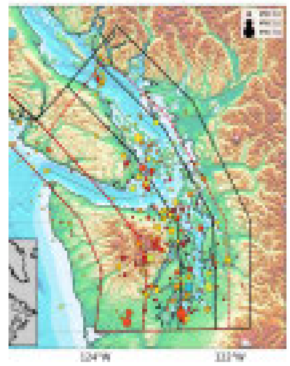
Updated 2020 estimates: Earthquake source model changes

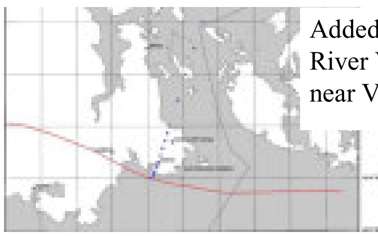


Credit: Goldfinger et al. 2017 Marine Geology

Added 4 more great earthquakes to Cascadia (now 10-17% chance in next 50 years)

Redefined the inslab source below Straits of Georgia





Added Leech River Valley fault near Victoria

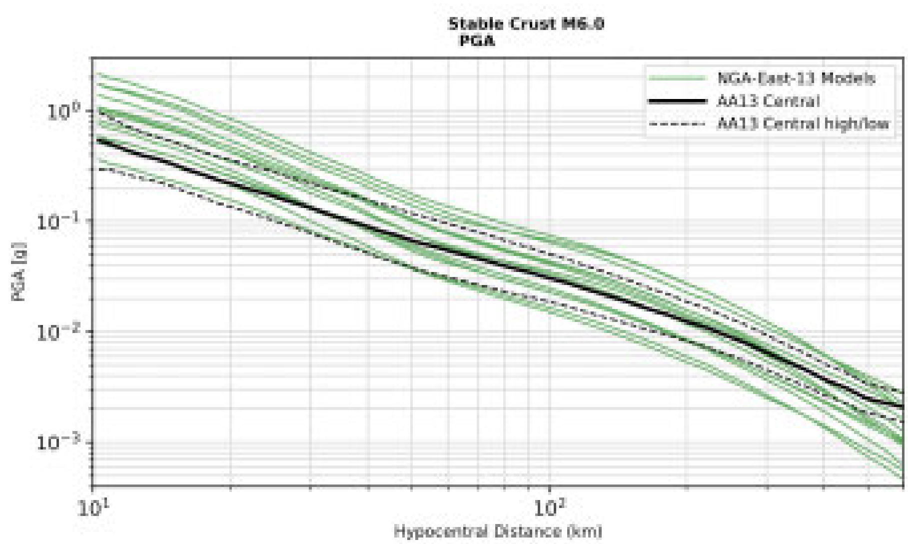
Eastern Canada substantially unchanged

Adams2019 11

Ground Motion Models (GMMs)

Relate shaking to the magnitude and distance of an earthquake.

Comparison of old (black) and new (green) relations for <u>Eastern</u> Canada



Adams2019 12

Ground Motion Models

Need different GMMs for
- Eastern Canada
- Western Canada crustal
- Subduction interface
- Inslab subduction

- 2015: representative suite approach to summarize all models and their uncertainty
- 2020: revert to classical approach - weighting 4 GMMs for each tectonic regime
- Newest relation: NGA-East - SSHAC level 3 study to characterize ground motions in Central and Eastern North America for reference hard-rock (3000 m/s) conditions.

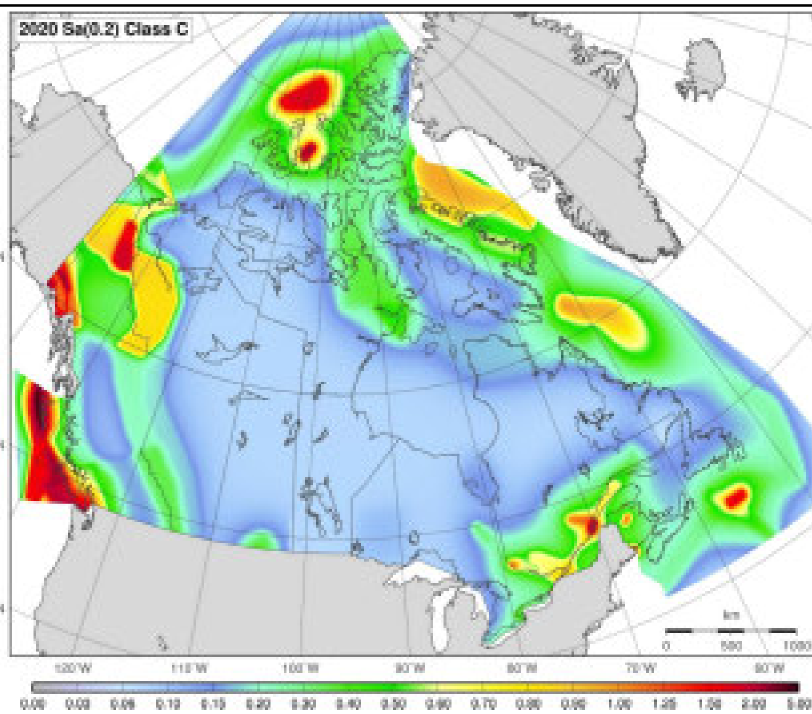
GMMs are still evolving:
- Some are fairly mature (e.g. NGA-West2 for active-crust earthquakes)
- Some are getting there (e.g. 2019 NGA-subduction) – but few records from M>8.5 subduction earthquakes
- Some are still immature (NGA-East) - lack of observational data from M>6

Choice of GMMs has a big impact on the estimated hazard

Adams2019 13

2020 Pattern of Seismic Hazard is very similar to 2015

Levels are rather different …



Adams2019 14

Seismic hazard changes from 2015

Comparing

2015 on Class C to
2020 on Vs30=450 m/s

Almost all increases from GMMs

East +30-60%

Montreal

Table 3 — 6th Generation seismic hazard values for selected localities in Canada, from east to west, compared with NBCC2015 values. Values are given for mean hazard at 2% in 50 years on Site Class C (units=g).

