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Catastrophic Earthquake Risk Mitigation: Risk Perception & Decision-Making

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2011 Great East Japan Earthquake

- Many surprises and lessons to learn: unimaginable scenarios , hard and soft protection, multi hazards, robustness and resilience, etc.
- Cooperation among victims, non-victims, Self-Defence Force, NGOs/NPOs

Many Improvements To Be Made

- Many critical issues at present …

Scientific community
- Natural sciences
- Social sciences
- Engineering

Immediate issues
- Politics
- Economy

Long-term issues
- Energy policy
- Health
- Security

Decision making

Uncertainty

Resilient & sustainable society

Lack of vision
Lack of leadership

DPRI & Cabot

Decision Making Under Uncertainty

- **Earthquake risk**: unpredictable, catastrophic, complex, societal risk, concentration in space/time, global issue
- Innovation in planning/design/construction/operation
- **Optimal and preferred seismic design levels**

  Cost-benefit analysis, life-cycle costing, bounded rationality, evaluation of risk mitigation measures
- **Portfolio approach for earthquake risk management**

  Modelling physical features of ground shaking, earthquake risk assessment for a portfolio of buildings, application to insurance

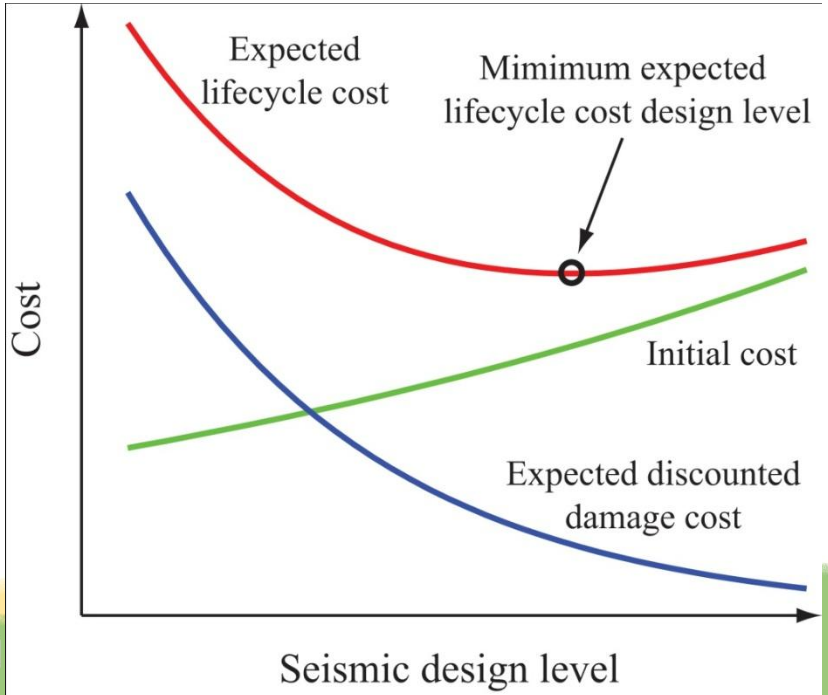
Optimal Seismic Design

- **Optimal seismic design**: minimum expected lifecycle cost of a building

$$LC(C_s,t) = C_0(C_s) + \sum_{j=1}^{n_s} \sum_{i=1}^{N_j(t)} \left(C_D(C_s|\delta_{ij}) + C_R(C_s|\delta_{ij}) \right) e^{-\gamma \tau_{ij}}$$

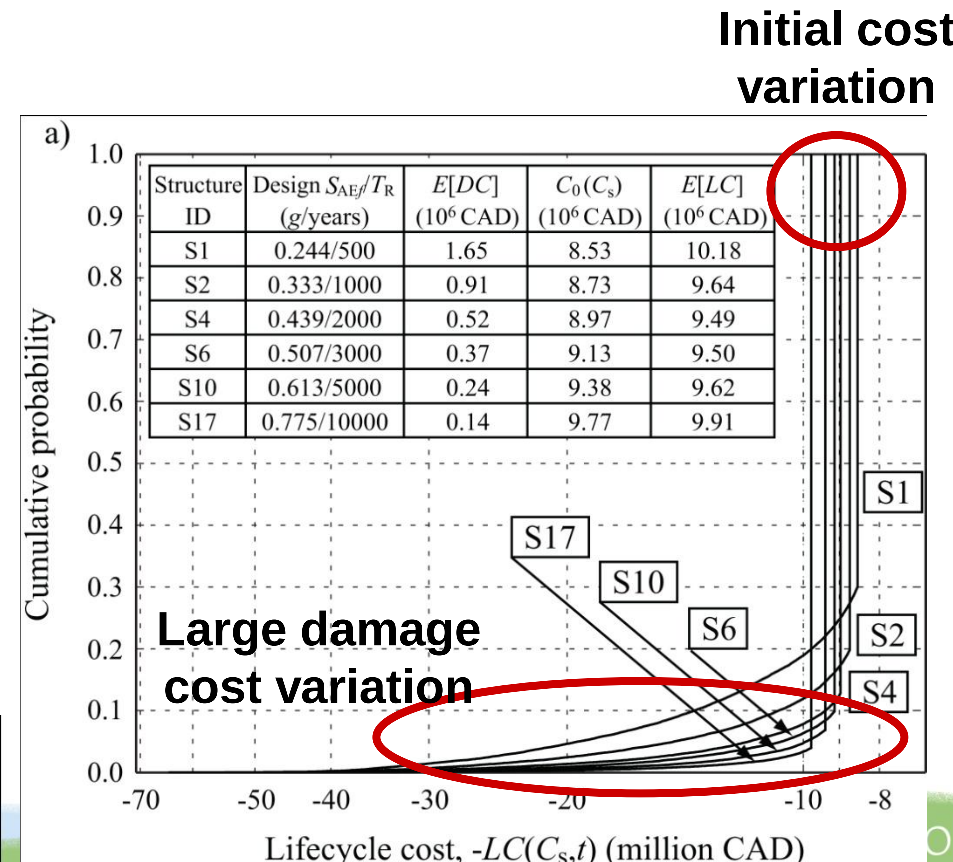
Initial cost — **Net present value of damage costs**

- Cost-benefit, lifecycle costing paradigm
- Risk-neutral approach
- May not be suitable for earthquake risk management

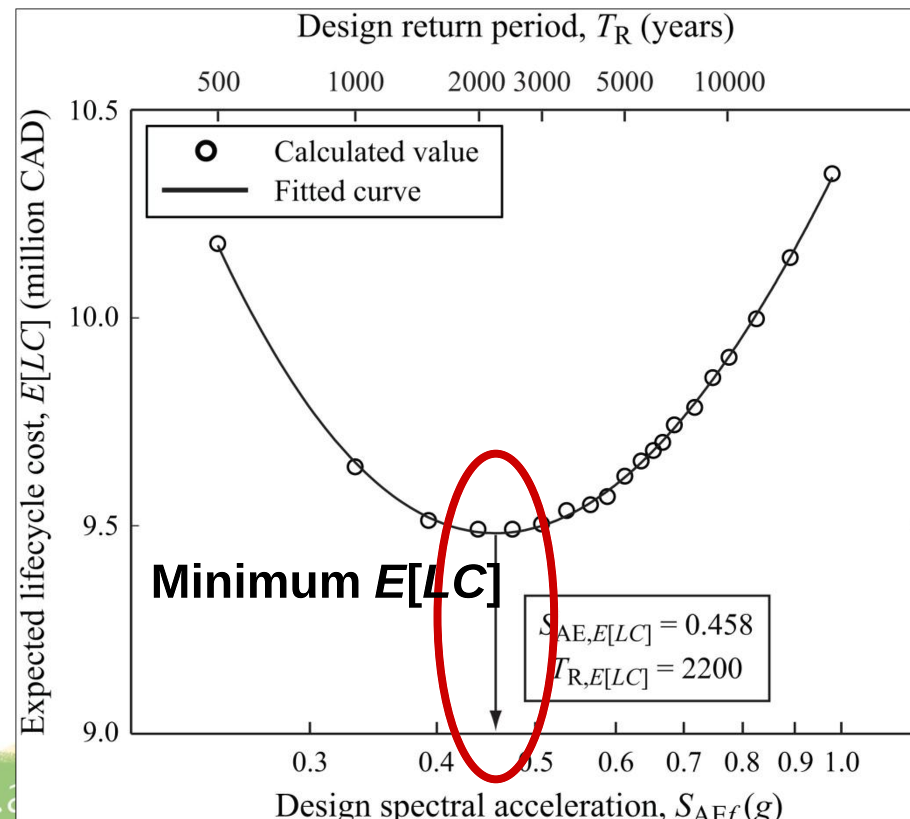


Example: Steel Building in Vancouver

- One "can" obtain a single seismic design level that minimises the expected lifecycle cost over an entire service period by considering all possible seismic events.



Structure ID	Design S_{AEf}/T_R (g/years)	$E[DC]$ (10^6 CAD)	$C_0(C_s)$ (10^6 CAD)	$E[LC]$ (10^6 CAD)
S1	0.244/500	1.65	8.53	10.18
S2	0.333/1000	0.91	8.73	9.64
S4	0.439/2000	0.52	8.97	9.49
S6	0.507/3000	0.37	9.13	9.50
S10	0.613/5000	0.24	9.38	9.62
S17	0.775/10000	0.14	9.77	9.91



Is $E[LC]$ Design Optimal?

