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Recent Advances in Increasing the Resilience and Sustainability of the School Infrastructure

Performance Based Seismic Retrofit Guidelines for Schools in British Columbia, Canada

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Outline

a. History and development of the Guidelines

b. Policy and direction with School Districts

c. Key technical aspects, including use of the on-line ‘Analyzer’ tool

d. Representative school seismic upgrade projects

e. The path forward

Introduction

Performance Based Seismic Retrofit Guidelines (SRG) were developed to meet the following goals of the Ministry of Education (MEd)

- Implement seismic retrofits that achieve a life safety performance in a cost effective manner
- To adopt a common engineering approach to the seismic retrofit of school buildings

SRG organization chart, a unique collaboration

Ministry of Education
SRG project lead

EGBC & Advisory Committee
Project Manager

University of British Columbia Earthquake Engineering Research Facility	**Seismic Peer Review Committee** (SPRC)	**External Peer Review** (EPR)	**Technical Review Board** (TRB)
• World Class Research • Computer models • Testing • Analyzer • Write guidelines • UBC professors, researchers • BC structural engineers	• Appointed by EGBC Council • Review Guidelines • Feedback to UBC team • Some guideline writing • BC structural engineers	• Independent external review • International state of the art • US structural engineers	• Resource to practicing engineers regarding the application of SRG • Review of all design concepts to ensure consistency • BC structural engineers
RESEARCH & GUIDELINE DEVELOPMENT			IMPLEMENTATION

Guideline development

- Program started 2004
- Interim Guidelines, 1st Edition July 2005
- Interim Guidelines, 2nd Edition" Nov 2006
- "Seismic Retrofit Guidelines, 1st Edition" SRG1 Sept 2011
- "Seismic Retrofit Guidelines, 2nd Edition" SRG2 Nov 2013
- **"Seismic Retrofit Guidelines, 3rd Edition" SRG3** Sept 2016
- "Seismic Retrofit Guidelines, 4th Edition" SRG2020 completed, release pending

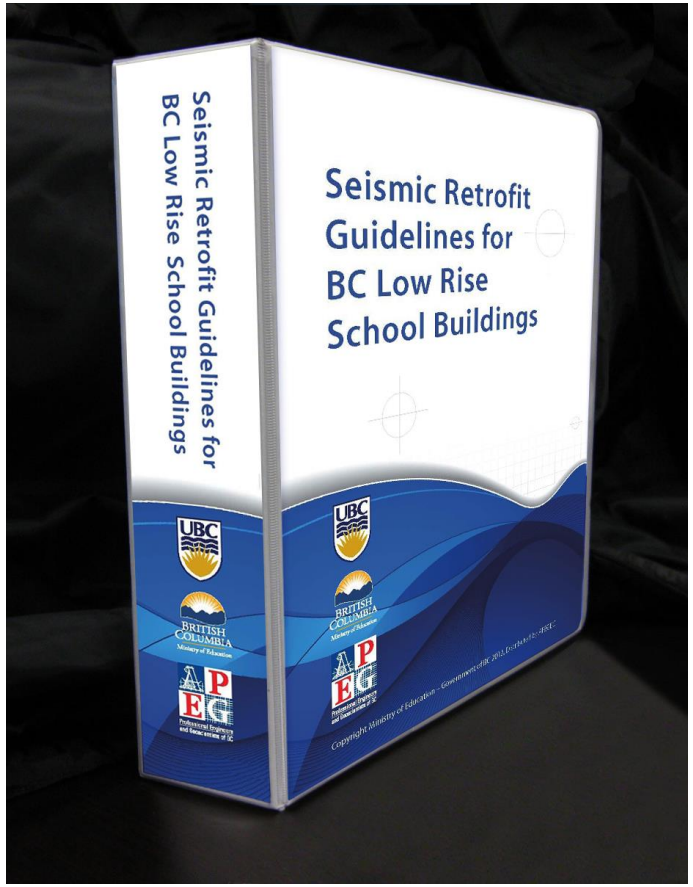
- Every release complete with training workshop for structural engineers, School District staff, key Ministry staff

- EGBC retains list of engineers, firms attending such sessions

- Directive that School Districts *must* follow these Guidelines, and *only* retain trained engineers/firms

Key deliverables

SRG manual



Vol.	Title
1	Overview
2	The Guidelines and Commentary
3	Seismic Performance Analyzer I User Guide
4	Prototype Description Reports
5	Technical Background
6	Experimental Test Results
7	Library of Retrofit Details
8	Example Retrofit Strategies
9	Site Specific Response Analysis (pending)
10	Post-Earthquake Evaluation Guidelines
11	Liquefaction Guidelines
12	Mid-rise Buildings (Analyzer II User Guide)

Key deliverables

On-line tool Analyzer

Key deliverables – Assessment of all schools in areas of moderate and high seismic hazard

- Completed early in the program
- For each individual ‘structural block’ or portion of a school facility
- Initial exemption for all buildings designed per NBCC 1990 or later
- Created list of all ‘blocks’ with risk rating of High, Medium, or Low

Key deliverables - Custom database developed

- All School Districts
- All schools
- Lists all ‘blocks’ by risk category
- All SPIRs
- Available to all SRG trained engineers, and MEd and District staff

District

39 - Vancouver

Risk Summary

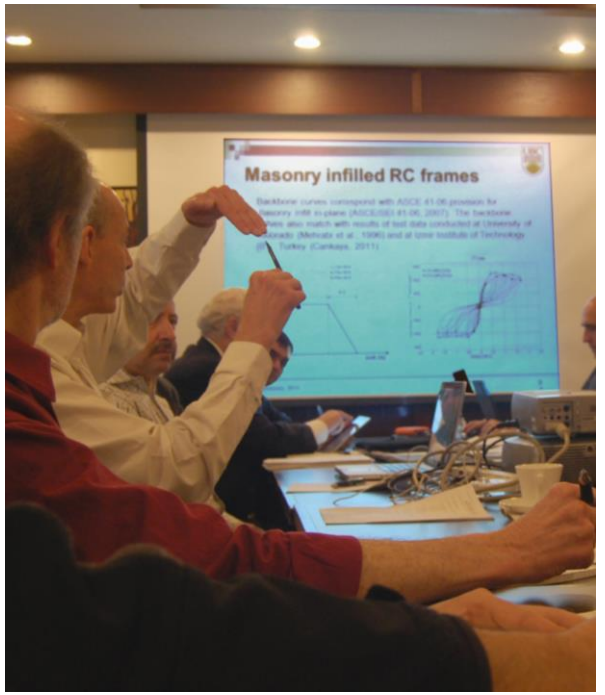
	H1	H2	H3	M	L	N/A
Facilities	51	3	17	15	3	20
Blocks	100	39	77	74	43	66

Facilities

Code	Name	Highest Risk Rating	Status	# of blocks	
3939067	Bayview Elementary School	H1	Structural Upgrade Required	3	Edit
3939130	Britannia Community Elementary	N/A	Complete	1	Edit
3939004	Britannia secondary school	H1	Mixed	4	Edit
3939088	Captain James Cook Elementary	N/A	Complete	5	Edit
3939094	Carnarvon Elementary School	H3	Structural Upgrade Required	3	Edit
3939137	Champlain Heights Annex	M	Non Structural Upgrade Required	2	Edit
3939128	Champlain Heights Elementary School	H3	Mixed	4	Edit

Key deliverables – Technical Review Board

- A mandatory review process that has proven to be very effective
- Has become very collaborative, regarding one trained structural engineer reviewing another's work
- Similarly, regarding one cost estimator reviewing another's work



Policy for School Districts to follow

Seismic Project Identification Report (SPIR)

- Standard template
- Standard published fees
- Structural engineer led
- Drawing review, site visits
- Assessment of risk
- If High risk, then prepare upgrade concept
- Stand alone seismic upgrade
- Includes A/M/E disciplines, cost consultant
- TRB review – structural, cost consultant