	Sa(0.2) 2015	**Sa(0.2) 2020**	% Change	Reason	Sa(2.0) 2015	**Sa(2.0) 2020**	% Change	Reason
St. John's	0.090	**0.18**	106	B	0.027	**0.041**	52	B
Halifax	0.11	**0.21**	90	B	0.029	**0.042**	45	B
Moncton	0.16	**0.29**	81	B	0.031	**0.047**	53	B
Fredericton	0.21	**0.38**	80	B	0.036	**0.056**	55	B
La-Malbaie	1.73	**2.2**	29	B	0.203	**0.26**	28	B
Québec	0.49	**0.77**	57	B	0.064	**0.097**	52	B
Trois-Rivières	0.36	**0.60**	[illegible]	B	0.052	**0.082**	[illegible]	B
Montréal	0.60	**0.84**	41	B	0.068	**0.098**	44	B
Ottawa	0.44	**0.66**	50	B	0.056	**0.082**	46	B
Niagara Falls	0.32	**0.44**	36	B	[illegible]	[illegible]	40	B
Toronto	0.25	**0.36**	46	B	[illegible]	[illegible]	42	B
Windsor	0.10	**0.17**	72	B	[illegible]	[illegible]	25	B
Winnipeg	0.05	**0.080**	47	B	[illegible]	[illegible]	23	B
Edmonton	0.10	**0.15**	46	B	0.019	**0.021**	10	B
Calgary	0.19	**0.23**	20	B,C	0.036	**0.033**	-9	B,C
Kelowna	0.14	**0.18**	27	B,C	0.063	**0.067**	6	A,B,C
Kamloops	0.15	**0.18**	25	B,C	0.064	**0.068**	7	A,B,C
Vancouver	0.85	**1.1**	36	B,C,D	0.256	**0.28**	10	A,B,C
Victoria	1.30	**2.0**	53	A,B,C,D,E	0.399	**0.51**	27	A,B,C,E
Tofino	1.46	**1.8**	23	A,B,C	0.535	**0.66**	23	A,B,C
Village of Q.C.	1.61	**2.3**	42	B,C	0.450	**0.60**	34	B,C
Inuvik	0.31	**0.39**	27	B,C	0.072	**0.077**	6	B,C

Reasons: A = Juan de Fuca activity rate, B = New GMMs, C = Sigma in new GMMs, D = Changes in inslab (GTP) source, E = Addition of Leech River Valley Fault.

Reasons:
B = New GMMs

Adams et al., Canada's 6th Generation Seismic Hazard Model, as Prepared for the 2020 National Building Code of Canada 12th Can Conf Eq Eng June 2019

Kolaj et al., Ground-motion models for the 6th Generation Seismic Hazard Model of Canada. 12th Can Conf Eq Eng June 2019

Adams2019 15

Seismic hazard changes from 2015

Comparing

2015 on Class C to
2020 on Vs30=450 m/s

West +5-50%

Some of increases from GMMs

Vancouver

Table 3 — 6th Generation seismic hazard values for selected localities in Canada, from east to west, compared with NBCC2015 values. Values are given for mean hazard at 2% in 50 years on Site Class C (units=g).

	Sa(0.2) 2015	**Sa(0.2) 2020**	% Change	Reason	Sa(2.0) 2015	**Sa(2.0) 2020**	% Change	Reason
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Fredericton	0.21	**0.38**	80	B	0.036	**0.056**	55	B
La-Mal	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Québec	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Trois-R	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Montré	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ottawa	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Niagara	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Toronto	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Windsor	0.10	**0.17**	72	B	0.017	**0.022**	25	B
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SP Reasons:
B = New GMMs,
C = Sigma in new GMMs,
D = Changes in inslab (GTP) source,

LP Reasons:
A = Juan de Fuca activity rate,
B = New GMMs,
C = Sigma in new GMMs,

Reasons: A = Juan de Fuca activity rate, B = New GMMs, C = Sigma in new GMMs, D = Changes in inslab (GTP) source, E = Addition of Leech River Valley Fault.

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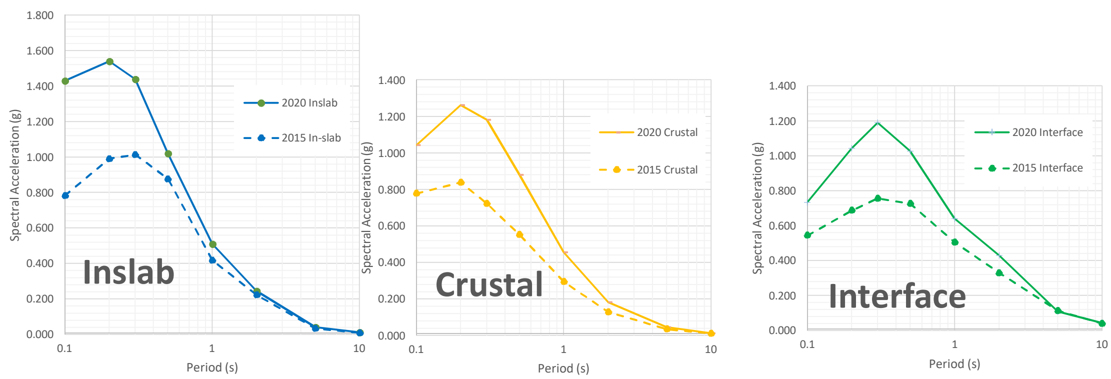
Change from 2015 Class C UHS for Victoria
(Vancouver is similar)

3 seismotectonic contributors:-

Inslab dominates at short periods;

Interface dominates at long periods

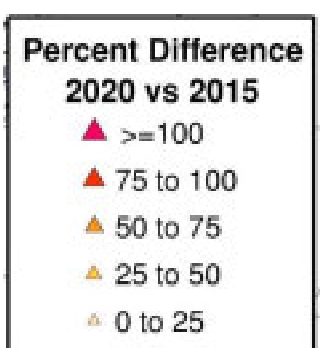
In 2020 all components have increased for T ≤ 2 s

