Assessment and Mitigation of Ground Motion Hazards from Induced Seismicity

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(with acknowledgement to many collaborators, especially Ghofrani and Assatourians)

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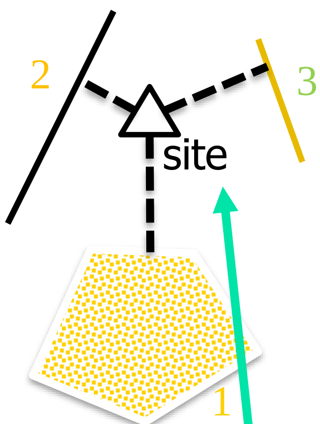
Assessing Earthquake Hazard – we all know how its done……
(using probabilistic methods -achieve reliability target)

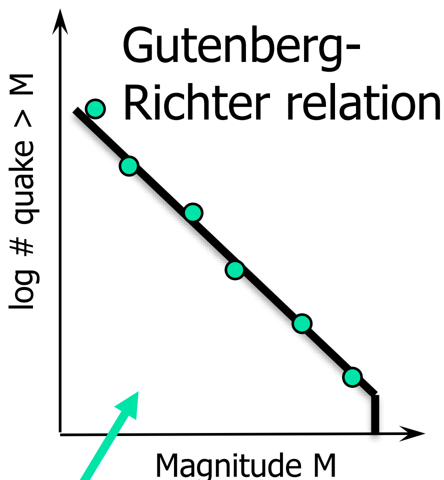
Buildings: withstand motions that have a likelihood of 2% in 50 years.
Critical facilities (i.e. major dams): withstand motions that have a likelihood of less than 1/10,000 per year (1% in 100 years)

1 Where?
(Earthquake locations)



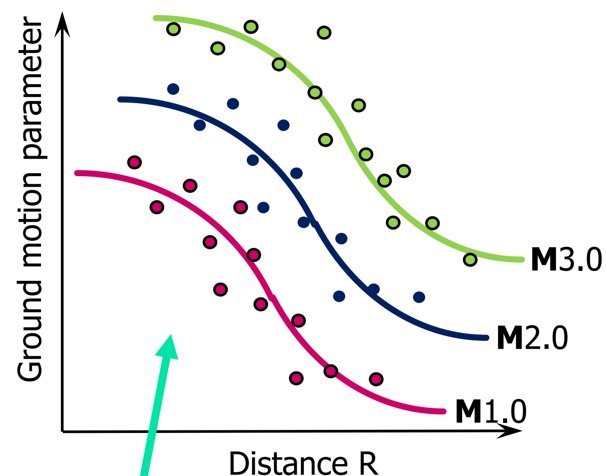
Events occur along faults or zones around a site

2 How often?
(Earthquake number, sizes, rates)



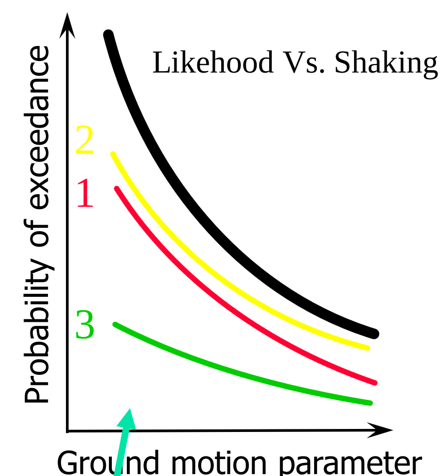
G-R relation measures earthquake size (magnitude) and rates in the zones

3 Ground motions
(Shaking vs distance relations)



Intensity of shaking depends on earthquake magnitude and distance

4 Hazard curve



Hazard (likelihood of strong shaking) calculated from location, size and rate of events

What drives hazard from induced events?