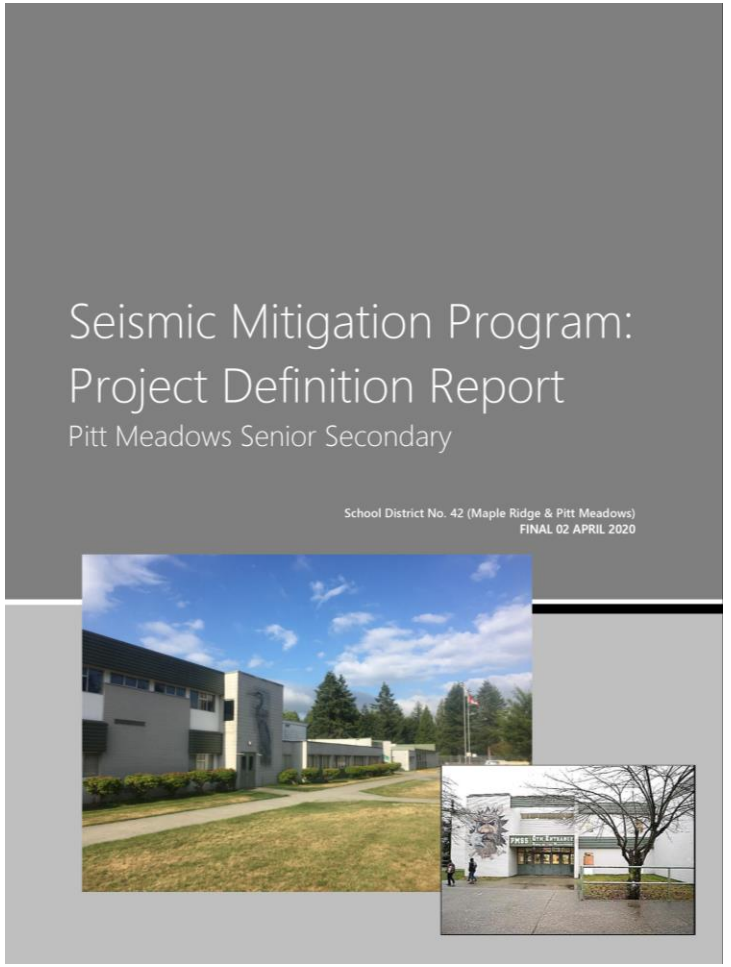
SPIR SUMMARY

No.	Technical Topic	Summary
1	School Name and School District	• •
2	Block No. / Name	• •
3	Floor Area	•
4	Year, Number of Storeys and Type of Construction	• • • • •
5	Soil Type	•
6	Liquefaction Potential	•
7	Risk (H1/H2/H3/M/L)	•
8	Life Safety Retrofit Features	• • • • •
9	Phased Retrofit Features	• • • • •
10	Enhanced Performance Retrofit Features	•
11	Schedule	•
12	Construction Risks	•
13	Cost Estimates	• •
14	PDR Requirements	•

Policy for School Districts to follow

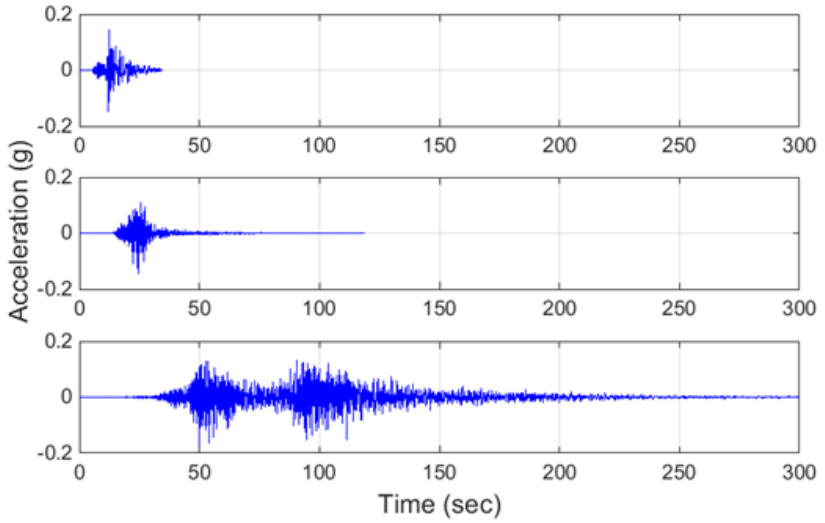
Project Definition Report (PDR)

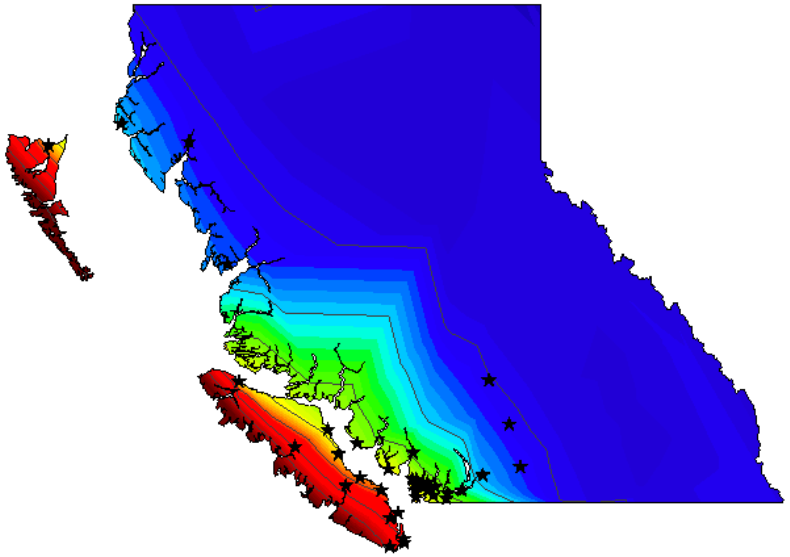
- Usually Architect led
- Assess options of
  - replacement with new school
  - seismic upgrade
  - combination of new and upgrade
- Cost estimates to now include all indirect costs:
  - phasing
  - temporary accommodation
  - moving costs
  - *possibly* AHJ requested added scope such as sprinklers, universal accessibility, minor other safety related items
  - all design and permit fees

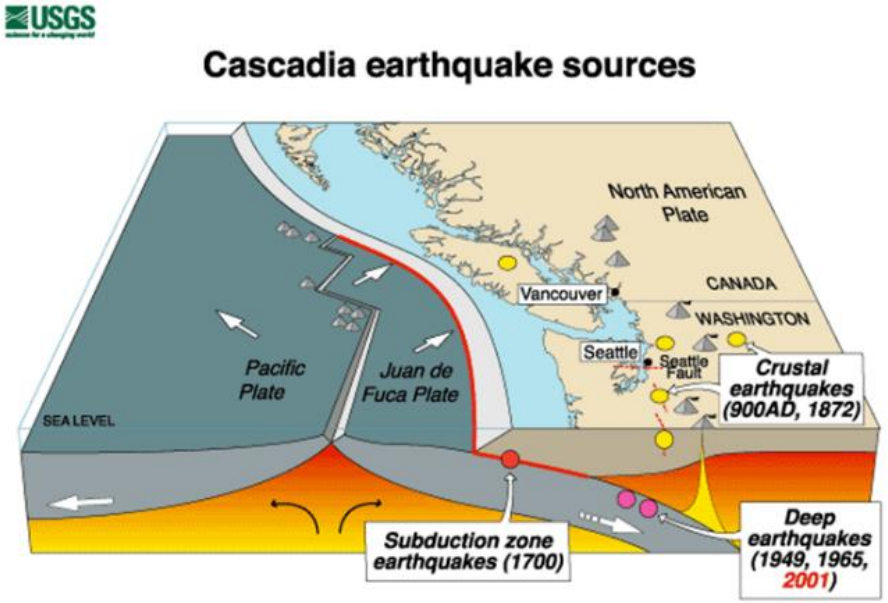


Seismic hazard and records

- Consistent with National Building Code of Canada UHRS, AEP 1/2475
- 3 Sources of earthquakes:
  - Crustal sources M 7+
  - Subcrustal (intraslab) sources M 7+
  - Subduction (interface) Cascadia M 9

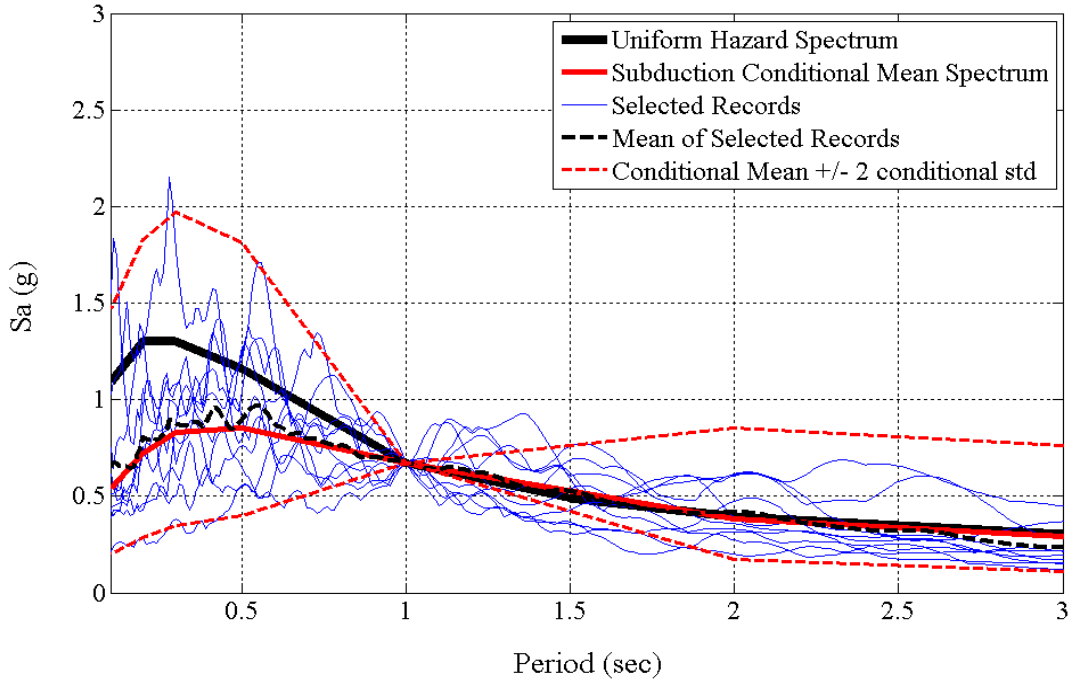






Seismic records for analyses for Analyzer I

- 20 records for each earthquake source
- 2 seismicity levels, High and Moderate
- Conditional Spectra used in SRG3
  - Both mean and variance are matched
  - 2 conditioning periods 0.5 and 1 sec used in CS (1 sec shown in figure)
- 240 records analyzed for each prototype