- Minimum $E[LC]$ design provides the most economical solution.
- However, it fails to take "uncertainty" into account
- Decision makers may prefer safer or riskier designs depending on their perceived risks
- The concept of bounded rationality recognises cognitive limitation of decision makers: ignorance of rare events, loss aversion, ambiguity aversion, myopic behaviour, etc.
- Decision theories beyond the risk neutral approach may provide valuable insight on "preferred seismic designs":

  Expected utility theory and cumulative prospect theory

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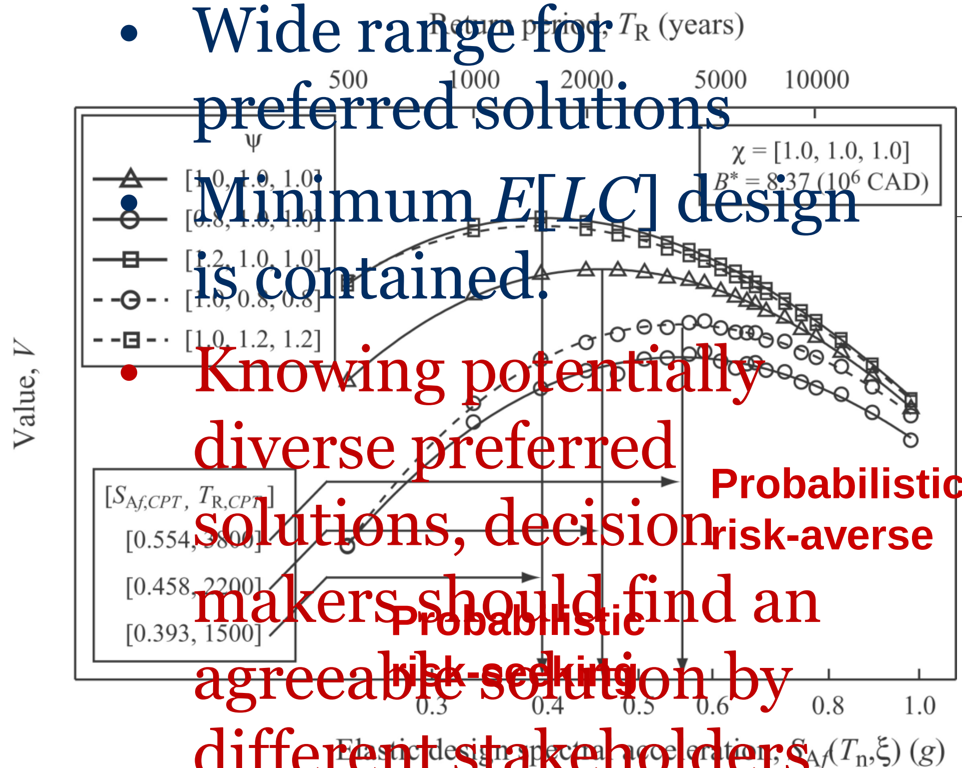
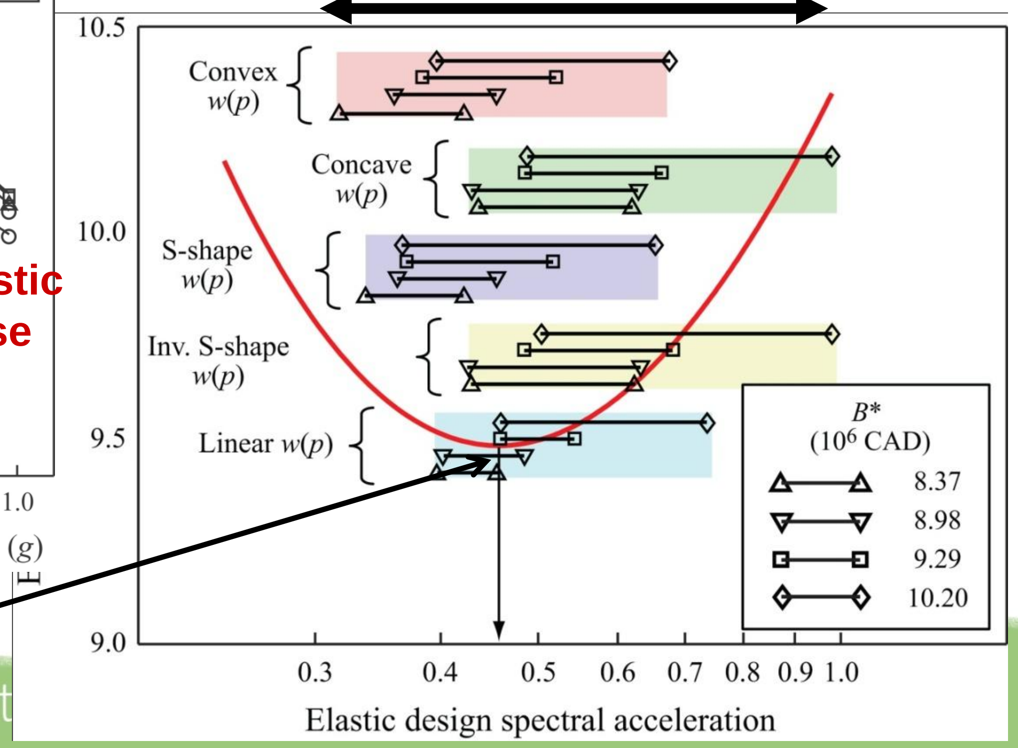
Preferred Seismic Design

- The cumulative prospect theory by Kahneman and Tversky is applied to the same problem.
- Wide range for preferred solutions
- Minimum $E[LC]$ design is contained.
- Knowing potentially diverse preferred solutions, decision makers should find an agreeable solution by different stakeholders.

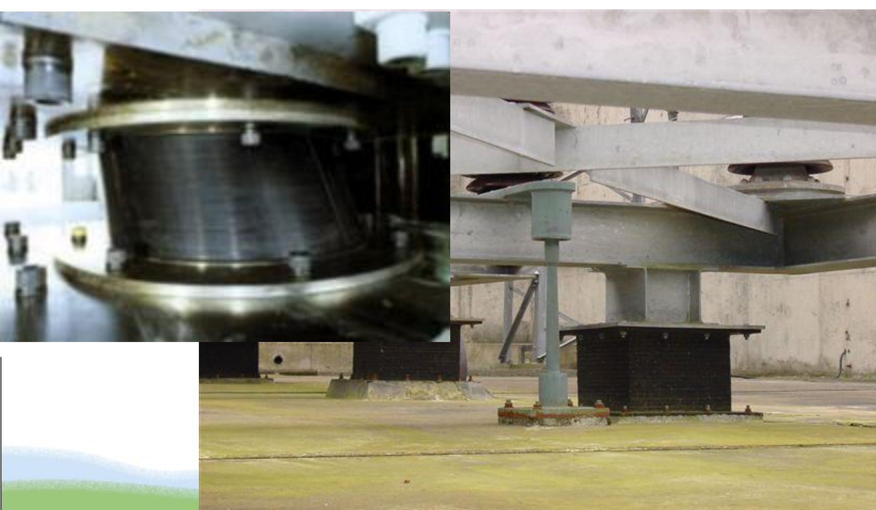


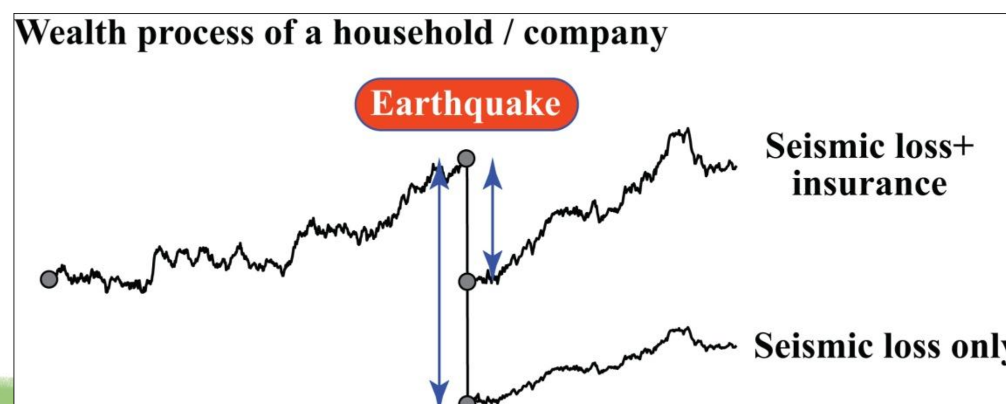


Optimal design level

Other Applications

- The decision making framework can be used to evaluate various earthquake risk mitigation options.
- Seismic retrofitting using seismic isolation: shifts natural vibration period to reduce structural responses
- Earthquake insurance: smoothes variation of asset/wealth and facilitates a quicker recovery