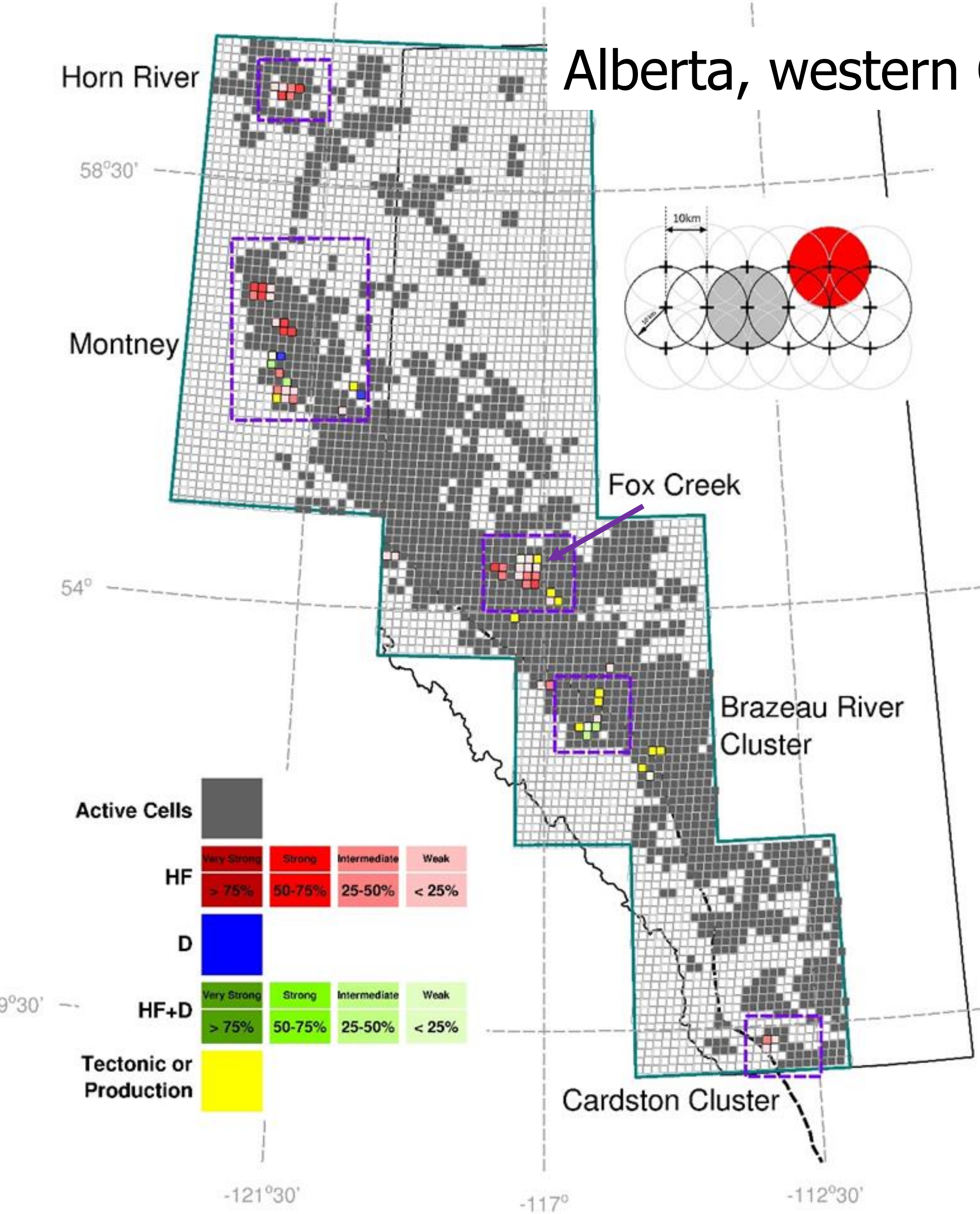
1. Likelihood of initiating a sequence (of **M**>3)
2. Productivity parameters for sequences
   - More productive sequences will have higher likelihood of a potentially damaging event (Gutenberg-Richter relation: 100 M3+, 10 M4+, 1 M5+)
   - Maximum and minimum magnitude
3. Ground motions from induced events, as a function of magnitude and distance
4. Uncertainties in all of the above

Lets go through a hazard exercise in which we consider these 3 key factors (and their uncertainty).

Example for Fox Creek (small town in Alberta, Canada).

Seismicity induced by hydraulic fracturing (HF).