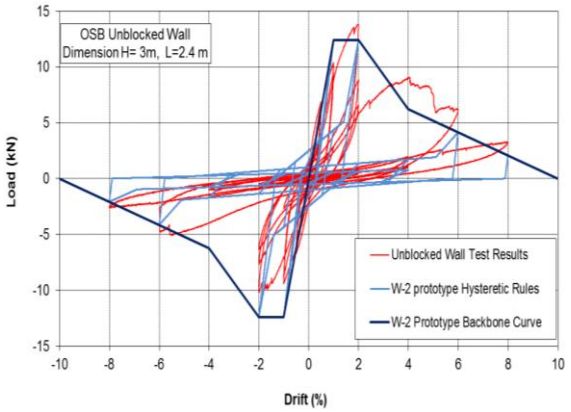
Building elements

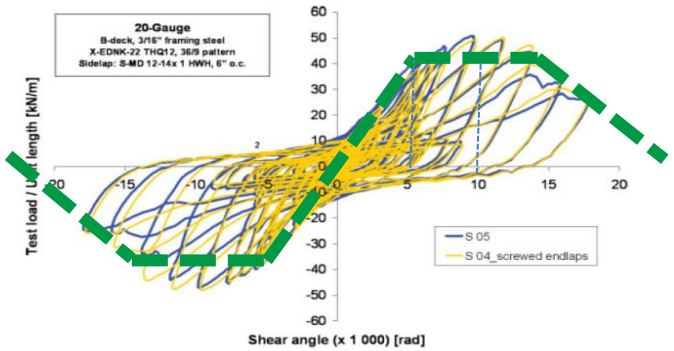
- 3 types of building elements considered in the analysis:
  - Lateral Deformation Resistance Systems, LDRS — 33 prototypes
  - Unreinforced masonry walls (URM), out-of-plane loading — 4 prototypes
  - Flexible diaphragms (wood and steel deck diaphragms) — 6 prototypes

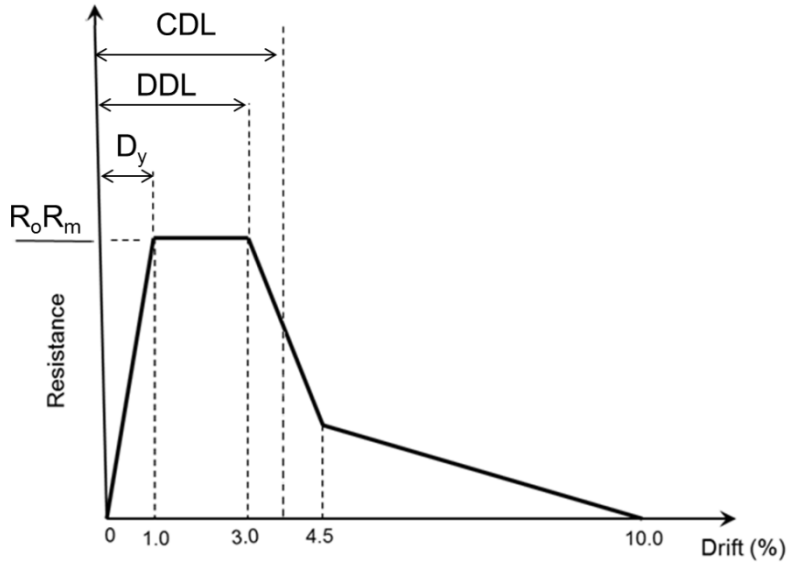
- Wide range of
  - LDRS heights and resistances
  - URM thicknesses and height
  - Diaphragm span lengths

Building elements behavior

- The cyclic force-deformation of prototypes are based on experimental results and literature







- DDL : Design Drift Limit
- CDL : Conditional Drift Limit
- R_m : Minimum Factored Resistance (%W)
- R_o : Over-strength related modification factor

33 Lateral Deformation Resistance Systems LDRS

Material	No.	Prototype Description	Max CDL (1)	R_o	Yield Drift
Wood	W-1	Blocked OSB / plywood shearwall	4.00%	1.7	1.0%
	W-2	Unblocked OSB / plywood shearwall	4.00%	1.7	1.0%
	W-3	Gypsum wallboard	4.00%	1.7	0.5%
	W-4	Horizontal boards	4.00%	1.7	1.0%
Steel	S-1	Concentric braced frame (tension only – moderately ductile)	3.50%	1.3	0.3%
	S-2	Concentric braced frame (tension only – limited ductility)	2.00%	1.3	0.3%
	S-3	Concentric braced frame (tension only – conventional construction)	1.50%	1.3	0.3%
	S-4	Concentric braced frame (tension compression – moderately ductile)	3.50%	1.3	0.3%
	S-5	Concentric braced frame (tension / compression – limited ductility)	2.00%	1.3	0.3%
	S-6	Concentric braced frame (tension / compression – conventional construction)	1.50%	1.3	0.3%
	S-7	Eccentric braced frame	3.50%	1.5	0.5%
	S-8	Moment frame (moderately ductile)	4.00%	1.5	1.0%
	S-9	Moment frame (ductile)	6.00%	1.5	1.0%
	S-10	Buckling-restrained braced frame (ductile)	4.50%	1.2	0.3%

Material	No.	Prototype Description	Max CDL (1)	R_o	Yield Drift
Concrete	C-1	Ductile Moment Frame	4.00%	1.7	1.0%
	C-2	Partially Ductile Moment Frame	3.00%	1.4	1.0%
	C-3	Non-ductile Moment Frame	0.50%	1.3	0.50%
	C-4	Squat shearwall (shear)	2.00%	1.3	0.1%
	C-5	Shearwall (shear)	2.00%	1.3	0.25%
	C-6	Moderately ductile shearwall (flexure)	1.50%	1.4	0.35%
	C-7	Non-ductile shearwall (flexure)	1.00%	1.3	0.35%
	C-8	Ductile shearwall (flexure)	2.00%	1.5	0.35%
Concrete Masonry	M-1	Wall sliding at base	2.00%	1.5	0.1%
	M-2	Unreinforced wall	1.50%	1.5	0.1%
	M-3	Reinforced wall	2.00%	1.5	0.25%
	M-4	Infill wall (Block crushing)	1.50%	1.5	0.1%
	M-5	Infill wall (Combined failure)	1.00%	1.5	0.1%
	M-6	Infill wall (Column shear)	0.50%	1.5	0.1%
Clay Brick	B-1	Brick wall	1.25%	1.5	0.1%
Rocking	R-1	Low aspect ratio (3)	5.0%	1.0	0.1%
	R-2	Medium aspect ratio (4)	5.0%	1.0	0.3%
	R-3	High aspect ratio (5)	5.0%	1.0	0.8%
Foundation	F-1	Sliding foundation	5.0%	1.0	0.25%

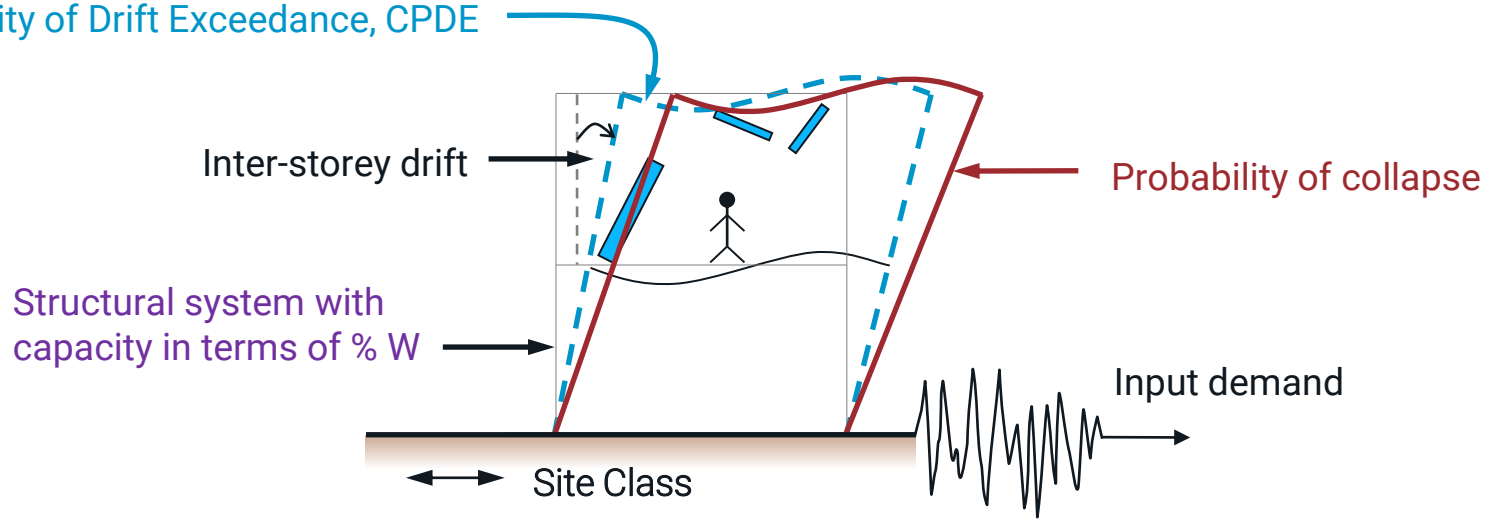
Vertical Non-LDRS Load Bearing Supports (VLS)