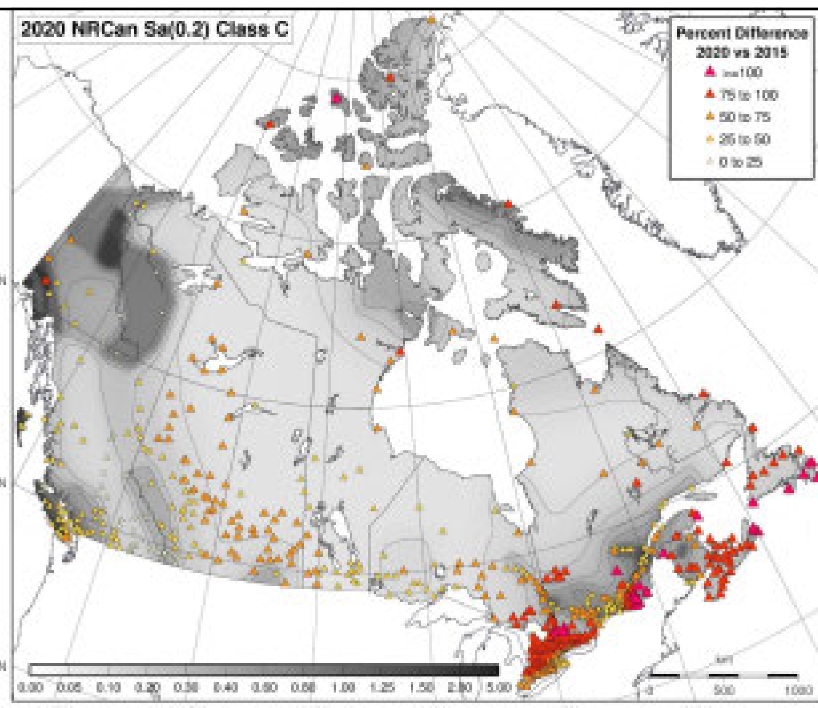


Adams2019 17

Seismic hazard changes from 2015

Comparing
2020 on Vs30=450 m/s
to 2015 on Class C





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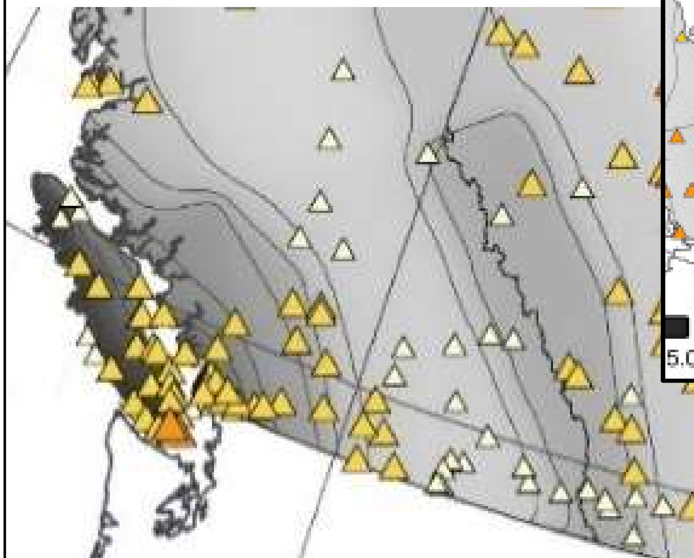
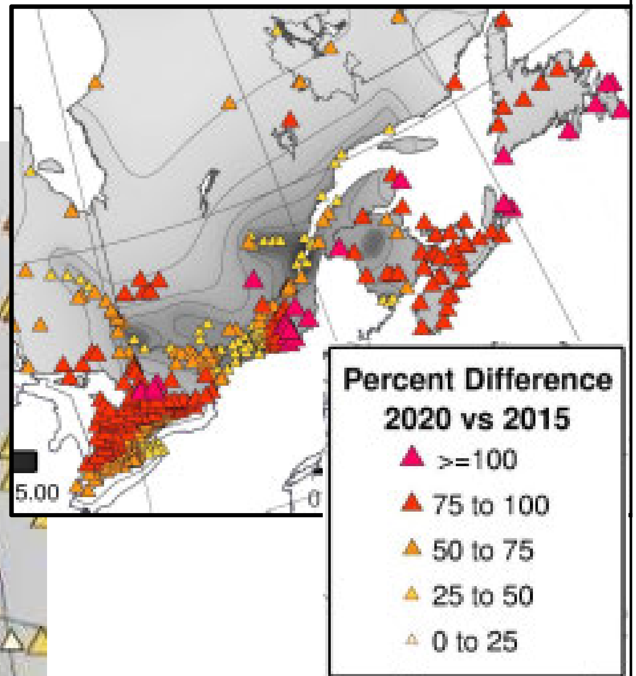
Change in Sa(0.2) from 2015

- all increases, driven mostly by GMMs





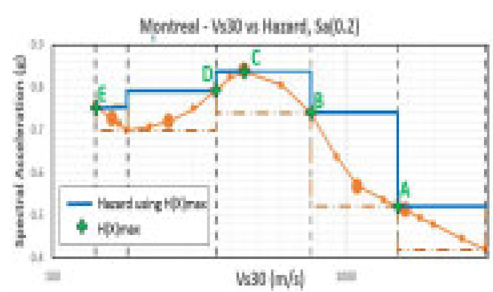
2020 Improvements in Site Amplification for NBCC

- In NBCC 2015 hazard is provided for reference ground conditions (Site Class C, Vs_{30} =450 m/s).
  - Foundation factors F(T) to obtain hazard for other site conditions (compare NEHRP Fa, Fv factors)
- For NBCC2020 we calculate & provide hazard
  - for Vs30 at 140 – 3000 m/s
    - continuous function - **preferred**
  - for Site Classes E-A
    - Discrete values with steps; highest hazard in class used
- Simplifies procedure & increases reliability of results

Users will be nudged to use Vs_{30} rather than Site Class

Table 4.1.8.4.B.
Values of F(0.2) as a Function of Site Class and PGA_{ref}

Site Class	Values of F(0.2)				
	$PGA_{ref} \leq 0.1$	$PGA_{ref} = 0.2$	$PGA_{ref} = 0.3$	$PGA_{ref} = 0.4$	$PGA_{ref} \geq 0.5$
A	0.69	0.69	0.69	0.69	0.69
B	0.77	0.77	0.77	0.77	0.77
C	1.00	1.00	1.00	1.00	1.00
D	1.24	1.09	1.00	0.94	0.90
E	1.64	1.24	1.05	0.93	0.85
F	(1)	(1)	(1)	(1)	(1)



Updated NBCC Performance Goals

Life Safety : Normal Importance Buildings
Life Safety plus : High Importance Buildings
Life Safety + Functional : Post Disaster Buildings

NBCC2020 strengthens code requirements for:

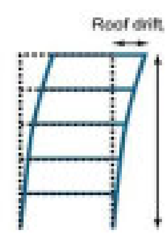
- POST DISASTER (e.g. hospital)
- HIGH IMPORTANCE buildings (e.g. school) and
- a small sub-set of NORMAL buildings (>30m, in high-seismic locations)

Material courtesy of J. Singh, NRC

Proposed NBCC2020 - Performance-Based Design

NBC2015	Ground Motion	Drift	Response
Post Disaster building	2% in 50 Years	$0.01h_s$	Inelastic

NBCC2020-Proposed	Ground Motion	Drift	Response
Post Disaster Building	2% in 50 Years	$0.01h_s$	? Inelastic
	5% in 50 Years	$0.005h_s$	Elastic
High Importance	2% in 50 Years	$0.02h_s$	Inelastic
	10% in 50 Years	$0.005h_s$	Elastic
Tall Normal SC4	2% in 50 Years	$0.025h_s$	Inelastic
	10% in 50 Years	-	Elastic