Alberta, western Canada

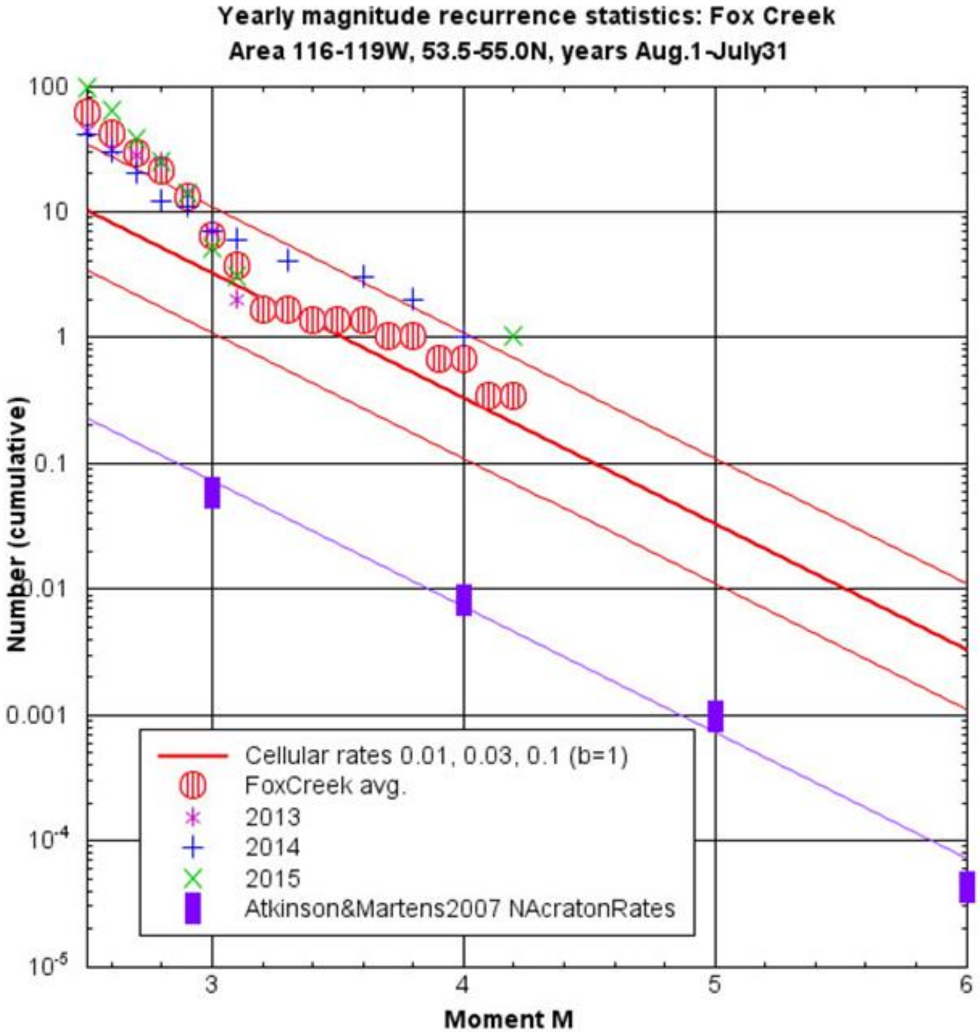


1. Likelihood of activation (**M**≥3): 0.01 to 0.03, per cell of 10 km radius (for cells with active HF wells) (averaged over a wide area; likelihood will vary greatly according to many risk factors)

Induced seismicity patterns for cells of 10 km radius. Dark grey cells had HF treatments (active cells). Likelihood of seismicity of **M**≥3 being spatially and temporally associated with either hydraulic fracturing (HF), disposal(D), or the combination of HF and disposal (HF+D) is indicated by shading. (from Ghofrani and Atkinson, 2016)

2. Productivity: Magnitude distribution for induced events, showing event rates vs. **M** (normalized to area of ~32,000 km^2) (area around Fox Creek)

- follows Gutenberg-Richter relation with b~1



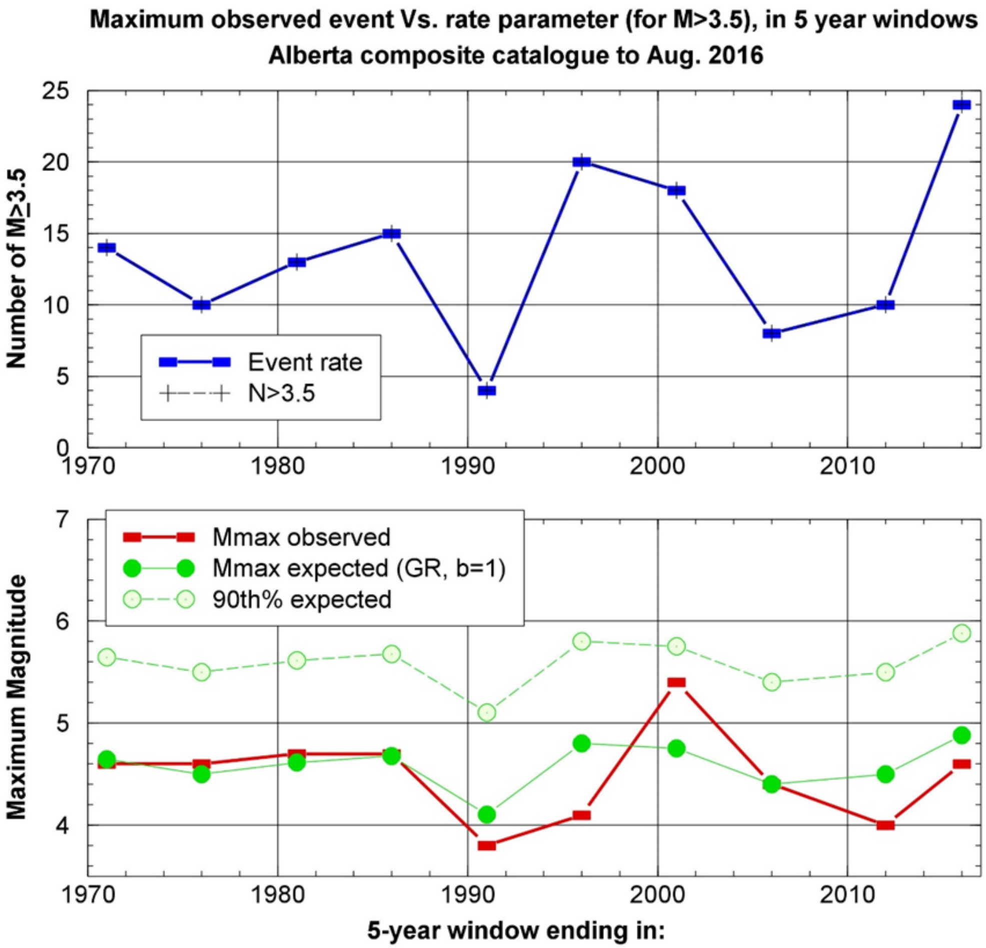
Magnitude-recurrence stats for Fox Creek area (box~160 km x 200 km). Red circles show avg. rates p.a. in Fox Creek over last 3 years. Red lines show expected rates based on 10-km cell activation probability for **M**3 of 0.01, 0.03, 0.1. Purple lines show natural seismicity rates in North American craton.