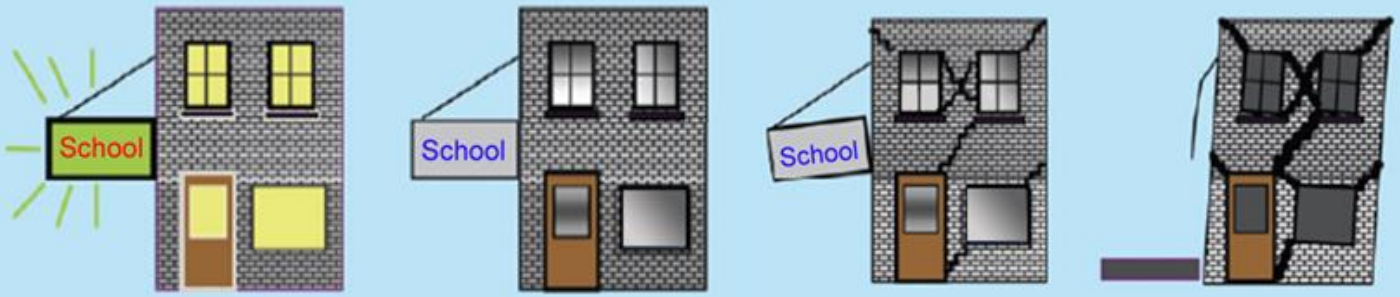
- Total Drift of the block shall conform to the Design Drift Limits (DDLs) for vertical non-LDRS load-bearing supports

Material	Type of Building Component	Design Drift Limit
Wood	Platform construction	6.0%
	Balloon construction	4.0%
	Post and beam without post / beam mechanical connections	3.0%
	Post and beam with post / beam mechanical connections	6.0%
Steel	All vertical elements	4.0%
Reinforced Concrete	Ductile Columns	3.0%
	Partially Ductile Columns	2.0%
	Non-ductile Columns	1.25%
Masonry	Reinforced walls rocking in-plane	4.0%
	Unreinforced walls rocking in-plane	3.0%
	Reinforced walls rocking out-of-plane	Wall Thickness
	Unreinforced walls rocking out-of-plane	Half Wall Thickness

Key technical aspects

Seismic risk to damage: Probability of Drift Exceedance, PDE
Conditional probability of Drift Exceedance, CPDE





Risk assessment – Risk rating

- Probability of DDL exceedance in 50 years PDE
  - Less than 2% — Low Risk
  - 2% - 5% — Medium Risk
  - 5 – 7% — High Risk H1
  - 7 – 10% — High Risk H2
  - More than 10% — High Risk H3

Diaphragms

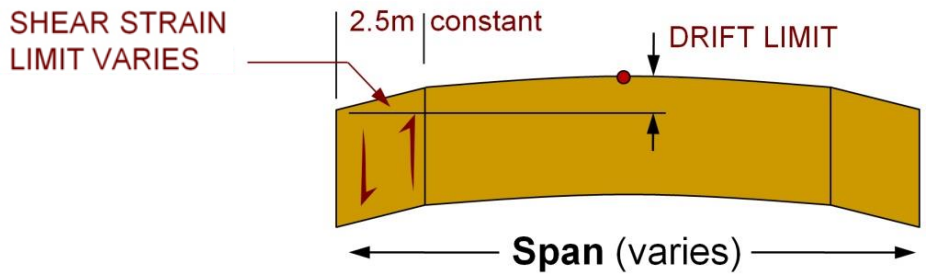
- Utilizing inelastic behaviour in the diaphragms
- Life Safety objectives
  - Probability of Design Shear Strain Exceedance (PSE) ≤ 2% in a period of 50 years.
  - Probability of Lateral Displacement Exceedance (PLDE) ≤ 2% in a period of 50 years.
  - Conditional Probability of Strain Exceedance (CPSE) ≤ 25%.

Prototype No.	Prototype Description	Maximum Shear Strain Limit	Differential Shear Strain Limit	R_o
D-1	Diaphragm – blocked OSB / plywood	3.0%	1.0%	1.7
D-2	Diaphragm – unblocked OSB / plywood	2.75%	0.9%	1.7
D-3	Diaphragm – horizontal boards	3.5%	1.15%	1.7
D-4	Diaphragm – steel deck (ductile)	1.5%	0.5%	1.67
D-5	Diaphragm – steel deck (moderately ductile)	1.0%	0.3%	1.67
D-6	Diaphragm – steel deck (low ductility)	0.5%	0.15%	1.67

Note:
(1) Maximum Shear Strain Limits are for Vancouver, Site Class C, 20 m span length, 3 m storey height.
(2) See 16.2(3) for other types of construction that qualify as Prototype D-2.

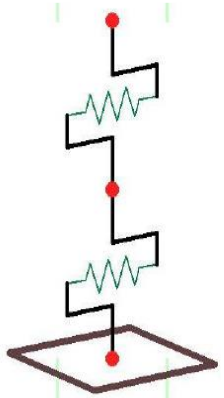
Steel deck diaphragm

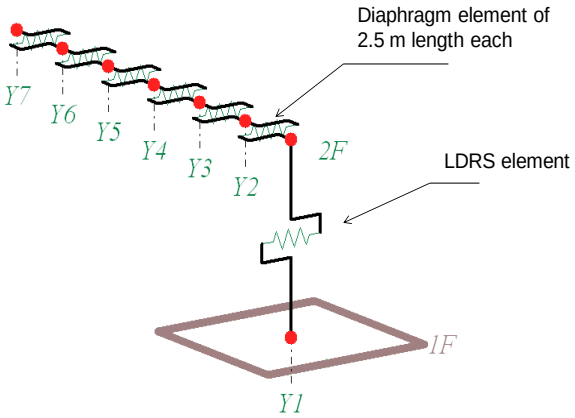
Wood diaphragm

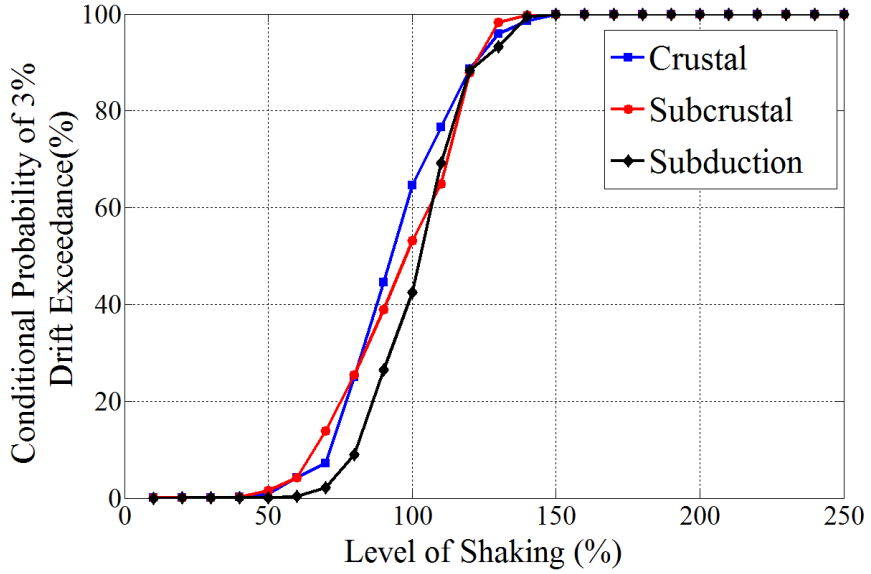


Structural analysis for every prototype

- Models developed based on the cyclic force-deformation obtained from experimental and literature results