New requirements for less severe but more likely events

Material courtesy of J. Singh, NRC

Cost Impact

Large increases in hazard can be addressed by relatively small increases in cost of new buildings

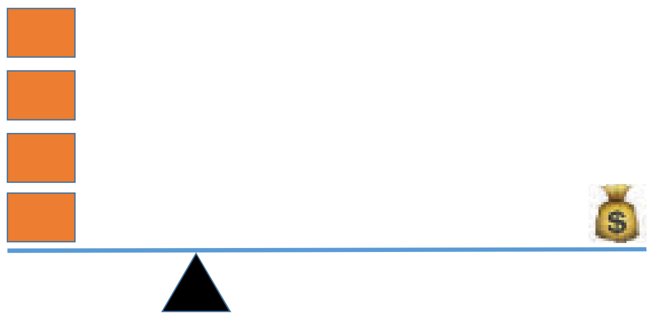


Photo By Arild Vågen - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=62504048

*Slide from J. Singh, **National Research Council Canada***

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NBCC2020 Hazard Impact Analysis

Cost of Seismic Force Resisting System came out as:

2.5% to 4% of the total building cost

Increased cost of NBCC2020 improvements (new hazard values and code changes):

Province	Change in total building cost
Alberta	**0.55%**
British Columbia	**0.64%**
Manitoba	**0.80%**
New Brunswick	**1.45%**
Newfoundland and Labrador	**1.69%**
Northwest Territories	**1.12%**
Nova Scotia	**1.63%**

Province	Change in total building cost
Nunavut	**1.81%**
Ontario	**1.24%**
Prince Edward Island	**1.87%**
Quebec	**1.07%**
Saskatchewan	**1.05%**
Yukon	**0.62%**

National Average 1.04%

Total building cost includes the cost of all structural, mechanical, electrical, and architectural components, and permanent OFCs in a new building ready for occupancy. Total building cost excludes cost of property, site services, permit and engineering fees (and similar 'soft' costs), and user/tenant supplied movable furniture/furnishings.

Work by John Sherstobitoff's group; material courtesy of J. Singh, NRC

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Application of NBCC2015 to Canada's global embassies

NRCan project for Global Affairs Canada

Aims to provide same level of seismic safety to Canadians working in our Embassies abroad

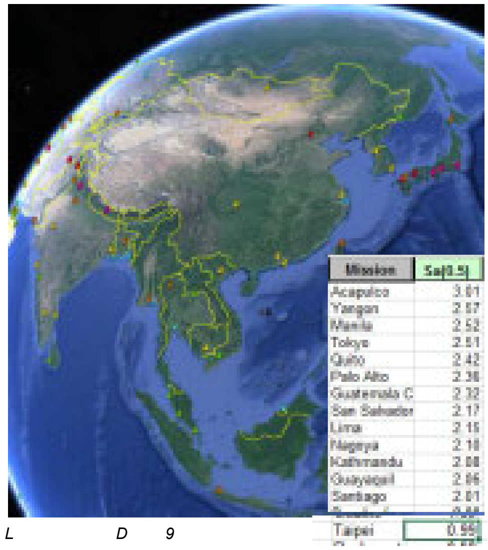
Assess NBCC hazard parameters at 232 cities

Provides PGA plus Sa(T) for T= 0.2-10 s at 2%/50yr annual probability

Method:

- Start from GEM* global hazard assessment where possible
- Otherwise use other published seismic hazard assessments
- Use tectonic-specific spectral shapes to adjust available parameters (typically PGA at 10%/50yr) to get range of spectral periods needed at 2%/50yr

Re ort to be i ued in late 2019



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* www.globalquakemodel.org

Final thoughts

- Estimates of seismic hazard in Canada have tended to increase with time
- Hazard estimates are chiefly controlled by the quality of available GMMs – yet more earthquake recordings needed
- Older buildings were often designed for lower seismic demand
- Performance based design will reduce impact of future moderate earthquake shaking
- Hazard increases of even 50% increase building cost by only 1%

  Should we design buildings for higher-than-estimated hazard? – saves future retrofit costs
- An earthquake-resistant building is a better building – e.g. against explosions

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Recent NRCan hazard papers at 12th Canadian Conference on Earthquake Engineering

D

Adams, J., Allen, T., Halchuk, S., Kolaj, M. (2019). *D l a t b .* 12th Can. Conf. Earthquake Engineering, Quebec City, paper 192-Mkvp-139

Kolaj, M., Allen, T., Mayfield, R., Adams, J., and Halchuk, S. (2019). *D D l a* 12th Can. Conf. Earthquake Engineering, Quebec City, paper 192-hHtH-159

Halchuk, S., Allen, T., Adams, J. and Onur, T. (2019). *5 a .* 12th Can. Conf. Earthquake Engineering, Quebec City, paper 192-WGm8-169

D

Adams, J., and Halchuk, S. (2019). *D b.* 12th Can. Conf. Earthquake Engineering, Quebec City, paper 192-H39s-279

Halchuk, S., Adams, J., Kolaj, M. , Allen, T. (2019). *5 b. l* 12th Can. Conf. Earthquake Engineering, Quebec City, paper 192-DMsa-149

h

Adams, J., (2019). . 12th Can. Conf. Earthquake Engineering, Quebec City, paper 192-cSSQ-149

Cassidy, J.F., Brillon, C., Adams, J., Rogers, G.C. (2019). *a a 5 C b* 12th Can. Conf. Earthquake Engineering, Quebec City, paper 192-w4Ki-248

Crane, S., Perry, C., Motazedian, D., Adams, J., (2019). *D* 12th Can. Conf. Earthquake Engineering, Quebec City, paper 192-GGsX-149

Adams2019 27

EVALUATION OF SEISMIC VULNERABILITY SCREENING INDICES USING EARTHQUAKE RECONNAISSANCE DATA

By Dr. A. Puranam, National Taiwan University

Abstract

Cities in seismic regions often have unknown numbers of older buildings vulnerable to strong earthquake ground motion. Simple methods are needed with urgency to screen these buildings. The problem is of immense proportions as it affects some of the largest cities in the world. Seismic vulnerability indices proposed by Hassan and Sozen (1997), Islam et al. (2017), NCREE (Chiou et al., 2017), and Shiga (1968) possess the required simplicity. The indices have different forms and have been calibrated through independent activities, but all imply that the key to building survival is in the relative sizes of elements resisting lateral inertial forces. An evaluation showed that differences among indices are unlikely to lead to wide differences in the cost-to-benefit ratio associated with their use especially if they are used to include the effects of all lateral-load resisting elements including masonry infill.