All rates normalized to same area, per annum.

Rates are very low for large events….. but probably non-zero

What controls maximum magnitude (Mx)?

Maximum observed magnitudes are correlated with earthquake rate parameters (follow Gutenberg-Richter scaling) (e.g. van der Elst et al., 2016)



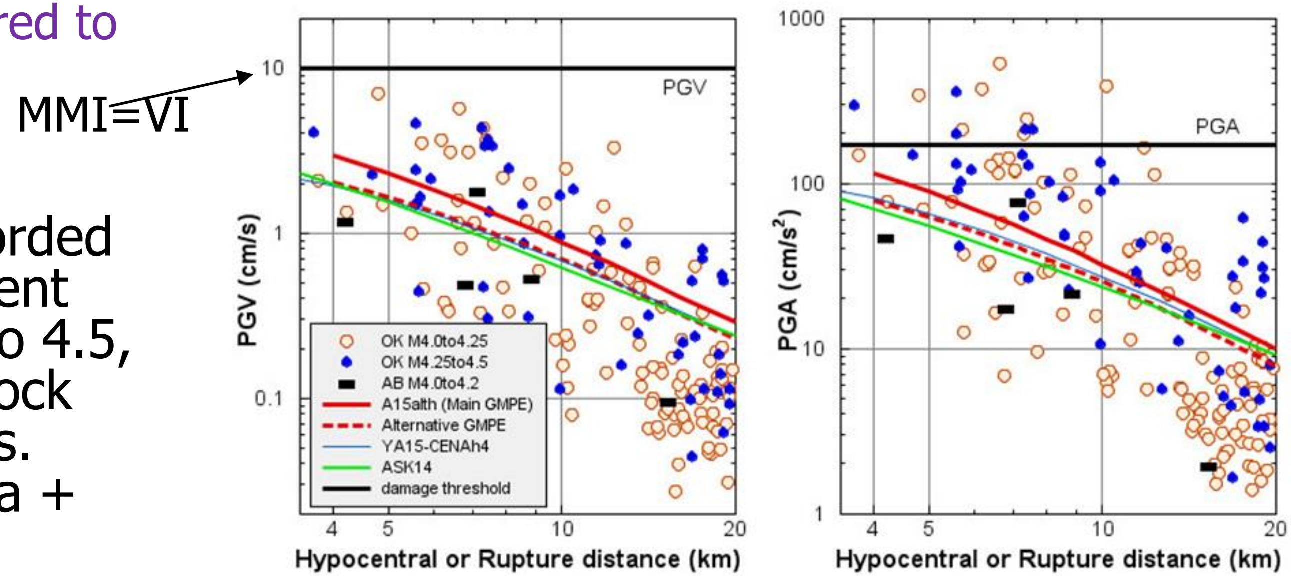
If the activity rate for **M**≥3 increases, the rate of larger events also increases…… so you will eventually see larger events, but their recurrence rates are low. So most events will be moderate.

Figure shows count of **M**≥3.5 in 5-year windows in western Canada oil/gas regions in top panel.

Lower panel shows observed Mmax in each window, along with value expected (N=1) for Gutenberg-Richter scaling with b=1.

3. Ground Motions (e.g. PGV, PGA)

Ground motions from events of **M**4 to 4.5 (compared to GMPE for **M**=4.25)



- Symbols show recorded horizontal-component motions for **M**4.0 to 4.5, converted to soft rock conditions (B/C), vs. distance (Oklahoma + Alberta)
- Lines show selected ground-motion prediction equations (GMPEs) proposed for induced events, for **M**=4.25
- Note scatter in data: some motions will be much stronger than median, and may cross damage threshold – especially at close distances

MMI VI (Damage Threshold):

Modified Mercalli Intensity VI considered the lower end of damage (e.g. cracks in walls, chimneys, etc.). MMI=VI corresponds to:

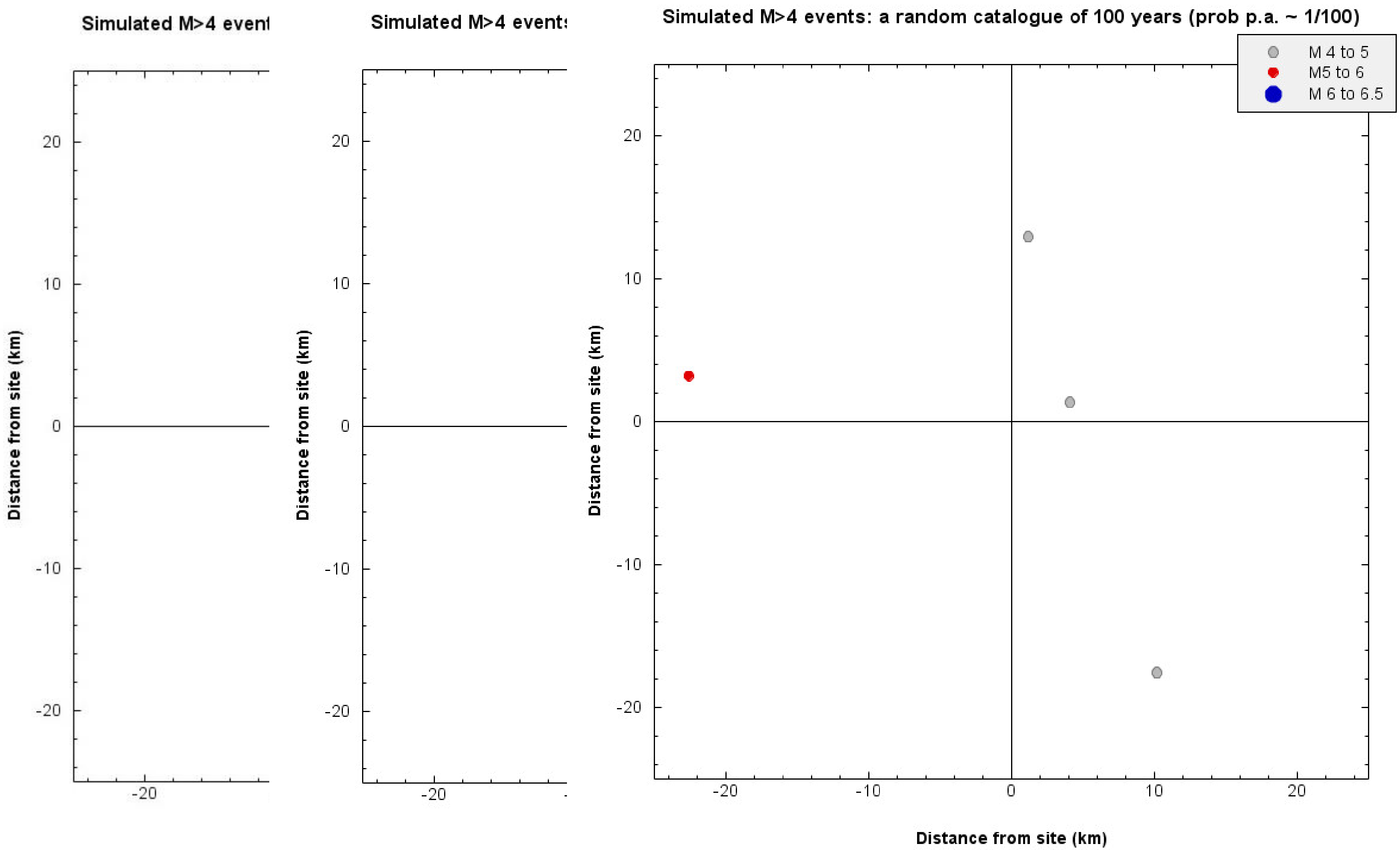
- Peak ground velocity (PGV) of ~10 cm/s (Worden et al., 2012; blasting guidelines)
- Peak ground acceleration (PGA) of ~170 cm/s^2

Simple probabilistic hazard calculation: Fox Creek

- Consider a large box, 50 km x 50 km, with a site in the middle
- Assume the rate parameters from Ghofrani&Atkinson, 2016 statistical study (with b-value of 1, and distribution of **M**max from 5.0 to 6.5) – similar to Fox Creek rates
- Use EQHaz (Assatourians and Atkinson, 2013) to simulate earthquake catalogues that could be realized over many trials (Monte Carlo)
- Two alternative ground-motion models that appear to be applicable to induced events, based on recent OK data (Yenier et al., 2017; Atkinson and Assatourians, 2017)
- Convert PGA and PGV from all events to MMI and take average of two MMI measures (using Worden et al.)