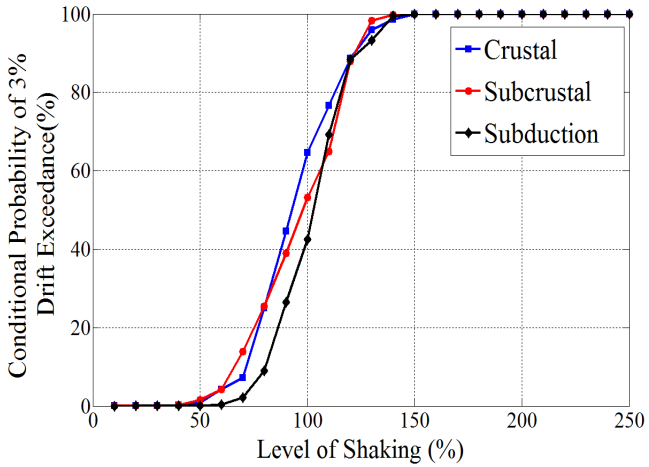


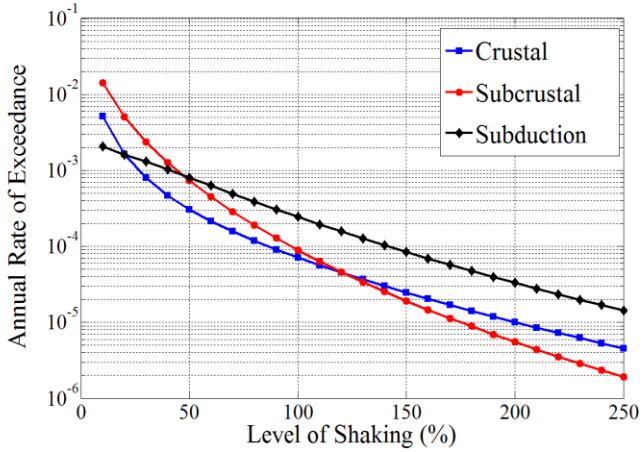


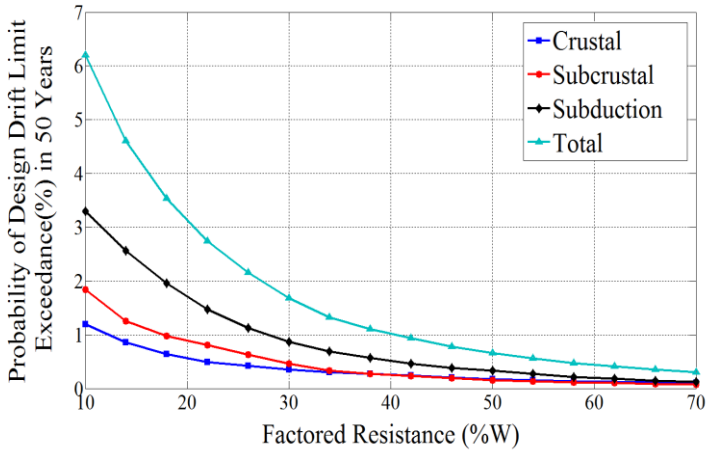
- Incremental non-linear dynamic analysis is performed for all ground motions and intensities, from 10% to 250% of code level

Probabilistic analysis

- Risk is obtained by summing the contributions from all levels of shaking and each hazard type



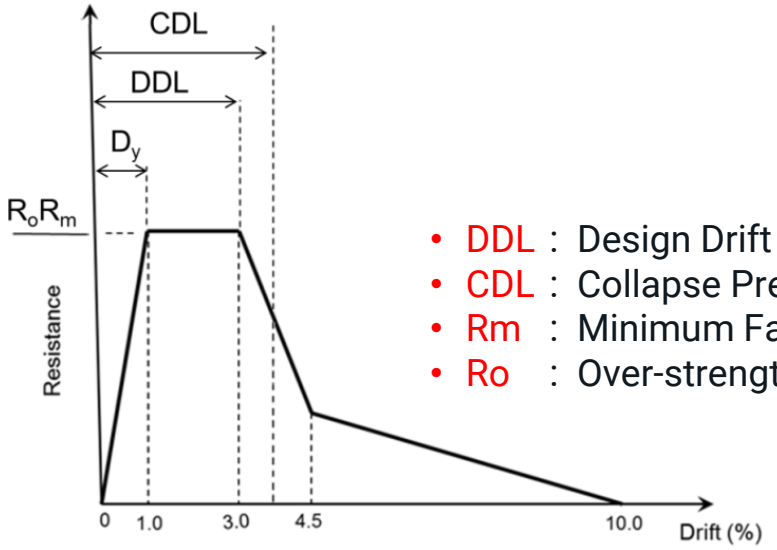




Life Safety performance objective

Life Safety performance objective for LDRS:

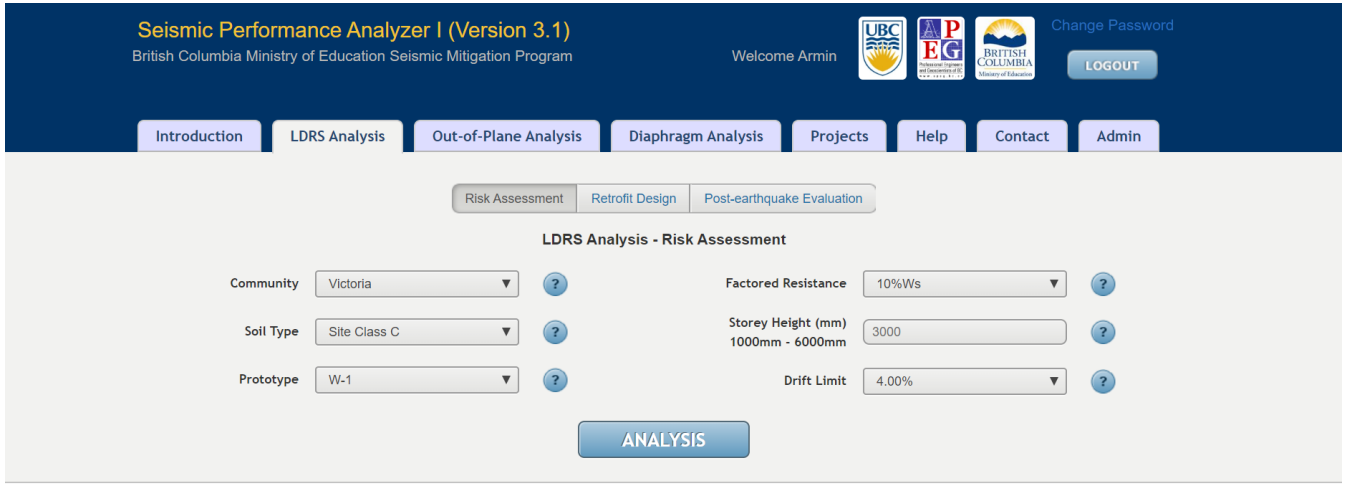
- Probability of DDL exceedance in 50 years; PDE < 2% based on incremental dynamic analysis
- Conditional probability of near failure drift (CDL) exceedance; CPDE ≤ 25%; for code level earthquake
- Enhanced performance: reduced drift limit approx. half way between Dy and DDL

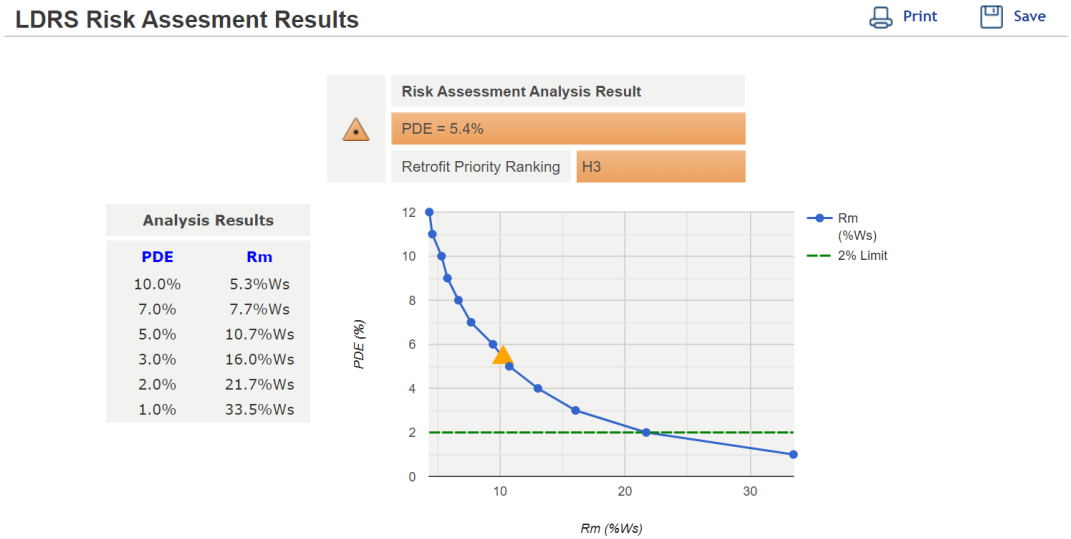


- DDL : Design Drift Limit
- CDL : Collapse Prevention Drift Limit
- Rm : Minimum Factored Resistance (%W)
- Ro : Over-strength related modification factor

Seismic Analyzer I

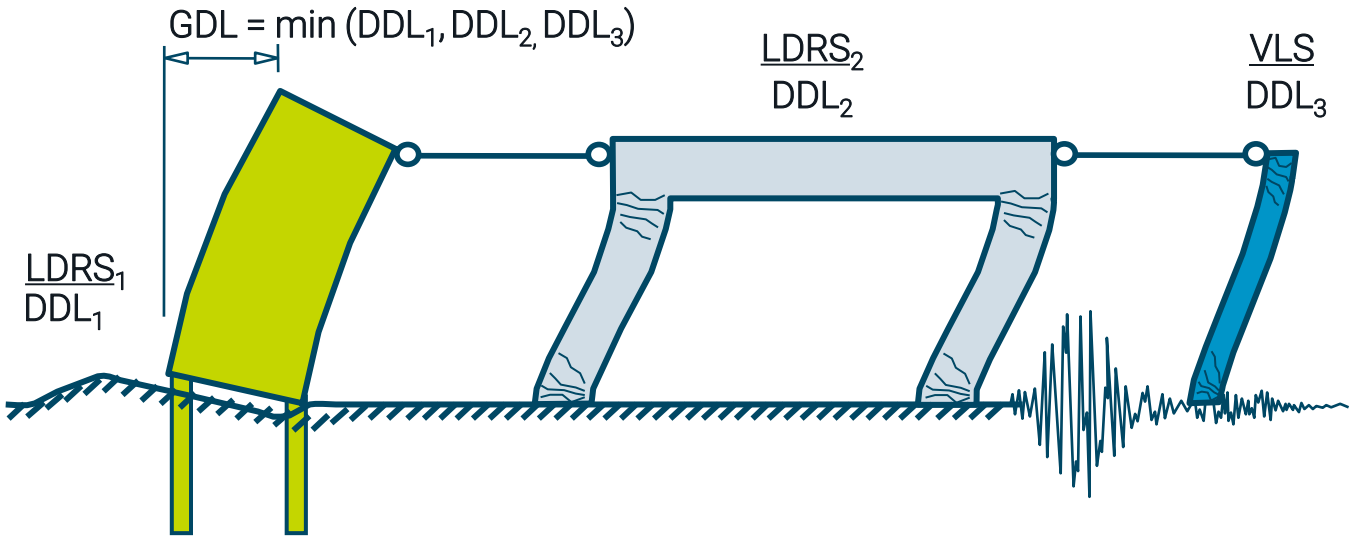
- User friendly access to over **45 million** pre-analyzed non-linear dynamic analysis results
- Used to perform **risk assessment**
- Obtain **retrofit resistance** for different design drifts
- Assist in post-earthquake evaluation