Keywords: seismic evaluation, seismic vulnerability, reinforced concrete, low-rise structures.

Biography

Dr. Aishwarya Y. Puranam is an Assistant Professor in the Department of Civil Engineering at National Taiwan University. She received her B.Sc. (2013), M.Sc. (2016) and Ph.D. (2018) from Purdue University in the United States. Her research interests include behavior of reinforced concrete structures subjected to seismic demands, large-scale experiments, and data preservation. She is an active member of ACI Committee 133 - Disaster Reconnaissance.


Evaluation of Seismic Vulnerability Screening Indices using Earthquake Reconnaissance Data
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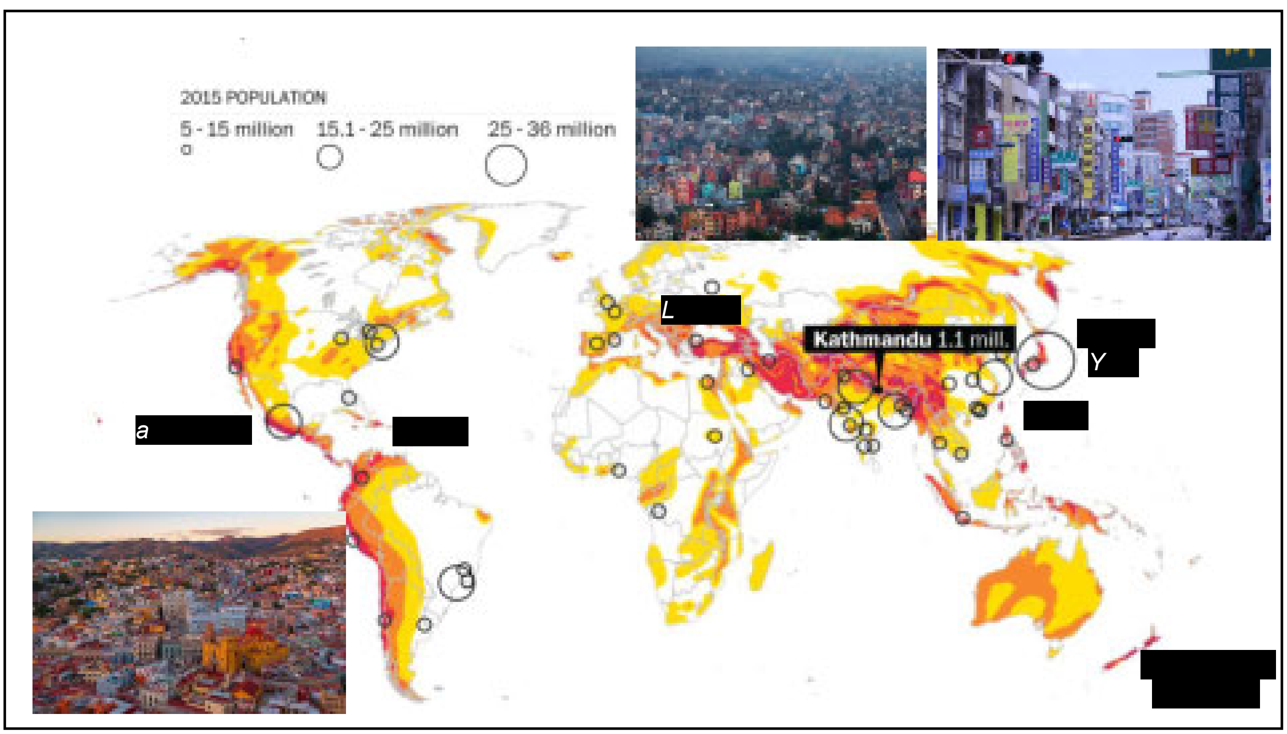
2015 POPULATION
5 - 15 million
15.1 - 25 million
25 - 36 million
Kathmandu 1.1 mill.
L [redacted]
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Y [redacted]
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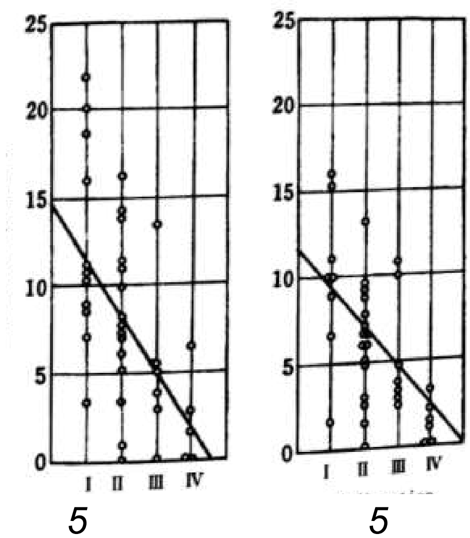
[redacted]

S. Otani (2000)

Table 1 Damage statistics of buildings from major earthquakes

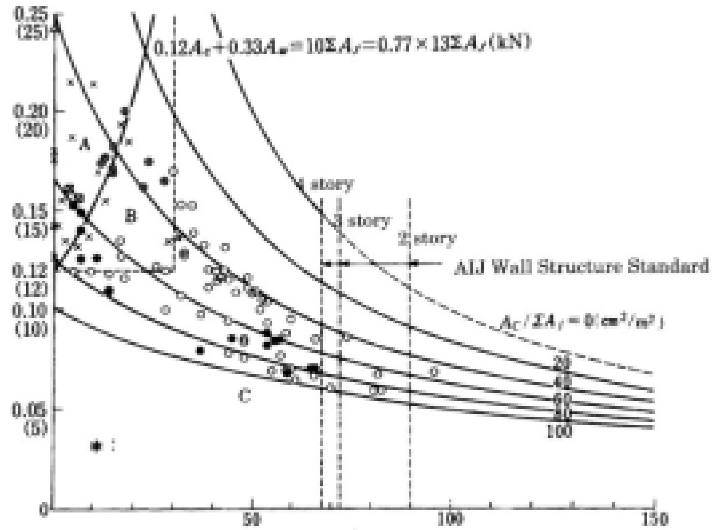
Earthquake, year	Operational damage	Heavy damage	Collapse	Total
Mexico City, 1985	4,251 (93.8%)	194 (4.3%)	87 (1.9%)	4,532
Lazaro Cardenas, Mexico, 1985	137 (83.5%)	25 (15.2%)	2 (1.2%)	164
Baguio City, Philippines, 1990	138 (76.2%)	34 (18.8%)	9 (5.0%)	181
Erzincan City, Turkey, 1992	328 (77.4%)	68 (16.8%)	28 (6.6%)	424
Kobe (pre-1981 construction), 1995	1,186 (79.4%)	149 (10.0%)	158 (10.6%)	1,493
Kobe (post-1982 construction), 1995	1,733 (94.0%)	73 (4.0%)	38 (2.1%)	1,844