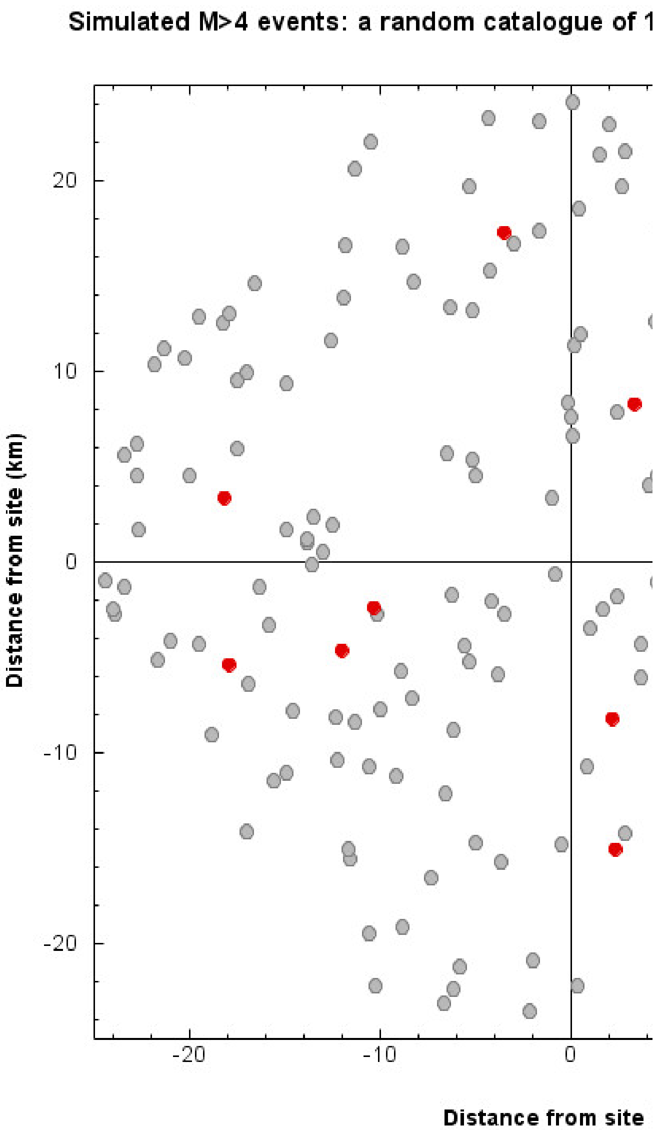
Simulated Catalogues: random 100 year snapshots