“Toolbox” approach

- Ability and recommendation to combine the contributions from different structural systems and components; new *and* existing
- All structural systems and components to generate their lateral resistance in a drift-compatible manner.
- Governing Deformation Limit (GDL) is the lowest deformation limit among all participating structural systems and components.



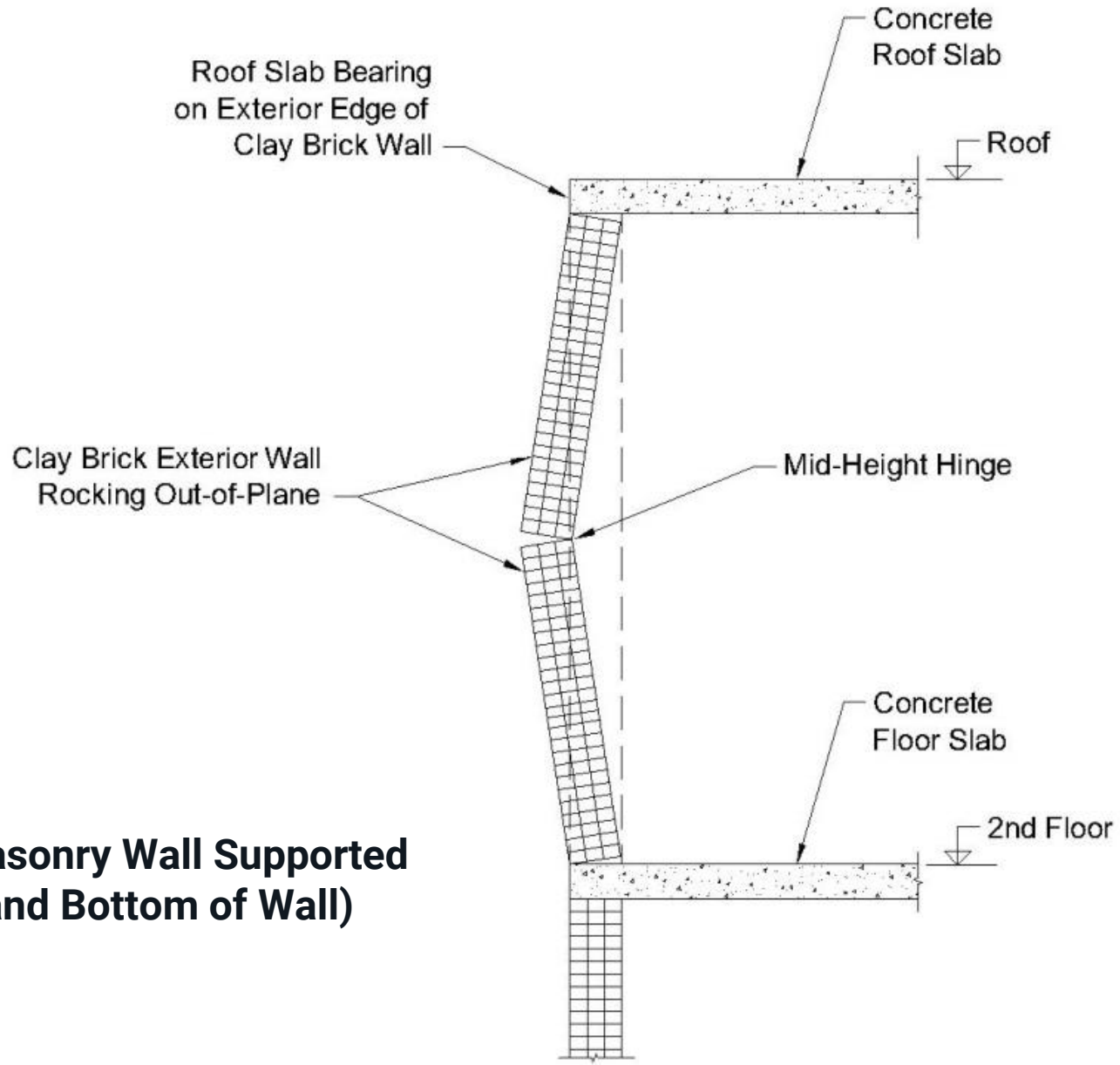
Out-of-Plane heavy partition walls

Prototypes for masonry walls rocking out of plane

Prototype No.	Prototype Description
OP-1	Cantilever unreinforced masonry wall
OP-2	Unreinforced masonry wall with inadequate connection at the top of the wall
OP-3	Unreinforced masonry wall supported laterally at top and bottom of wall
OP-4	Cantilever masonry wall with vertical reinforcement and footing

Out-of-Plane heavy partition walls

Prototype OP-3 shown



(Unreinforced Masonry Wall Supported Laterally at Top and Bottom of Wall)

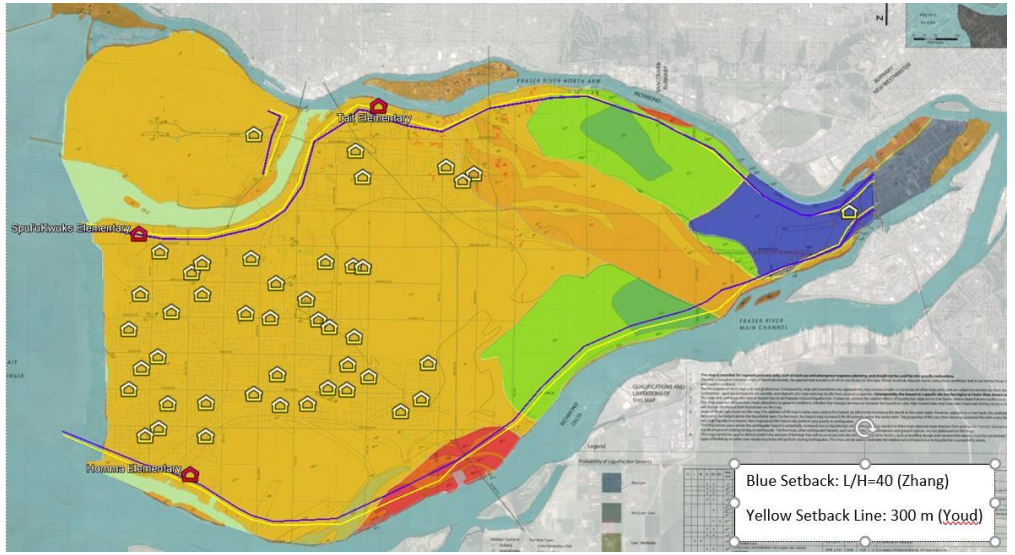
SRG3 laboratory testing of an OP-3 wall

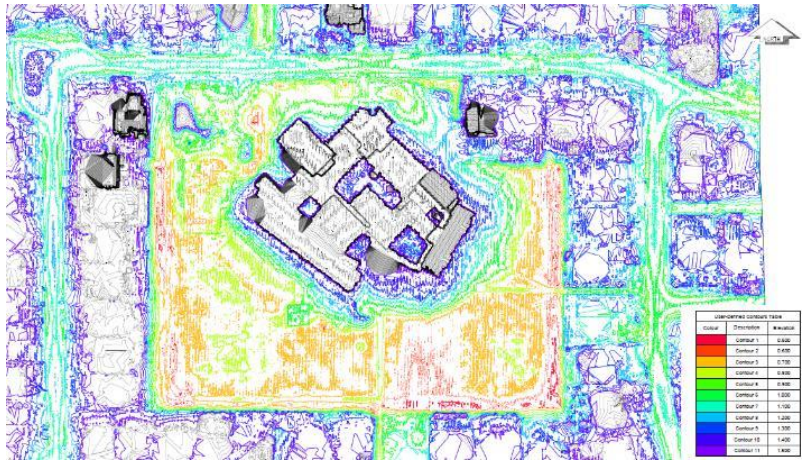
SRG3 laboratory testing of a unique retrofit of an OP-3 wall