1923 Kanto Earthquake (Nakagawa et al.)



1968 Tokachi-Oki Earthquake (Shiga et al.)

$$\tau_{avg} = 10\frac{kN}{m^2}\left(\frac{\Sigma A_{floor}}{A_{RCcol} + A_{wall}}\right)$$



$$\frac{A_w}{\Sigma A_f}\,(cm^2/m^2)$$

1992 Erzincan Earthquake (Hassan and Sozen, 1997)

$$\frac{(A_{RCwall} + 0.1A_{Mason\ \ wall})}{\Sigma A_{floor}}$$

L

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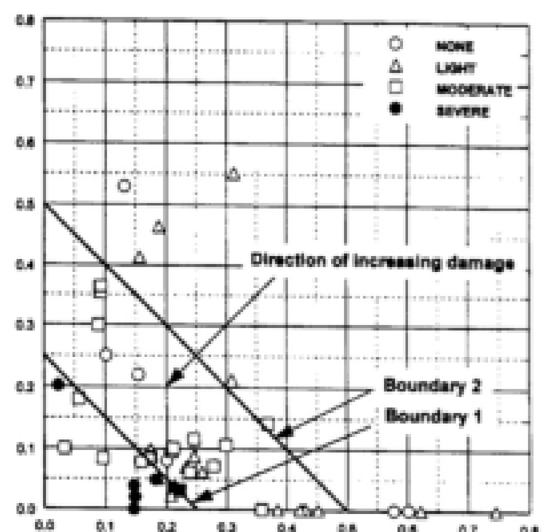

L L $0.5\frac{A_{RCcol}}{\Sigma A_{floor}}$

Comparing Screening Indices using Field Data

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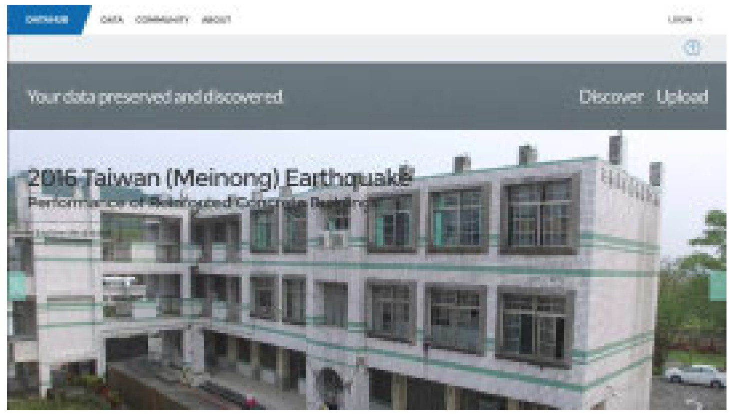

Taiwan (Meinong) Earthquake, February 2016

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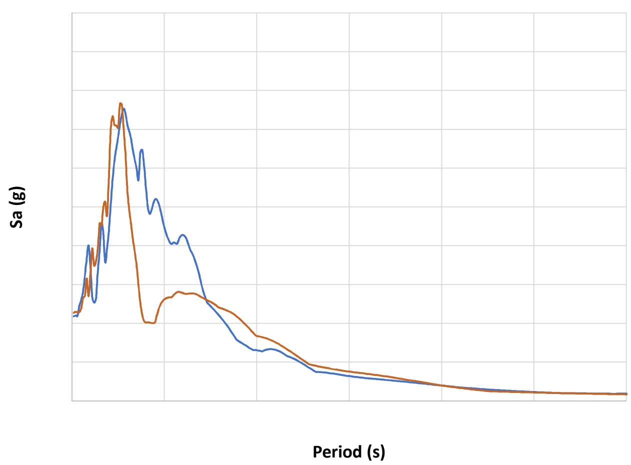
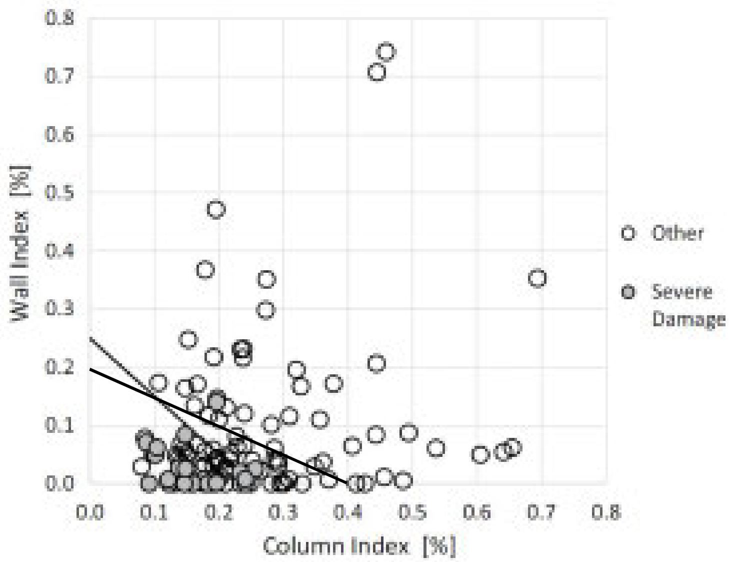




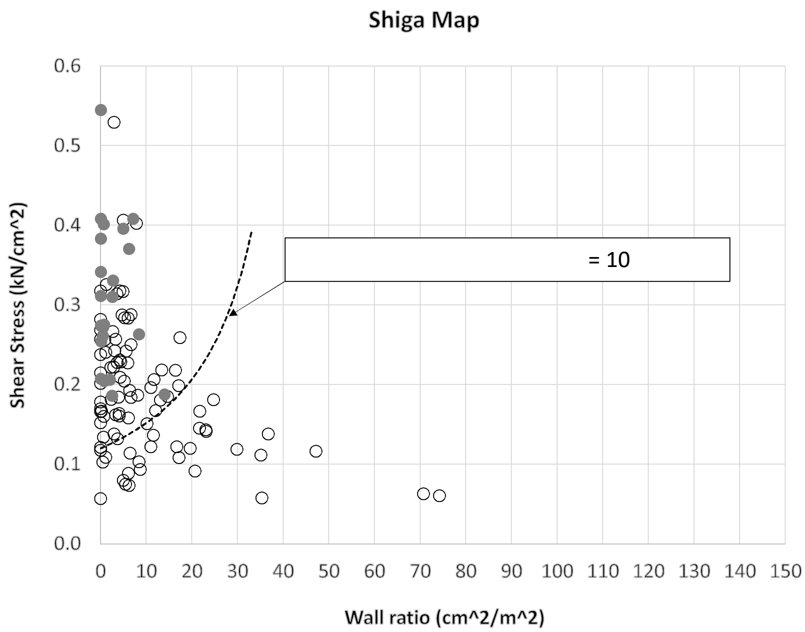
Shiga Map (1968)

$$\tau_{avg} = 10\,\frac{kN}{m^2}\left(\frac{\Sigma A_{floor}}{A_{RC_{col}}+A_{wall}}\right)$$