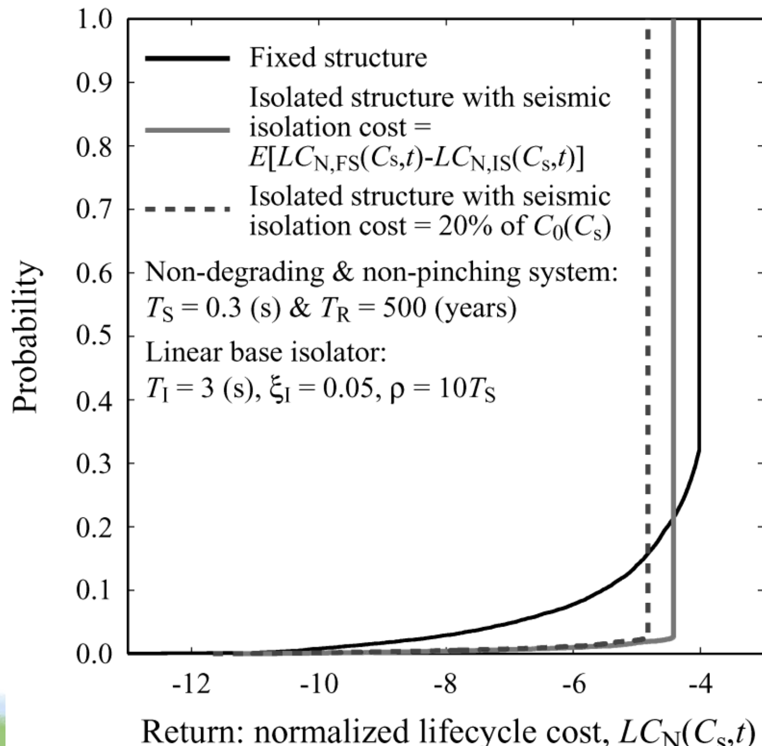




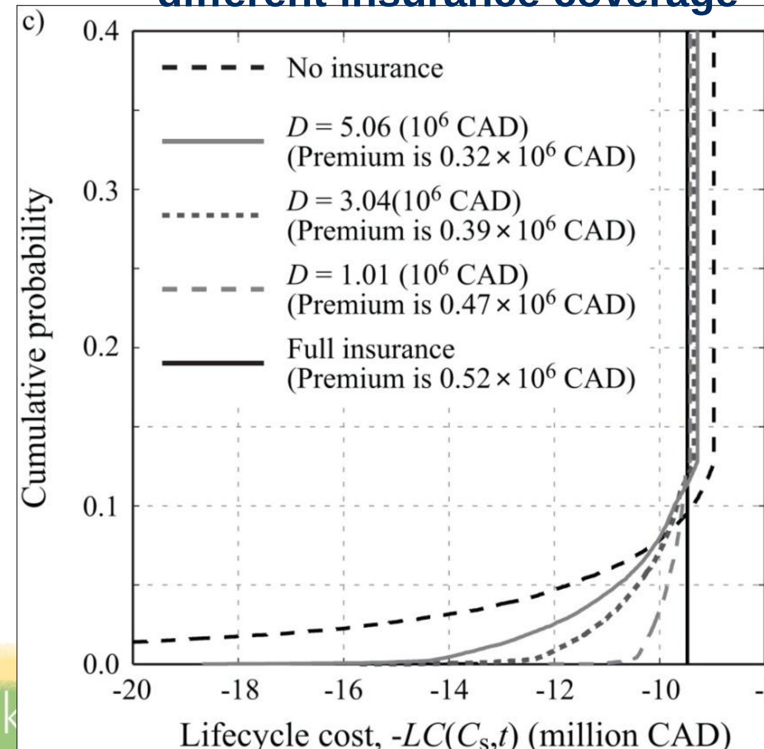
Example: Isolation and Insurance

- Both base isolation and insurance change the probability distributions of the lifecycle cost (reduction of uncertainty).
- These measures should be regarded as a tool to control earthquake risk in a proactive manner.

***LC* curves for base isolated structures**



***LC* curves for a structure with different insurance coverage**

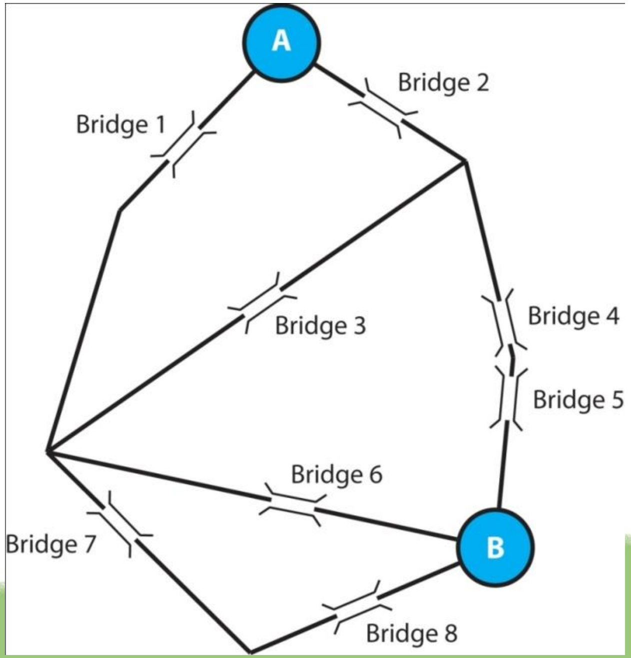


Need for Portfolio Approach

- The catastrophic nature of earthquake disaster is related to: spatiotemporally correlated damage and loss.
- This physical feature must be characterised adequately in hazard modelling.
- This affects the seismic performance assessment of spatially distributed systems.

Example:

- Bridges are vulnerable to ground shaking, intensities of which are correlated in space.
- Accessibility from A (patient) to B (hospital) depends on damage states of bridges.



Spatial Correlation Model

- Adopt a multi-variate lognormal model for ground motion parameters:

$$\log SA_{ik}(T_i) = f(\mathbf{M}_k, R_{ik}, \lambda_{ik}, T_i) + \eta_k(T_i) + \varepsilon_{ik}(T_i)$$

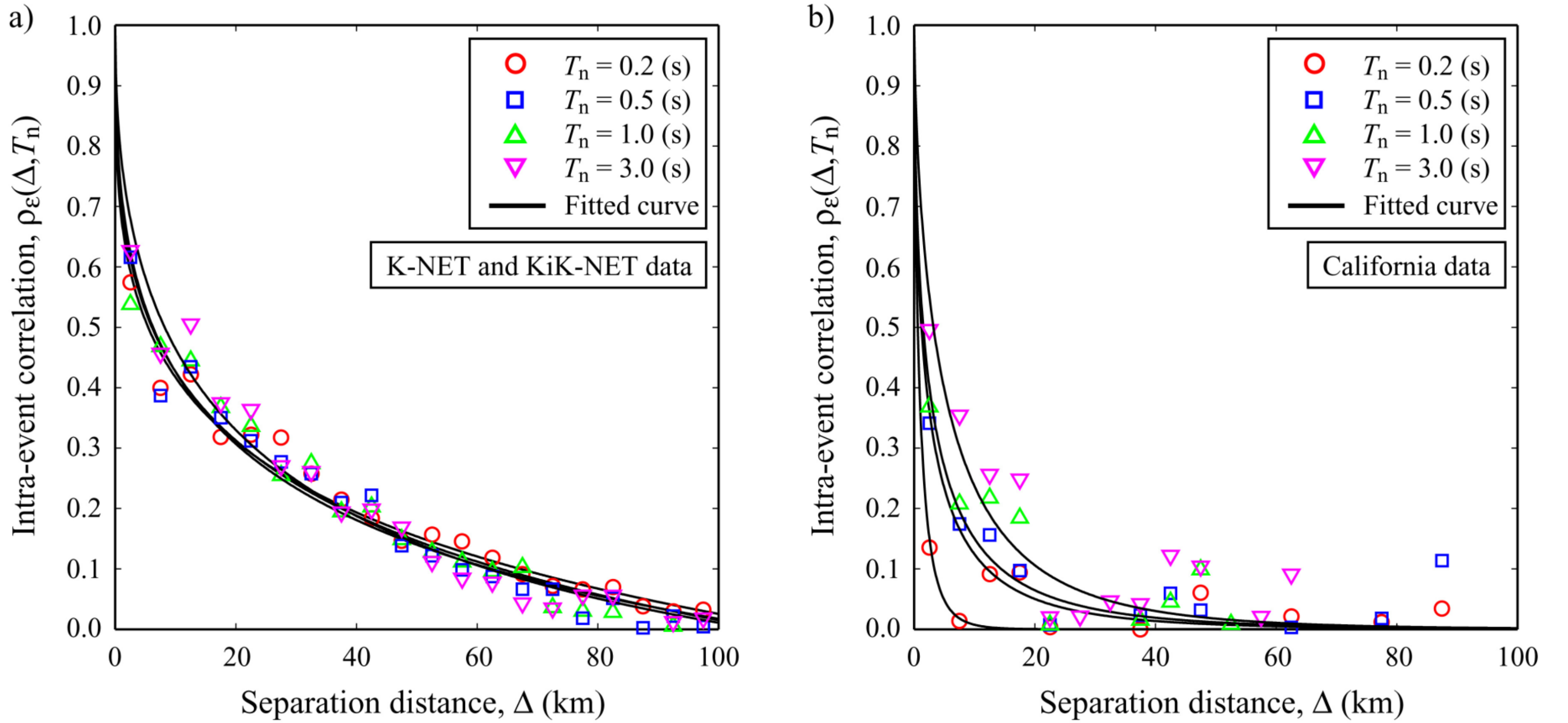
$$\log SA_{jk}(T_j) = f(\mathbf{M}_k, R_{jk}, \lambda_{jk}, T_j) + \eta_k(T_j) + \varepsilon_{jk}(T_j)$$

$$\rho_T(\Delta_{ij}, T_i, T_j) = \rho_\eta(T_i, T_j)\frac{\sigma_\eta(T_i)\sigma_\eta(T_j)}{\sigma_T(T_i)\sigma_T(T_j)} + \rho_\varepsilon(\Delta_{ij}, T_i, T_j)\frac{\sigma_\varepsilon(T_i)\sigma_\varepsilon(T_j)}{\sigma_T(T_i)\sigma_T(T_j)}$$

- Characterise $\rho_\varepsilon(\Delta, T)$: (i) calculate residuals; (ii) construct data pairs; (iii) evaluate semivariogram; and (iv) estimate spatial correlation.