Special study on liquefaction

- New predictions of lateral and vertical deformations for “Inland schools” versus “Near-shore schools”
- Inland: sites > 300 m from river or ocean and non liquefiable crust > 3 m
- Use of LiDAR to determine local site terrain: important for lateral spreading effects

- Resulted in *very significant savings* on mitigation for liquefaction effects





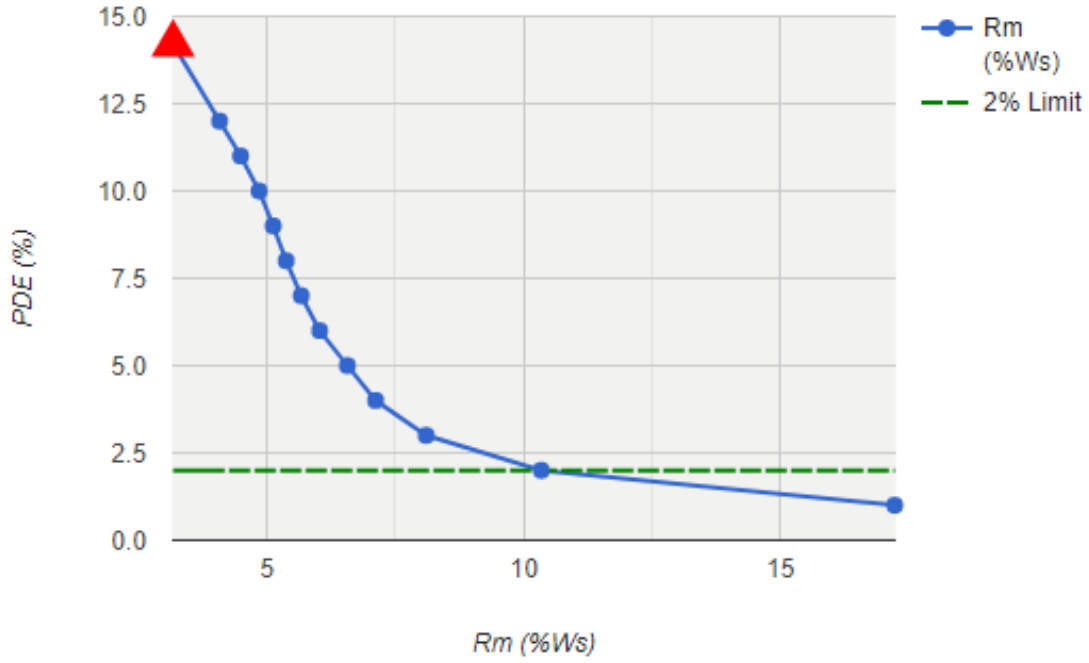

Seismic Performance Analyzer I (Version 3.1)
British Columbia Ministry of Education Seismic Mitigation Program
Welcome 149656
Change Password
LOGOUT
Introduction
LDRS Analysis
Out-of-Plane Analysis
Diaphragm Analysis
Projects
Help
Contact
Risk Assessment
Retrofit Design
Post-earthquake Evaluation
LDRS Analysis - Risk Assessment
Community
Coquitlam
Soil Type
Site Class C
Prototype
W-4
Factored Resistance
4%Ws
Storey Height (mm)
1000mm - 6000mm
3660
Drift Limit
4.25%
ANALYSIS

LDRS Risk Assessment Results

LDRS Risk Assessment Result	
PDE = 14.2%	
Retrofit Priority Ranking	H1

Analysis Results

PDE	Rm
10.0%	4.9%Ws
7.0%	5.7%Ws
5.0%	6.6%Ws
3.0%	8.1%Ws
2.0%	10.3%Ws
1.0%	17.2%Ws



Risk Assessment | Retrofit Design | Post-earthquake Evaluation

LDRS Analysis - Retrofit Design

Community	Coquitlam	Storey Height (mm) 1000mm - 6000mm	3660
Soil Type	Site Class C	Drift Limit	3.50%
Prototype	W-4		

ANALYSIS

LDRS Retrofit Design Results

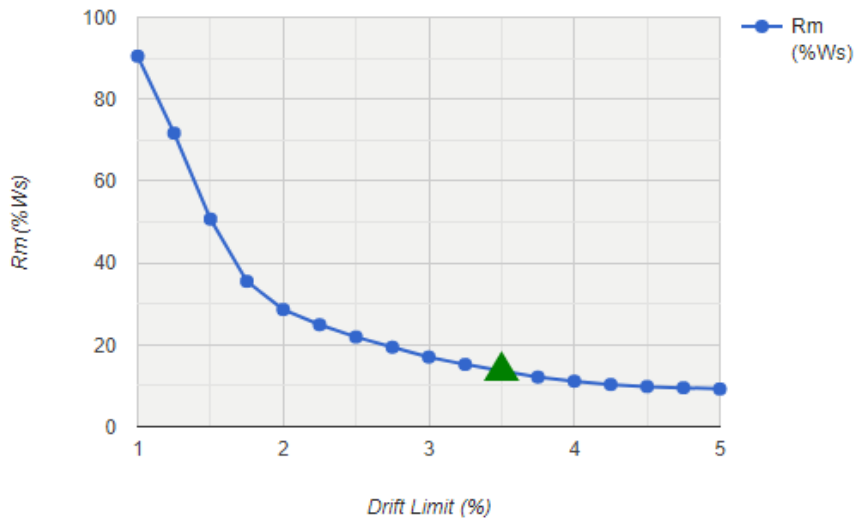
Print Save

Analysis Result for PDE=2%

Rm(%Ws) = 13.6%

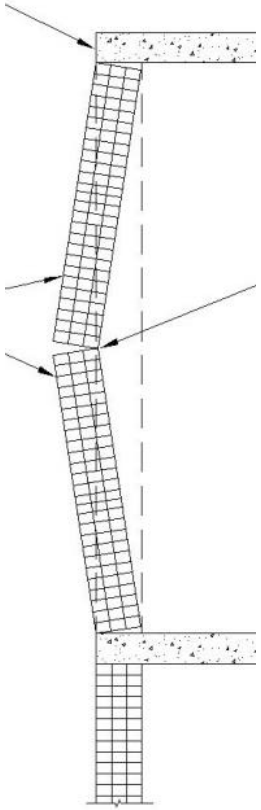
Analysis Results for PDE=2%

Drift Limit	Rm
2.00%	28.6%Ws
2.25%	24.9%Ws
2.50%	21.9%Ws
2.75%	19.4%Ws
3.00%	17.0%Ws
3.25%	15.2%Ws
3.50%	13.6%Ws



Existing High risk building with prototype C-3

Rapid assessment of retrofit options, prototype options, foundation requirements



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Risk Assessment | Retrofit Design

Out of Plane Analysis - Retrofit Design

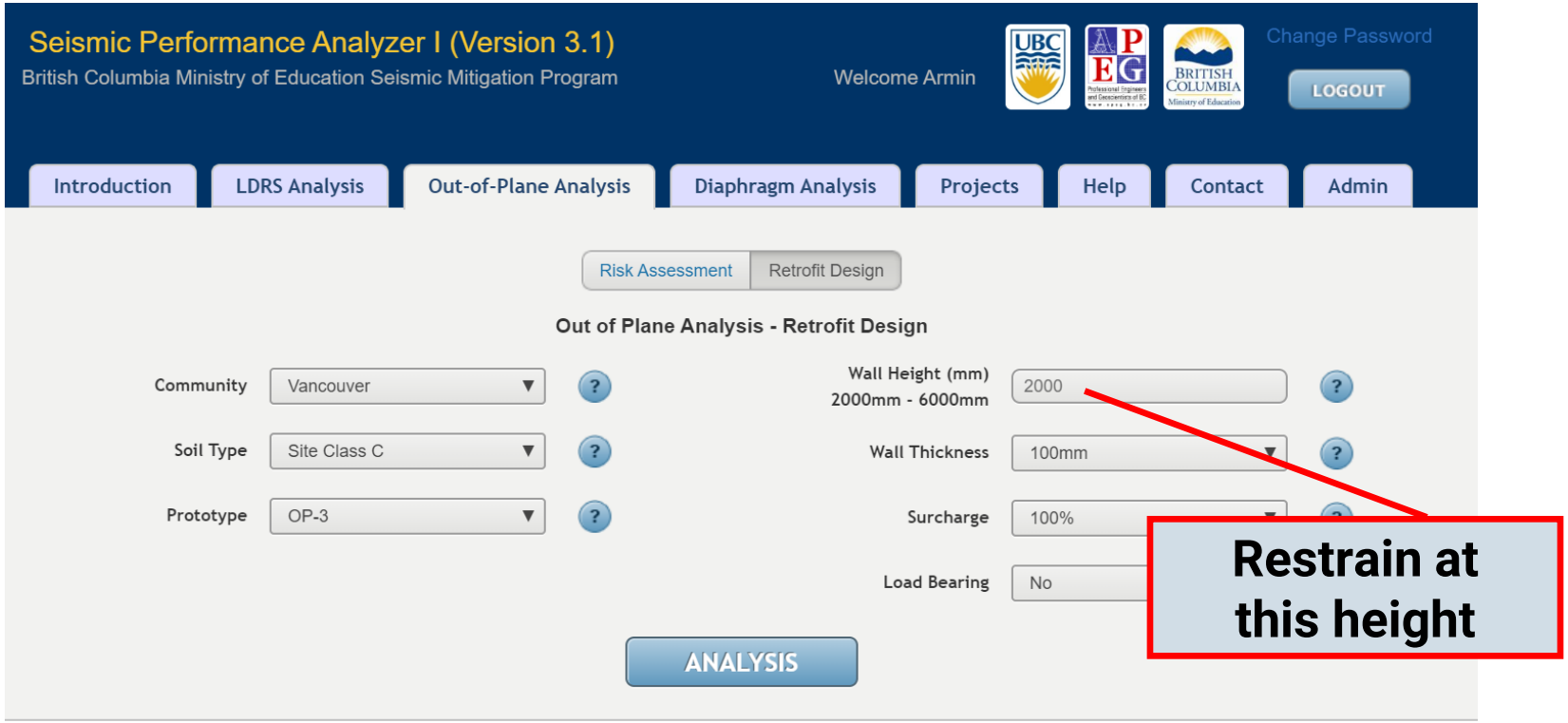
Community	Vancouver	Wall Height (mm) 2000mm - 6000mm	3000
Soil Type	Site Class C	Wall Thickness	100mm
Prototype	OP-3	Surcharge	100%
		Load Bearing	No