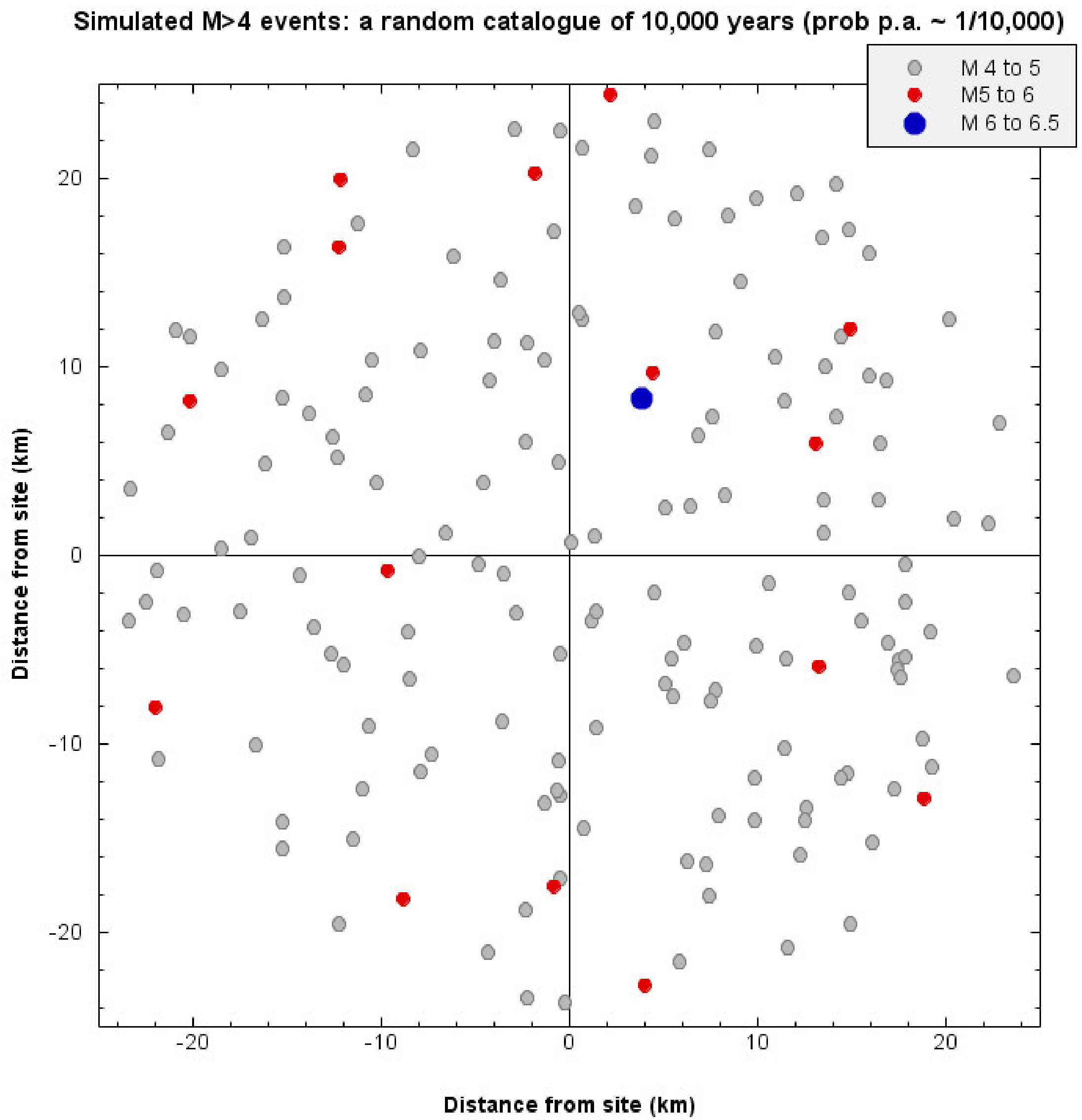
- does not look very troubling……

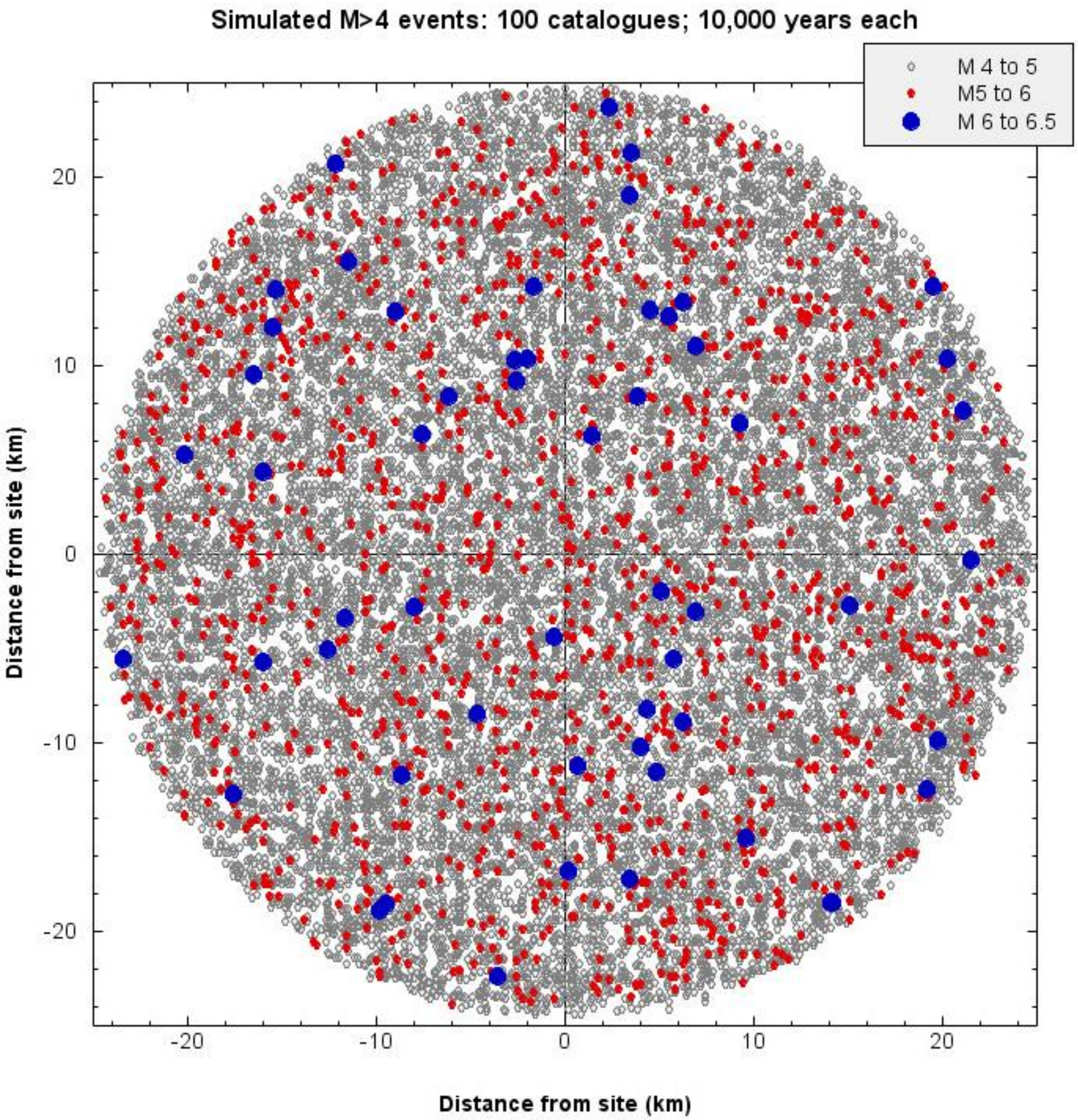


Simulated Catalogues: random 10,000 year snapshots

-for 1/10,000 p.a., we need to withstand the largest ground motion from among these