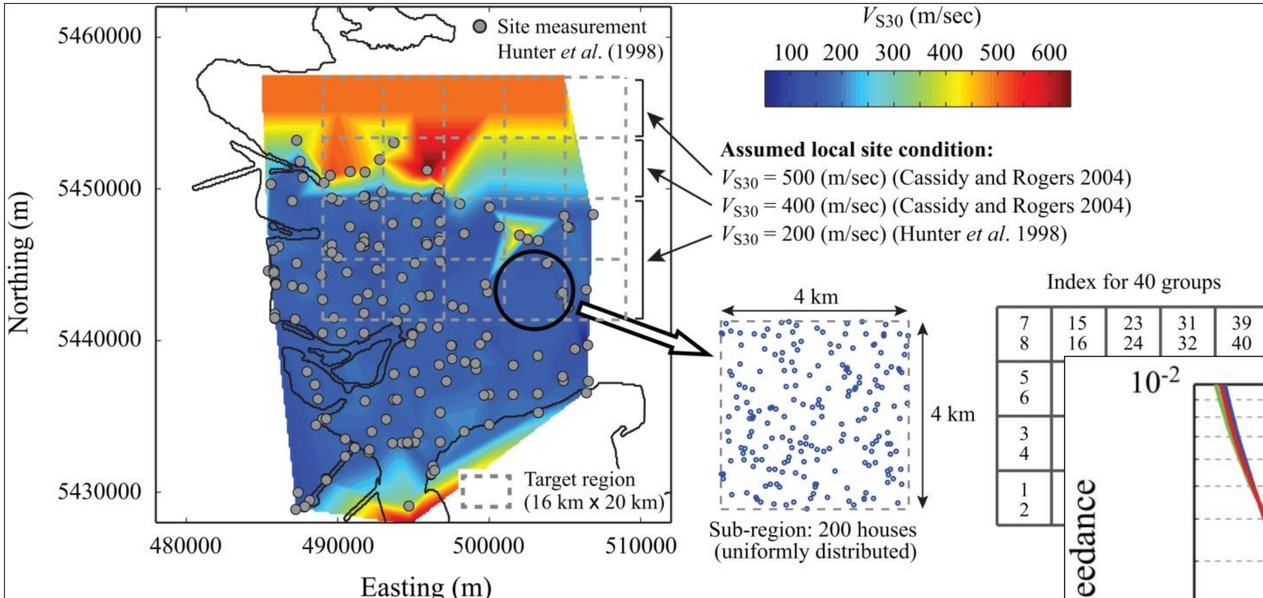
$$\rho_\varepsilon(\Delta, T) = 1 - \frac{1}{2}\left(\frac{\sigma_d(\Delta, T)}{\sigma_\varepsilon(T)}\right)^2$$

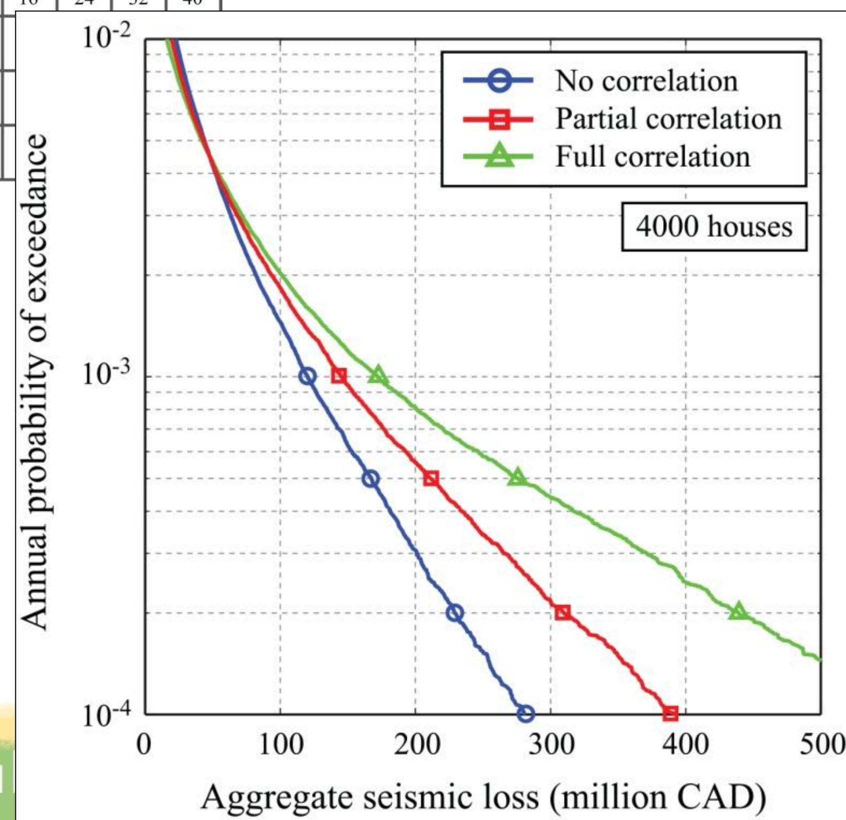
Spatial Correlation of Ground Motions



- The intra-event correlation can be characterised as an exponential decay curve in terms of separation distance.
- The developed models are used in seismic risk analysis to generate correlated simultaneous shakings at different sites.

Impact of Spatial Correlation





- 4000 wooden houses in Vancouver (20 km by 16 km)
- Spatial correlation affects the right upper tail of the aggregate seismic loss curve.

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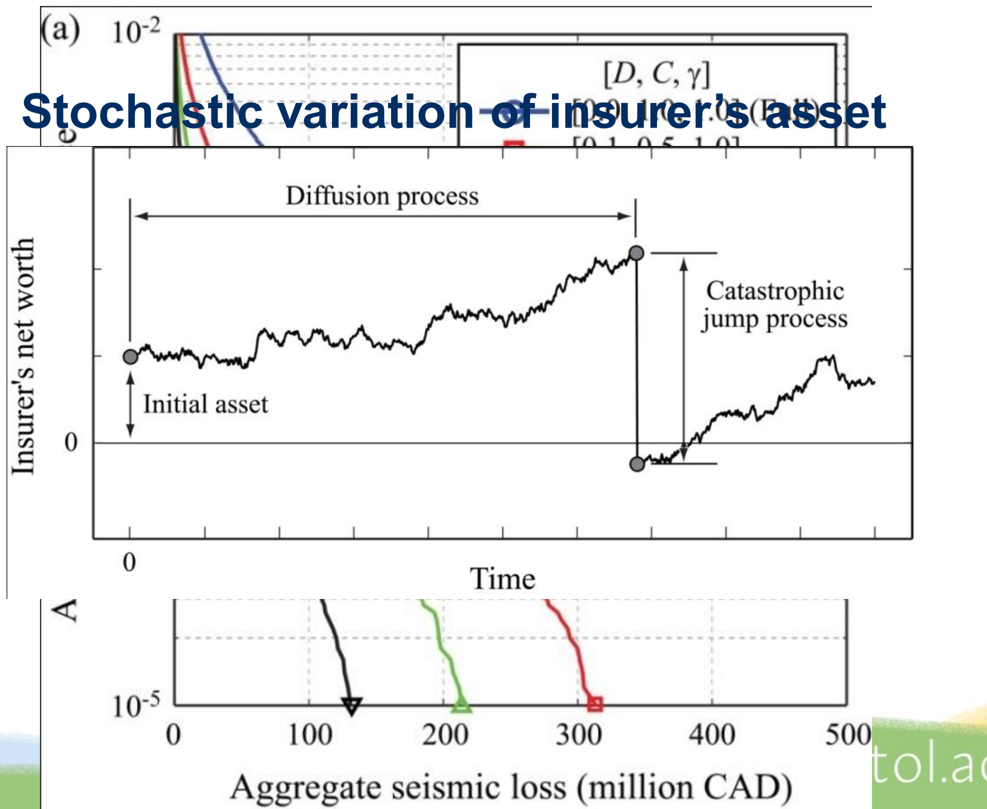
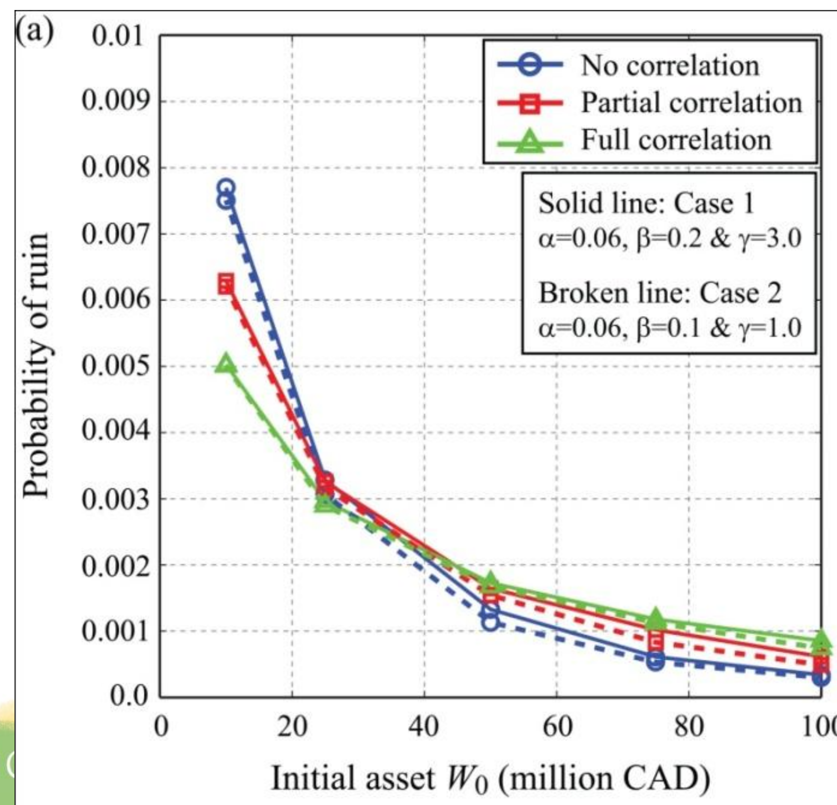
Insurance Portfolio Management

- Insurance parameter (e.g. deductible) affects the earthquake insurance portfolio (left figure).
- By considering stochastic asset for an insurer, insurer’s probability of ruin can be assessed for various scenarios.