ANALYSIS

Out of Plane Retrofit Design Results

Print Save

Out of Plane Retrofit Design Result
PDE = 4.1%
CPDE = 74.1%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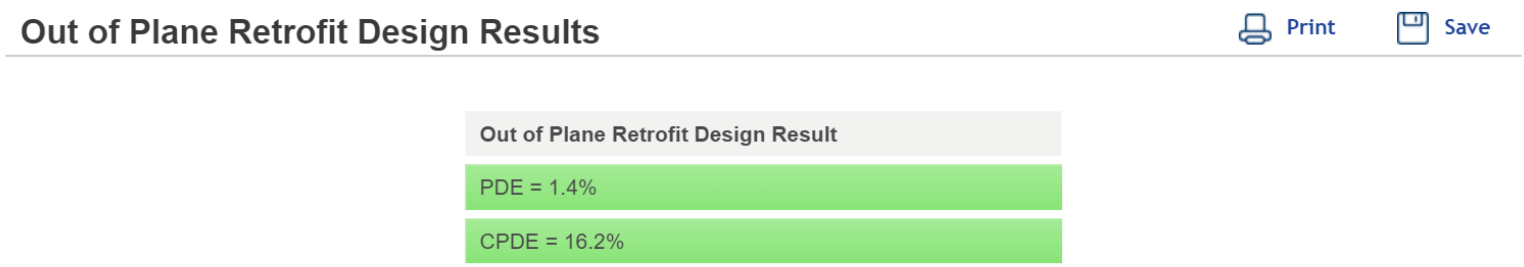
Out of Plane Analysis - Retrofit Design
Community
Vancouver
Soil Type
Site Class C
Prototype
OP-3
Wall Height (mm)
2000mm - 6000mm
2000
Wall Thickness
100mm
Surcharge
100%
Load Bearing
No
ANALYSIS
Restrain at this height


Out of Plane Retrofit Design Results
Print
Save
Out of Plane Retrofit Design Result
PDE = 1.4%
CPDE = 16.2%

Various upgrade schemes : interior and exterior concrete walls & piers

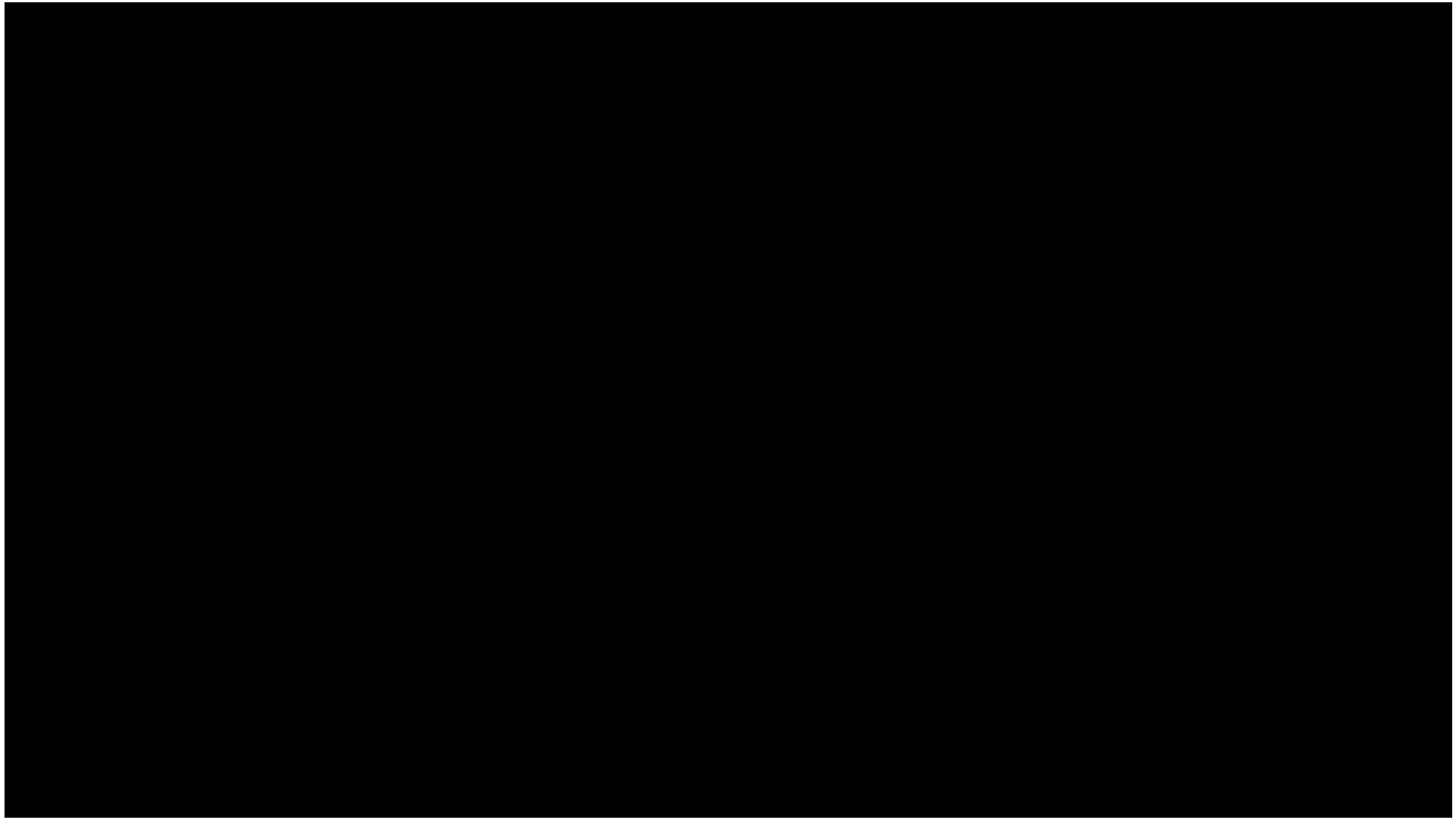
Heritage buildings with conventional and base isolation upgrades

Extensive use of FRP

Base Isolation upgrade of 120 year old school building; plane shown by dashed line

Liquefaction mitigation using “ring beam” concept to deal with lateral spread; structural beam becomes a sidewalk

Full scale test for verification of retrofit capacity and also post earthquake inspection training



Current status of MEd's Seismic Mitigation Program, Feb 2021

- 186 schools completed
- 29 under construction
- 13 proceeding to construction (in design)
- 19 in business case development
- 244 remaining to be addressed

- $ 1.8 billion dollars spent on program to date

  seismic upgrades and total replacement

- EGBC has endorsed the use of SRG for *all* buildings in BC, up to four storeys

Current status & future state of SMP

- Work on next edition of SRG is in progress
- Due Sept 2023
- Will consider
  - different earthquake intensities
  - ‘higher’ performance levels
  - resilience

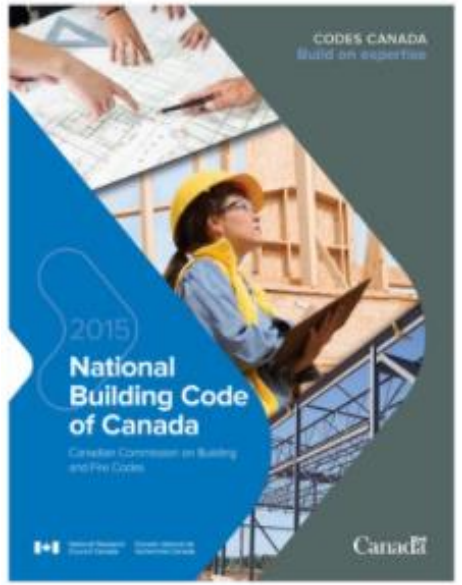
- Funding for continuation of seismic retrofits of schools continues

“What is coming?

- BC: “… Building and Safety Standards Branch has a mandate to adopt requirements for existing buildings by 2024. New requirements for existing buildings are expected to address energy efficiency, climate, and disaster resilience.

  Seismic resilience is also a focus of this work.”

- Canada: Joint Task Group is in place to assess options regarding a national code for Existing Buildings; perhaps for implementation as early as 2025. Seismic performance requirements intended to be included.



Thank you