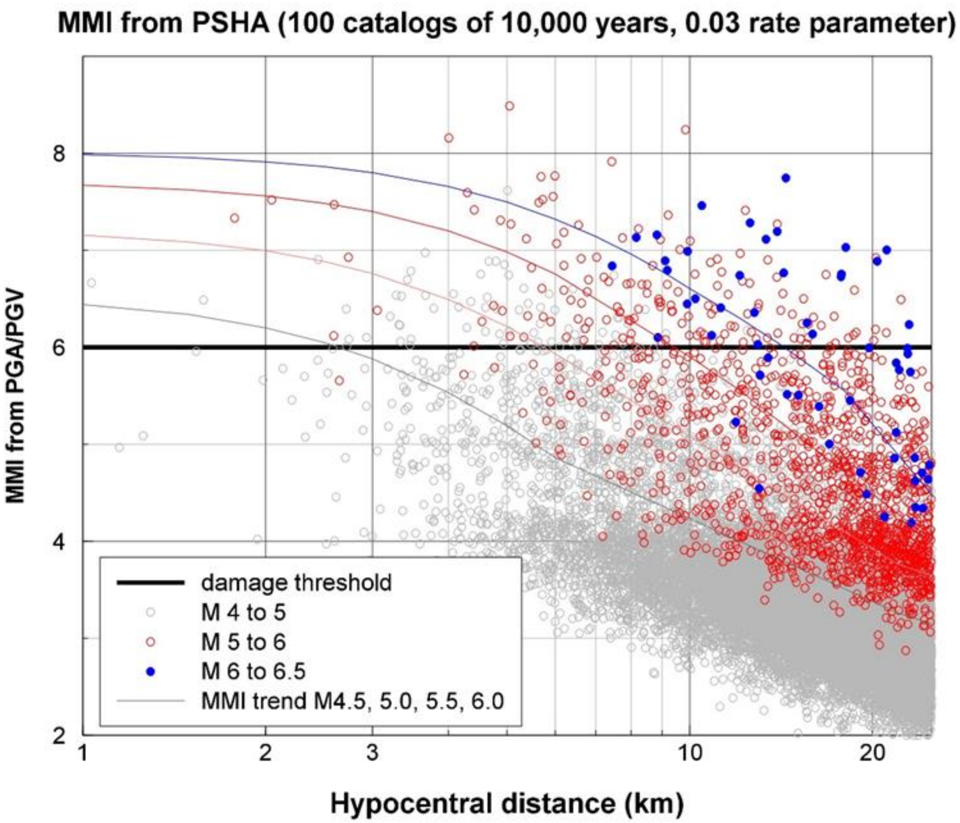


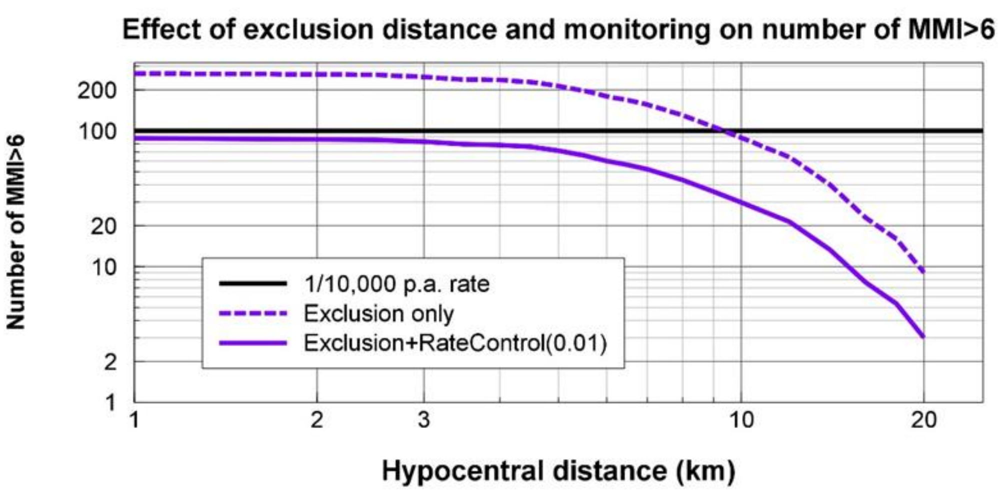




Simulated Catalogue: 1,000,000 years

-for 1/10,000 p.a. we need to withstand the 100th largest ground motion





Ground motions generated from 1,000,000 year catalog (including variability):

- if our goal is to have no greater than 1/10,000 p.a. chance of exceeding damage threshold (MMI=VI), we need to have no more than 100 exceedences of black line…

Lower plot shows effect of:
- exclusion distance only (dashed line)
- combination of exclusion distance plus a protocol to limit the rate of events, from the edge of the exclusion zone to a distance of 25 km (to <2 events of **M**>2 per annum within 25 km)

Importance of a real-time monitoring and response protocol

- Exclusion zones alone may not provide sufficiently-low probabilities, because contributions from beyond that zone are important
- Regional monitoring in the 5km to 25 km radius is needed to determine regional rate parameters and fine-tune mitigation strategies
- Develop an appropriate response protocol (i.e. if the annual rate of induced **M**>2 in the zone from 5 to 25 km exceeds 1, adjust operations to obtain a reduced activity rate)

Conclusions:

- Likelihood of strong ground motion near critical facilities can be kept to low levels through:
  - 1- exclusion zone aimed at eliminating threats from moderate nearby events
  - 2- monitoring and response protocol to limit rate of events beyond the exclusion zone

Thanks for your attention
Questions?

"We know how to start earthquakes, but we are still far from being able to keep them under control"

Jean-Philippe Avouac, *California Institute of Technology*

Photo: Eugene Richards, National Geograp