Stochastic variation of insurer’s asset





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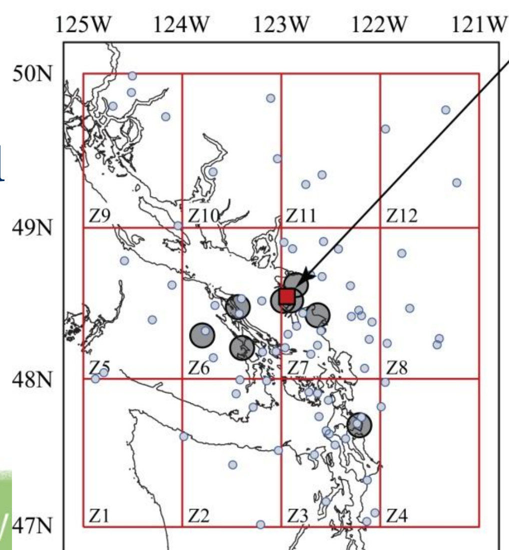
Catastrophe Earthquake Bond Design

- The portfolio-based seismic loss model can be used for designing/developing an optimal trigger mechanism of catastrophe bond.
- It serves as an alternative risk transfer tool for institutional organisations. The CAT bond achieves low credit risk and liquidity risk, but is subjected to model risks (inaccuracy in designing CAT bond parameters).

Example:

Trigger scenarios can be devised using a suitable loss model.

Alternatively, triggers can be designed based on observed shaking intensities.



Vancouver (2000 wood-frame houses)

Earthquakes in Zone 6: Loss threshold = 20 M CAD

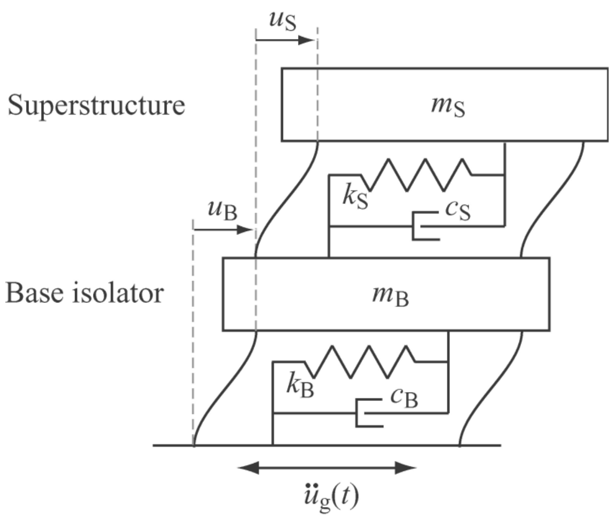
M_w	Lat.	Lon.	Depth (km)	Loss (M CAD)	Loss trigger	Scenario trigger
5.23	49.13	123.60	54.9	0.04	0	0
6.31	48.81	123.59	72.0	44.55	1	0
5.71	49.12	123.40	43.6	0.39	0	0
6.63	48.89	124.00	87.1	56.23	1	0
6.01	48.78	123.39	87.8	0.10	0	0
6.67	49.09	123.87	52.9	6.99	0	0
5.61	48.74	123.89	42.2	0.30	0	0
6.66	48.78	123.25	67.6	16.29	0	0
5.27	49.03	123.62	5.8	1.03	0	0
6.79	48.92	123.97	35.2	13.46	0	0
7.03	49.08	123.64	44.0	178.11	1	1

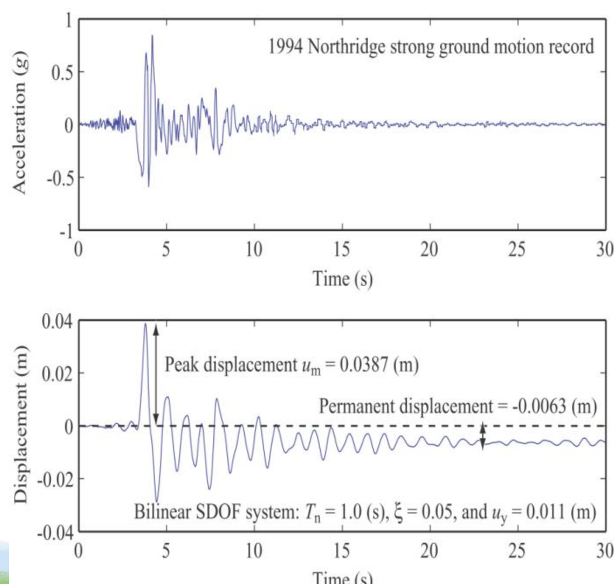
Trigger parameters for Zone 6:
M_w >= 6.8 & Depth <= 70 km → **Positive error : 0**, **Negative error : 2**, **Total error : 2**