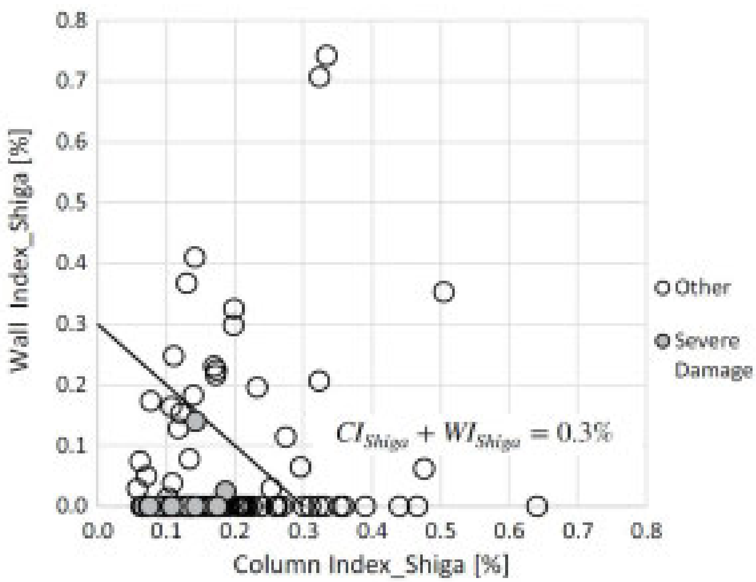
$$WR = A_{RCwall}/\Sigma A_{floor}$$

.

$$0.12\Sigma A_{RCcol} + 0.33\Sigma A_w \qquad \Sigma A_{floor}$$



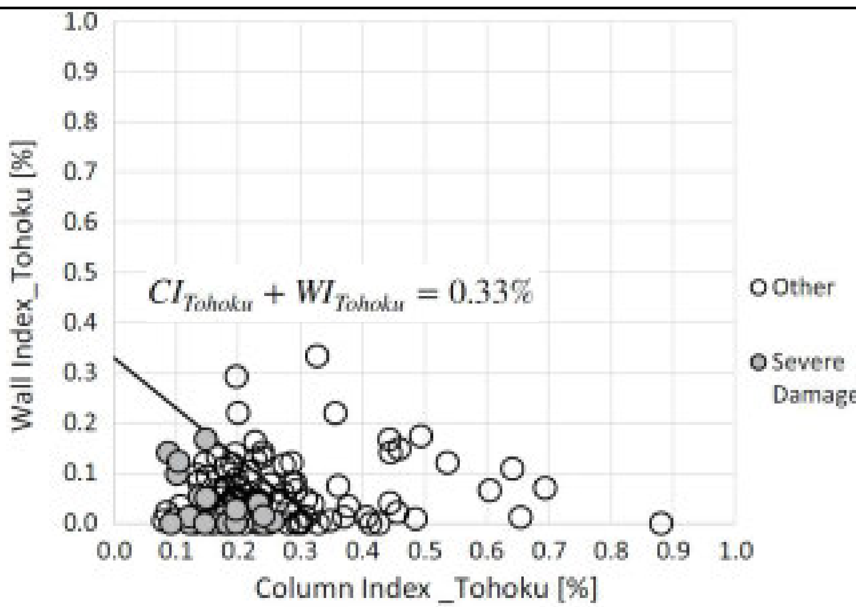
$$WI_{Shiga} = \frac{\Sigma A_{RC_w}}{\Sigma A_{floor}}$$



$$CI_{Shiga} = \frac{1}{2.75} \times \frac{\Sigma A_{RC_{col}}}{\Sigma A_{floor}}$$

a *a* *L*

$$WI_{Tohoku} = \left(\frac{\Sigma A_{Wall}}{\Sigma A_{floor}}\right)/5$$



$$CI_{Tohoku} = \left(\frac{\Sigma A_{RC_{col}}}{\Sigma A_{floor}}\right)/2$$

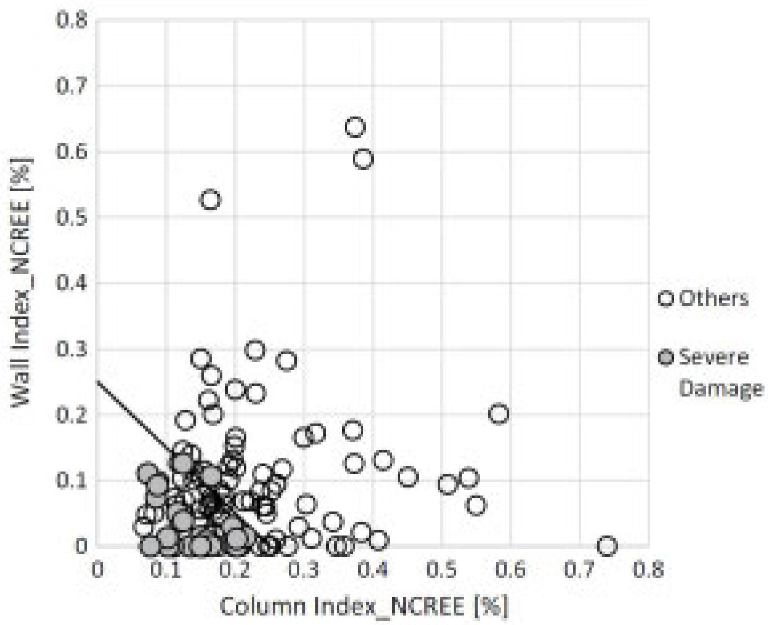
b 99 L

Seismic Capacity

$$\begin{cases} A_p = 100CFR_{eq} - (0.4+0.05N_f)/(1.62-0.24N_f) & \textit{if} \quad CFR_{eq} \geq (0.4-0.05N_f)\% \\ A_p = 0 & \textit{Otherwise} \end{cases}$$