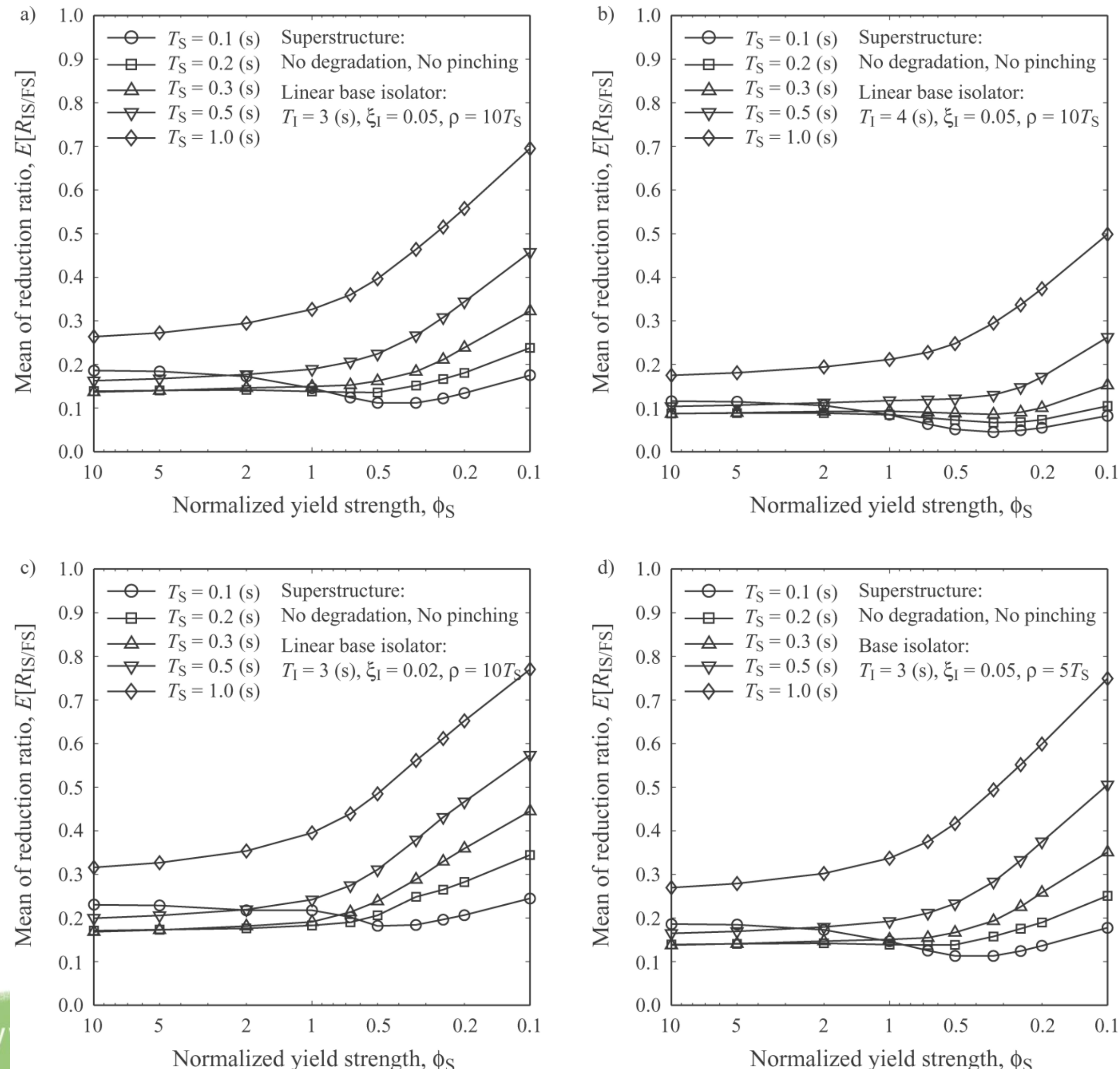
Current and Future Challenges

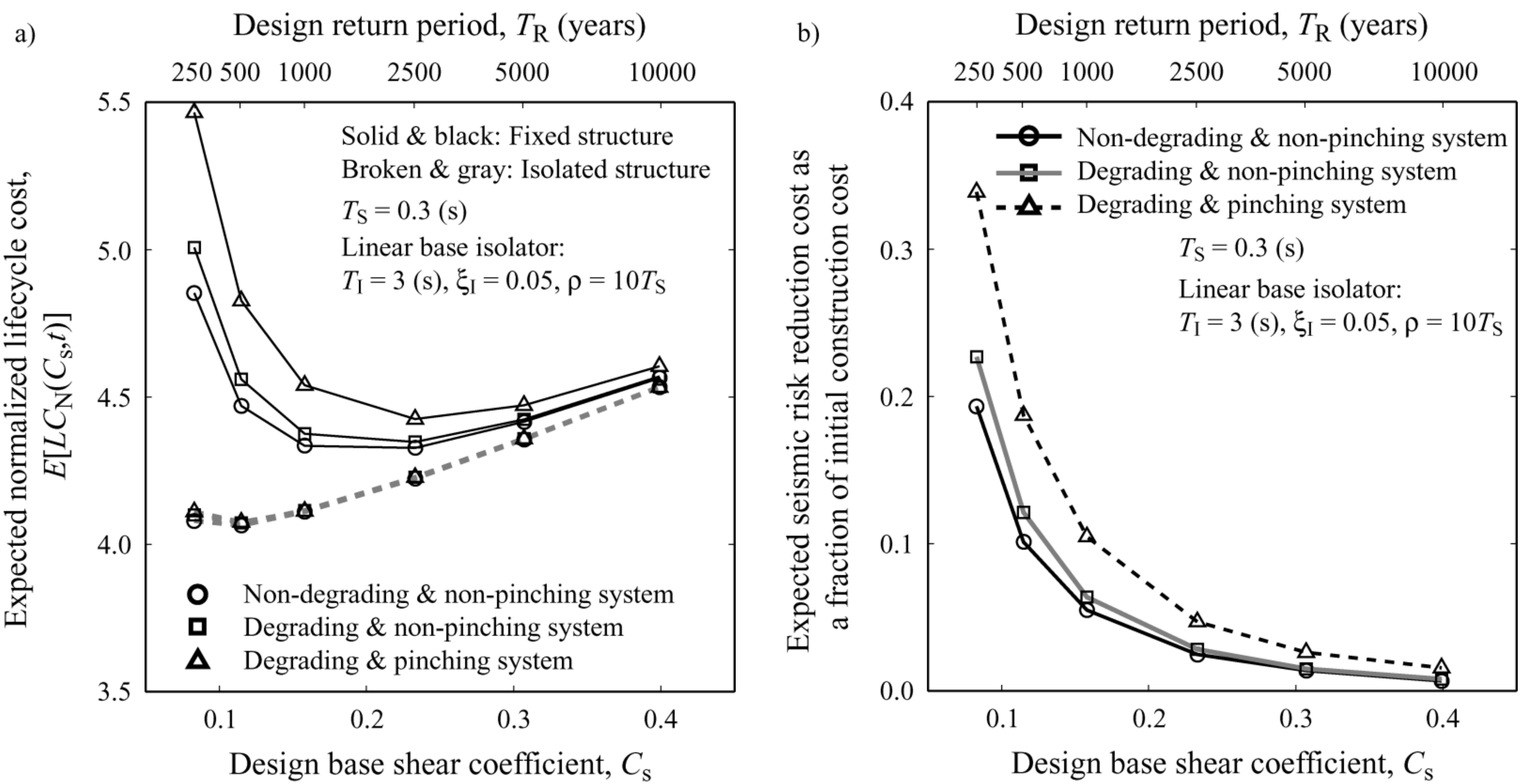
- Effective tools for quantitative and probabilistic analyses
- Different engineering systems require different solutions and tools (e.g. time and spatial extent)
- Modelling complexity for both within and between systems (e.g. robustness and interdependency)
- Multi-hazards (e.g. earthquakes, tsunami, typhoon, volcanoes, flood)
- Beyond natural sciences and engineering: decision-making by addressing critical human/community aspects (e.g. resilience). Need for suitable metrics for such criteria.

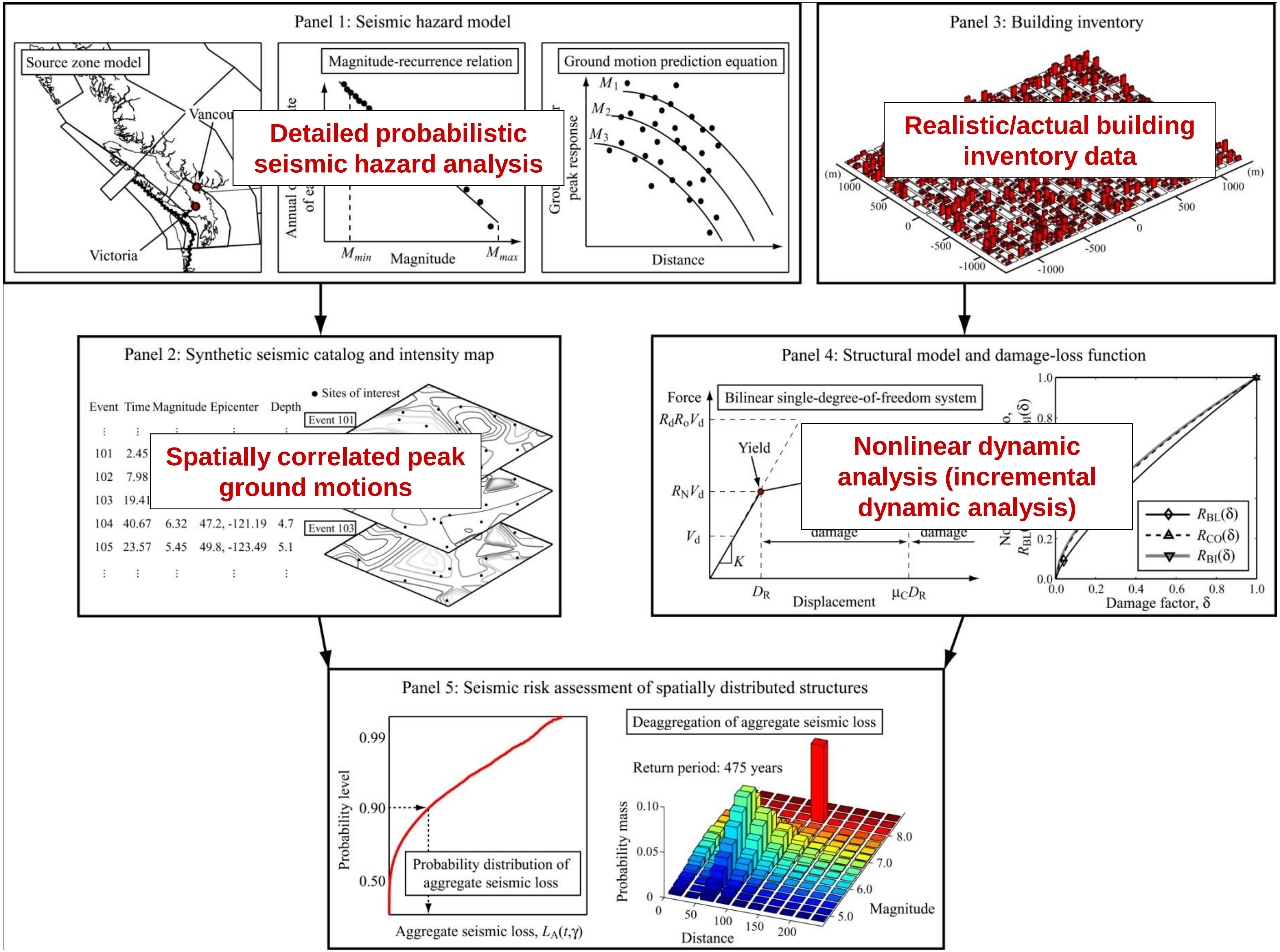
Additional Materials


u_S
Superstructure
m_S
k_S
c_S
u_B
Base isolator
m_B
k_B
c_B
$\ddot{u}_g(t)$


1994 Northridge strong ground motion record
Acceleration (g)
Time (s)
Peak displacement u_m = 0.0387 (m)
Permanent displacement = -0.0063 (m)
Bilinear SDOF system: T_n = 1.0 (s), ξ = 0.05, and u_y = 0.011 (m)
Displacement (m)
Time (s)

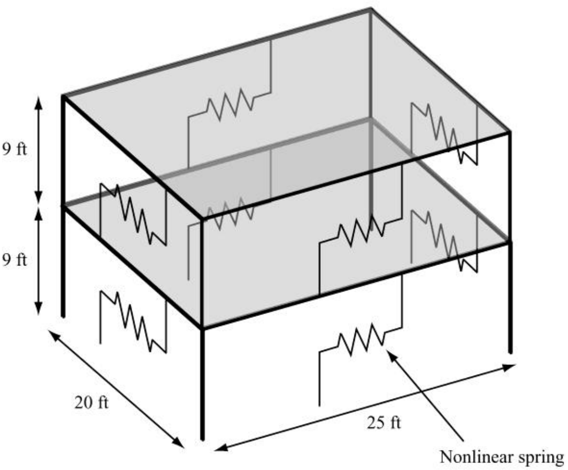

a)
T_S = 0.1 (s)
T_S = 0.2 (s)
T_S = 0.3 (s)
T_S = 0.5 (s)
T_S = 1.0 (s)
Superstructure:
No degradation, No pinching
Linear base isolator:
T_I = 3 (s), ξ_I = 0.05, ρ = 10T_S
Mean of reduction ratio, $E[R_{IS/FS}]$
Normalized yield strength, ϕ_S
b)
T_S = 0.1 (s)
T_S = 0.2 (s)
T_S = 0.3 (s)
T_S = 0.5 (s)
T_S = 1.0 (s)
Superstructure:
No degradation, No pinching
Linear base isolator:
T_I = 4 (s), ξ_I = 0.05, ρ = 10T_S
Mean of reduction ratio, $E[R_{IS/FS}]$
Normalized yield strength, ϕ_S
c)
T_S = 0.1 (s)
T_S = 0.2 (s)
T_S = 0.3 (s)
T_S = 0.5 (s)
T_S = 1.0 (s)
Superstructure:
No degradation, No pinching
Linear base isolator:
T_I = 3 (s), ξ_I = 0.02, ρ = 10T_S
Mean of reduction ratio, $E[R_{IS/FS}]$
Normalized yield strength, ϕ_S
d)
T_S = 0.1 (s)
T_S = 0.2 (s)
T_S = 0.3 (s)
T_S = 0.5 (s)
T_S = 1.0 (s)
Superstructure:
No degradation, No pinching
Base isolator:
T_I = 3 (s), ξ_I = 0.05, ρ = 5T_S
Mean of reduction ratio, $E[R_{IS/FS}]$
Normalized yield strength, ϕ_S


a)
Design return period, T_R (years)
250 500 1000 2500 5000 10000
Solid & black: Fixed structure
Broken & gray: Isolated structure
T_S = 0.3 (s)
Linear base isolator:
T_I = 3 (s), ξ_I = 0.05, ρ = 10T_S
Expected normalized lifecycle cost, $E[LC_N(C_s,t)]$
5.5
5.0
4.5
4.0
3.5
Non-degrading & non-pinching system
Degrading & non-pinching system
Degrading & pinching system
0.1 0.2 0.3 0.4
Design base shear coefficient, C_s
b)
Design return period, T_R (years)
250 500 1000 2500 5000 10000
Expected seismic risk reduction cost as a fraction of initial construction cost
0.4
0.3
0.2
0.1
0.0
Non-degrading & non-pinching system
Degrading & non-pinching system
Degrading & pinching system
T_S = 0.3 (s)
Linear base isolator:
T_I = 3 (s), ξ_I = 0.05, ρ = 10T_S
0.1 0.2 0.3 0.4
Design base shear coefficient, C_s

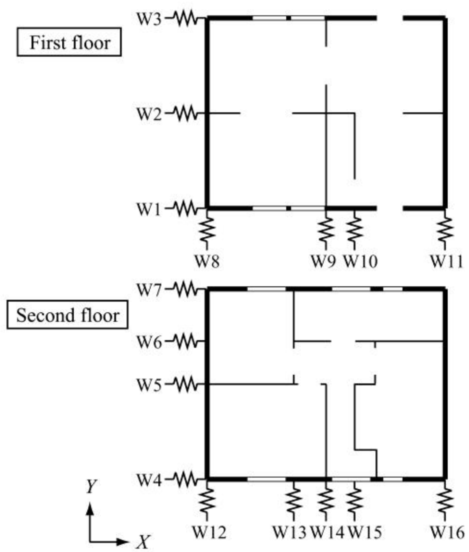


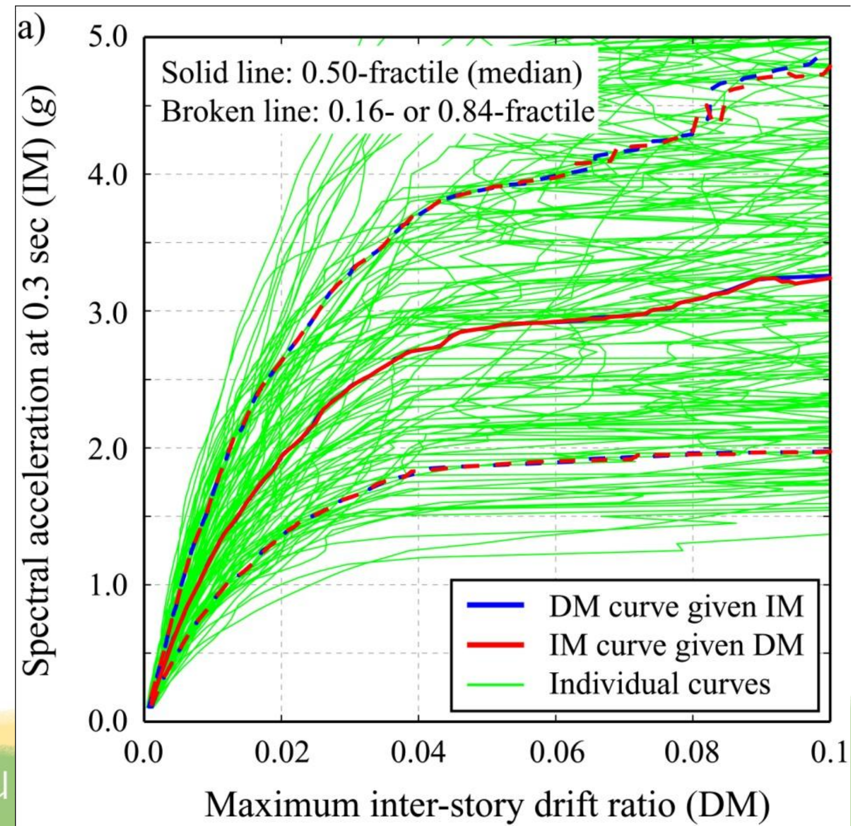
Panel 1: Seismic hazard model
Source zone model
Victoria
Magnitude-recurrence relation
Magnitude
M_{min}
M_{max}
Ground motion prediction equation
M_1
M_2
M_3
Distance
Detailed probabilistic seismic hazard analysis
Panel 3: Building inventory
Realistic/actual building inventory data
Panel 2: Synthetic seismic catalog and intensity map
Sites of interest
Event Time Magnitude Epicenter Depth
101 2.45
102 7.98
103 19.41
104 40.67 6.32 47.2, -121.19 4.7
105 23.57 5.45 49.8, -123.49 5.1
Event 101
Event 103
Spatially correlated peak ground motions
Panel 4: Structural model and damage-loss function
Force
Bilinear single-degree-of-freedom system
$R_d R_o V_d$
Yield
$R_N V_d$
V_d
K
D_R
$\mu_C D_R$
Displacement
Nonlinear dynamic analysis (incremental dynamic analysis)
$R_{BL}(\delta)$
$R_{CO}(\delta)$
$R_{BI}(\delta)$
Damage factor, δ
Panel 5: Seismic risk assessment of spatially distributed structures
Probability level
Probability distribution of aggregate seismic loss
Aggregate seismic loss, $L_A(t,\gamma)$
Deaggregation of aggregate seismic loss
Return period: 475 years
Probability mass
Magnitude
Distance