$$CFR_{eq} = \frac{\sum A_c}{\sum A_f} + \frac{0.9 \times (2.63\sum A_{rcw4} + 1.50\sum A_{rcw3} + 0.50\sum A_{bw4} + 0.40\sum A_{bw3})}{\sum A_f}$$

$$WI_{NCREE} = \frac{1.0\sum A_{rcw4} + 0.57\sum A_{rcw3} + 0.19\sum A_{bw4} + 0.15\sum A_{bw3}}{\sum A_f}$$



$$CI_{NCREE} = \frac{0.42\sum A_c}{\sum A_f}$$

Boundary

Hassan's	Shah's view of Hassan's	Chiou's (NCREE)	Shiga's	Islam's (Tohoku)
$CI + WI = 0.25\%$	$\frac{1}{2}CI + WI = 0.2\%$	$CI_{NCREE} + WI_{NCREE} = 0.25\%$	$CI_{Shiga} + WI_{Shiga} = 0.3\%$	$CI_{Tohoku} + WI_{Tohoku} = 0.33\%$

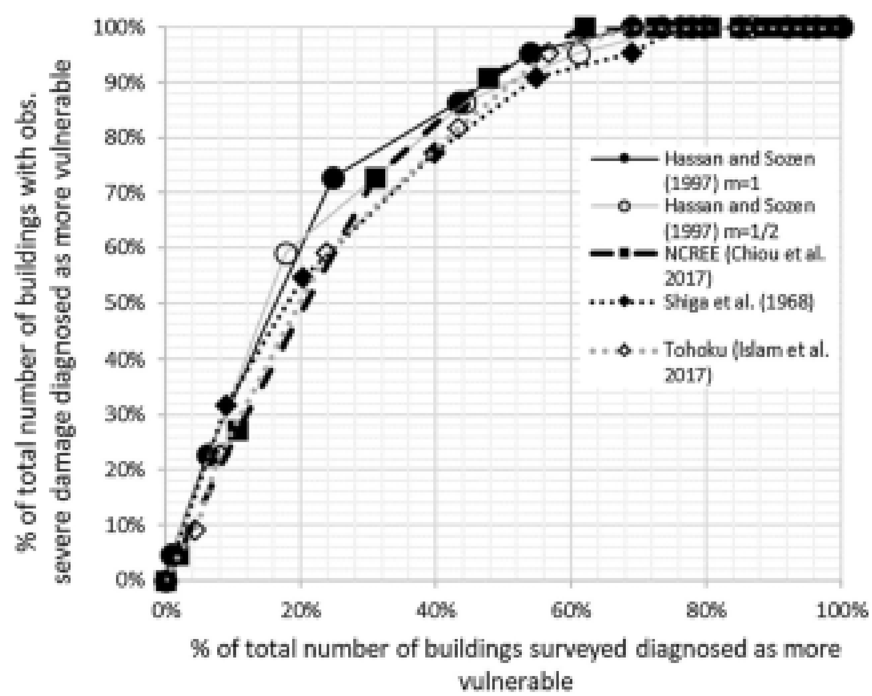
Column Area

Hassan's	Shah's view of Hassan's	Chiou's (NCREE)	Shiga's	Islam's (Tohoku)
$\frac{1}{2}\Sigma A_{RC_{Col}}/\Sigma A_{Floor}$	$\frac{1}{4}\Sigma A_{RC_{Col}}/\Sigma A_{Floor}$	$\frac{1}{2.4}\Sigma A_{RC_{Col}}/\Sigma A_{Floor}$	$\frac{1}{2.75}\Sigma A_{RC_{Col}}/\Sigma A_{Floor}$	$\frac{1}{2}\Sigma A_{RC_{Col}}/\Sigma A_{Floor}$

Wall Area

Hassan's	Shah's view of Hassan's	Chiou's (NCREE)	Shiga's	Islam's (Tohoku)
$\Sigma A_{RC_{W}}/\Sigma A_{Floor}$	$\Sigma A_{RC_{W}}/\Sigma A_{Floor}$	$0.57 \text{ to } 1 \times \Sigma A_{RC_{W}}/\Sigma A_{Floor}$	$\Sigma A_{RCw}/\Sigma A_{Floor}$	$\frac{1}{5}\Sigma A_{RCw}/\Sigma A_{Floor}$ *

*The method was not conceived for buildings with RC walls



Thank you for your time!

Questions?

SEISMIC ASSESSMENT AND RETROFIT OF SCHOOL BUILDINGS IN BRITISH COLUMBIA, CANADA

By Dr. C.E. Ventura, University of British Columbia

Abstract

In 2004, the Province of British Columbia, on the West Coast of Canada, announced a 10-15 year, $1.5 billion seismic retrofit program for the province's 750 at-risk public schools. The purpose of this earthquake preparedness initiative is to accelerate the upgrading of school public safety in the moderate and high seismicity regions of the province. Given the magnitude of the mitigation program, the province's Ministry of Education made a commitment to support the development of state-of-the-art performance-based seismic engineering technology for achieving optimum safety within a cost-effective mitigation framework, which could not be achieved based on current practice. This paper gives an overview of the formulation of performance-based structural assessment and retrofit design guidelines, which are being used by engineers to determine retrofit strategies for schools in British Columbia.

The three overall objectives of the guidelines are enhanced life safety, cost effective retrofits and user-friendly technical guidelines. The life safety philosophy of these guidelines is enhanced life safety through minimizing the probability of structural collapse by the use of rational performance-based methods of earthquake damage estimation. Cost-effective strategies are achieved by a combination of the development of rational minimum resistance requirements and the qualitative formulation of preferred retrofit methods. The development of these requirements is based on probabilistic nonlinear dynamic incremental analyses using ground motions specific to the three different sources of ground motions in the region: crustal, subcrustal and subduction sources. User-friendly technical guidelines have been developed and presented in the form of pre-determined minimum lateral resistance requirements and a simple-to-use web-based seismic performance calculator to enable an engineer to perform a seismic risk assessment or a retrofit design for any of the structural systems, typical of schools in the region. This tool, called "Seismic Analyzer" provides the engineer with immediate, user-friendly access to the large electronic database of analysis results. This format permits the practitioner to capitalize on the benefits of advanced performance-based engineering techniques without subjecting them to undertake sophisticated non-linear time history analyses.

The retrofit methodology begins by separating a school facility into a number of discreet "blocks" based on type of construction, vintage and layout. Blocks are then analyzed independently of one another and in many cases no all the blocks in a school facility need seismic upgrading. The methodology allows for an efficient upgrade of existing