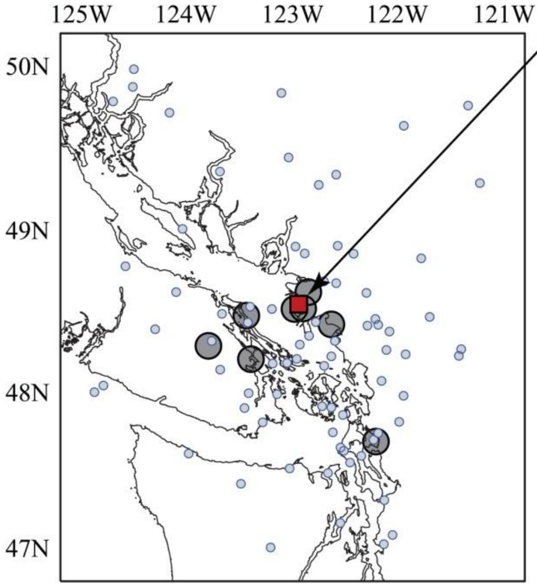
Generic structural model



Plan view





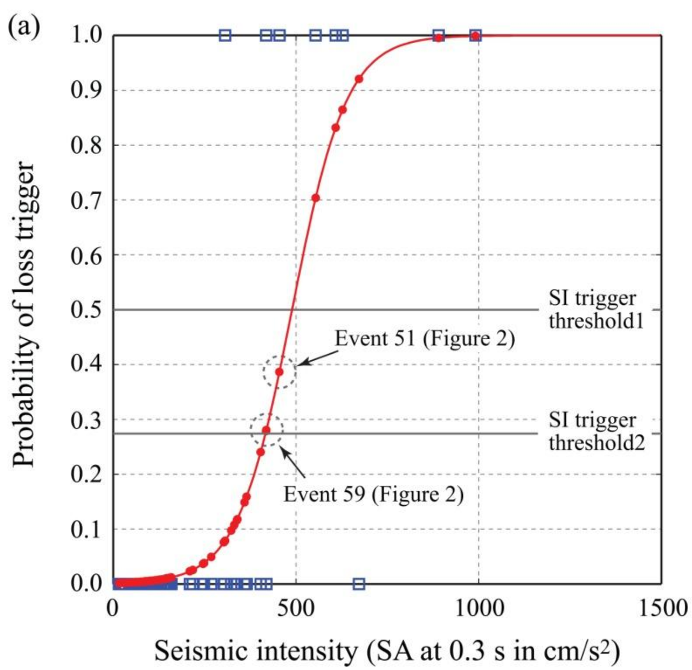


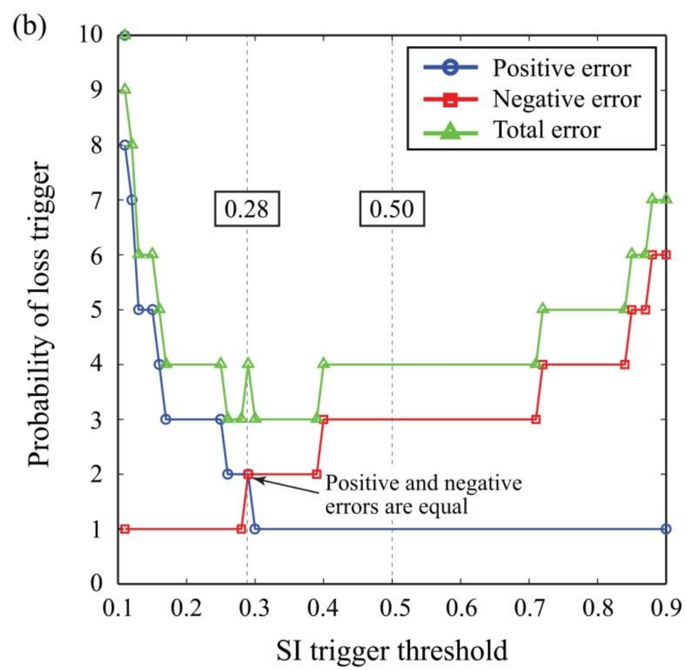
Loss threshold = 20 M CAD

Event ID	M_w	Lat.	Lon.	SA at 0.3 s (cm/s²)	Loss (M CAD)	Loss trigger	Logistic model	SI trigger1	SI trigger2
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
50	5.23	49.13	123.60	106.4	0.04	0	0.006	0	0
51	6.31	48.81	123.59	454.6	44.55	1	0.387	0	1
52	5.71	49.12	123.40	053.5	0.39	0	0.003	0	0
53	6.63	48.89	124.00	608.6	56.23	1	0.832	1	1
54	6.01	48.78	123.39	090.2	0.10	0	0.005	0	0
55	6.67	49.09	123.87	337.8	6.99	0	0.116	0	0
56	5.61	48.74	123.89	209.7	0.30	0	0.023	0	0
57	6.66	48.78	123.25	403.2	16.29	0	0.240	0	0
58	5.27	49.03	123.62	99.5	1.03	0	0.005	0	0
59	6.79	48.92	123.97	418.8	13.46	0	0.281	0	1
60	7.03	49.08	123.64	890.6	178.11	1	0.995	1	1
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

SI trigger threshold1 : 0.50 → **Positive error : 0**, **Negative error : 1**, **Total error : 1**

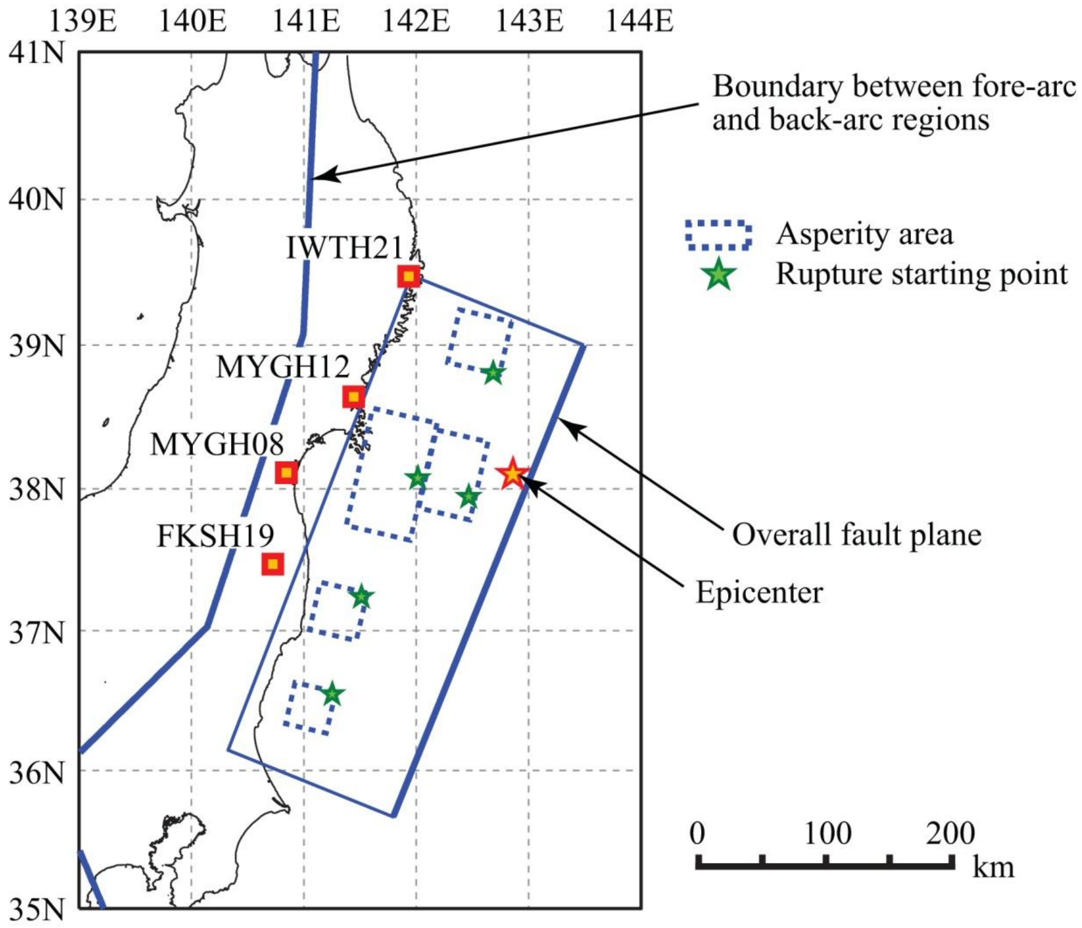
SI trigger threshold2 : 0.28 → **Positive error : 1**, **Negative error : 0**, **Total error : 1**





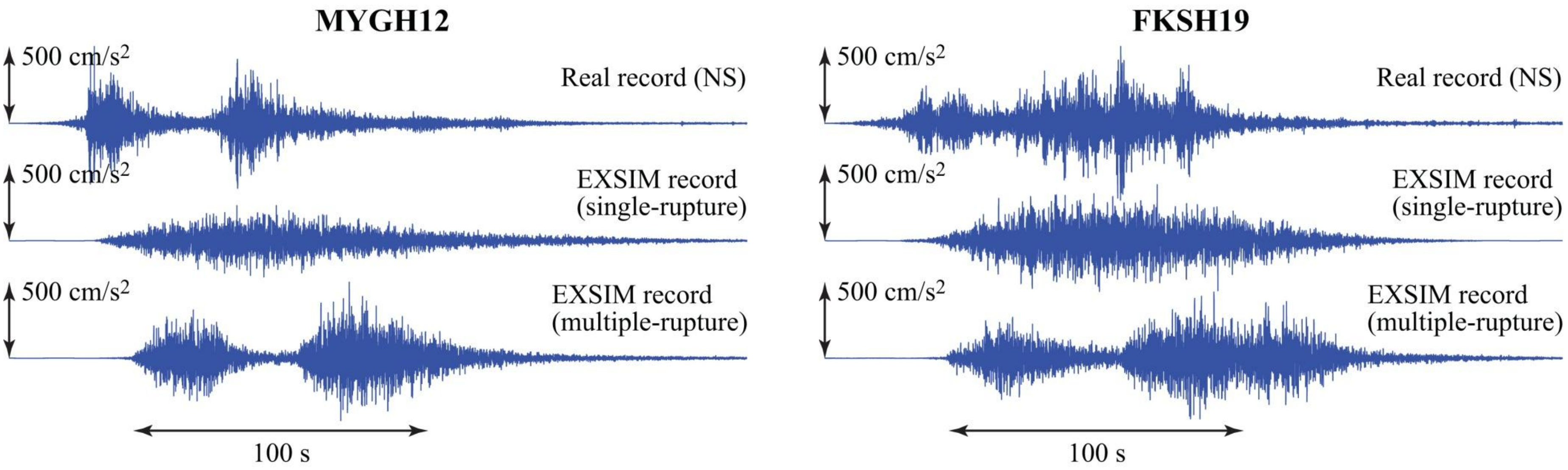
Loss threshold		Scenario-based method[1] ($K = Z$)			Scenario-based method[2] ($K = 10$)			Station-intensity-based method[3]			Station-intensity-based method[4]		
		Partial corr.	No corr.	Full corr.	Partial corr.	No corr.	Full corr.	Partial corr.	No corr.	Full corr.	Partial corr.	No corr.	Full corr.
Case I	20 M CAD	613.25	581.25	679.5	462.25	361	480.5	509.25	888.75	264.5	447.5	570.75	270.75
	70 M CAD	154.0	86.75	187.0	128	54.5	147.75	151.75	184.5	56.5	120.75	120.25	56.0
	100 M CAD	83.5	34.0	103.0	71.5	22.75	89.25	92.0	85.75	38.75	77.75	65.75	40.5
Case II	20 M CAD	817.0	672.25	846.25	579.75	404.5	618.75	576.75	905.5	278.25	426.75	542.25	280.5
	70 M CAD	169.0	96.0	218.5	118.75	60.25	165.25	132.0	186.0	64.75	92.0	135.5	63.5
	100 M CAD	73.25	21.75	124.75	60.25	23	103	72.75	72.5	34.5	48.25	50.0	34.25

Case Study II: M9.0 Tohoku Event



- Real records (KiK-net, surface motions) at four sites
- EXSIM records – single-rupture model
- EXSIM records – multiple-rupture model (based on inversion analysis by Kurahashi & Irikura (2011))
- Calibration of EXSIM models based on general rupture information (Ghofrani et al., 2012)

Ground Motion Time-History



- Real records show multiple phases of seismic wave arrivals.
- EXSIM-single-rupture records show single-phase wave arrivals.
- EXSIM-multiple-rupture records show multiple-phase wave arrivals, similar to the real records.