The 2010-2011 Canterbury earthquake sequence: from paleoseismology to policy

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SESE, Arizona State University, April 6, 2016
A $1.1 B question for central government

Is this what phased retreat looks like?

Bexley: A modern suburb built at sea-level in a designated high-risk flood zone on ChCh’s most liquefaction susceptible soils (1/75 to 1/100 yr threshold)
2003 – 13 June 2011

ΔE_{Tot} (m)

- >1.0
- 0.5 to 1.0
- 0.4 to 0.5
- 0.3 to 0.4
- 0.2 to 0.3
- 0.1 to 0.2
- 0.0 to 0.1
- 0.0 to -0.1
- -0.1 to -0.2
- -0.2 to -0.3
- -0.3 to -0.4
- -0.4 to -0.5
- -0.5 to -1.0
- >-1.0

Holocene sediments
Pleistocene sediments
Neogene volcanics
Mesozoic Metasediments

Greendale Fault Surface Rupture

Christchurch City
Former Alluvial Channel

Largest M_w Faults
Blind Faults

0 20 km
0 2 km
Christchurch: The Rockfall Prone City
Talk Outline

• Geologic, seismologic and societal context for the 2010-2011 Canterbury earthquake sequence
• CES environmental effects and paleoseismic precursors
• Can paleoseismology influence policy?
• Where to from here?
Geologic setting of NZ
Christchurch: a city built mostly on Holocene sediments at the diffuse, modestly deforming, eastern periphery of a tectonically active orogen

Quigley et al., Tectonophysics, 2016
Dense seismic and geodetic networks

Pre-mainshock lidar

A flat agricultural grid in the epicentral region

Christchurch: a densely instrumented and gridded natural sandbox

Ground motion characterization (4 Sept)
- 29 ground motion stations within 30km of the source
- Max values: horizontal PGA = 0.76g, vertical PGA = 1.30g, horizontal PGV = 115cm/s
- 5 stations with horizontal PGAs above 0.4g

5828 geodetic marks, 88849 cadastral marks within 100 km of rupture
2000-2010: A decade of blissful seismic quiescence beneath the Canterbury Plains

A NIMBY earthquake culture
No obvious ‘seismic hangover’ from earthquakes >140 yrs ago

A well documented liquefaction hazard
Mw max 7.2

A history of earthquake clustering
Highest decadal seismicity rates in the region near location of largest recent earthquakes (aftershocks?)

Seismologic and societal context

Seismicity Sept 1, 2000 to Sept 3, 2010
M ≥ 3.0, 0-15 km depth

1995 Cass M 6.2
1994 AP M 6.7
1994 M 6.0
1946 M 6.2
1869 Mw 4.8
1870 Mw 5.7

1995 M 6.0
1995 M 6.0
1994 M 6.0
1994 M 6.0
1869 Mw 4.8
1870 Mw 5.7

Data source: Geonet
Six years (and counting) of seismic activity

Data source: Geonet

Seismologic and societal context

Seismicity Sept 4, 2010 to July 1, 2013
M ≥ 3.0, 0-15 km depth

Decrease in seismicity rate

Increase in seismicity rate
G-R scaling of the CES and the preceding 60 yrs of seismicity in the same region

Comparison of pre-CES and CES Gutenberg-Richter statistics

**CES seismicity**

4 Sept 2010 - 4 Sept 2012
Lat° = -43.096 to -43.964
Long° = 171.947 to 173.404

\[ \log_{10} N(\geq m) = 6.78 - 1.07m \]
3.0 ≤ m ≤ 5.0  \( R^2 = 0.9995 \)

**pre-CES seismicity**

3 Sept 1940 - 3 Sept 2010
Lat° = -43.096 to -43.964
Long° = 171.947 to 173.404

\[ \log_{10} N(\geq m) = 5.29 - 0.97m \]
3.0 ≤ m ≤ 5.0  \( R^2 = 0.9859 \)

Quigley et al. 2016
Modified Omori’s Law Scaling:
The most likely time for a damaging earthquake to occur is immediately after a damaging earthquake has occurred.

Search and rescue, building inspections, land use planning, science communication

Quigley et al, 2016
Predicting earth science website traffic in natural disasters using a modified Omori-Utsu law for aftershock decay.
Continental earthquakes can be structurally complex

$GF M_o \approx 60\% CES M_o$

*importance of blind faults

The 2010-2011 Canterbury Earthquake Sequence

Quigley et al., Tectonophysics, 2016
Blind fault earthquakes can represent the highest shaking hazard.

Quigley et al., Tectonophysics, 2016
Earthquake comparisons: Counting the costs

<table>
<thead>
<tr>
<th>Date and Year</th>
<th>Mag (M_w)</th>
<th>Epicentre</th>
<th>Time</th>
<th>Max PGA</th>
<th>Casualties</th>
<th>Building Damage</th>
<th>Liquefaction</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 September 2010</td>
<td>7.1</td>
<td>30 km W</td>
<td>4:36 am</td>
<td>0.6g (0.3g CBD)</td>
<td>0 fatalities</td>
<td>To older brick &amp; URM</td>
<td>Widespread in eastern suburbs</td>
<td>4-5 billion</td>
</tr>
<tr>
<td>22 February 2011</td>
<td>6.2</td>
<td>10 km SE</td>
<td>12.51 pm</td>
<td>2.2g (0.8g CBD)</td>
<td>185 fatalities</td>
<td>All pre-1970s &amp; several modern buildings with eccentric design</td>
<td>Extreme damage in many eastern Christchurch suburbs</td>
<td>15-20 billion</td>
</tr>
<tr>
<td>13 June 13 2011</td>
<td>6.0</td>
<td>10 km SE</td>
<td>2.20 pm</td>
<td>2.2g (0.4g CBD)</td>
<td>0 fatalities</td>
<td>Further residential damage in Port Hills &amp; already damaged CBD buildings</td>
<td>Further damage in eastern Christchurch suburbs</td>
<td>c. 1.5 billion</td>
</tr>
<tr>
<td>23 December 2011</td>
<td>5.9</td>
<td>10 km E</td>
<td>3.18 pm</td>
<td>0.96g^4 (0.25g CBD)</td>
<td>0 fatalities</td>
<td>Minor, but several instances of progressive failure</td>
<td>Minor damage in eastern Christchurch suburbs</td>
<td>c. 26 million</td>
</tr>
</tbody>
</table>

Loss of life and most damage occurred in an ‘aftershock’
Most fatalities in two building collapses – building stock performed well from life safety perspective but poorly from a ‘post-event functionality’ perspective
Five geologic fatalities

Berryman, 2012
Earthquake environmental effects: surface rupture

Quigley et al., 2012
Rupture-induced river avulsion

Damage to lifelines

Land-damage: livestock impacts

Damage to structures

Characterisation of fault rupture displacements, impacts, and future hazards
High resolution datasets

Airborne lidar

Terrestrial lidar

Lidar differencing
Analogue modelling of surface ruptures:
What controls rupture morphology and displacement variations? Where is the best place to site a trench, and what fractures will most faithfully record prior earthquakes? Predicting rupture morphologic evolution

TALC: t = 2 cm, d=15 mm
Fault rupture behaviour in time and space

Hornblow et al., Tectonophysics, 2014
Digging laterally along fault to expose paleochannel cross-sections and measure piercing points (channel facies and margins)
The penultimate earthquake:
Between ~22 and ~28 ka
Consistent slip-at-a-point

2010 offset measured along structure on surface \( H = 60 \pm 10 \text{ cm} \)

Offset on upper channel:
\( H = 65 \text{ cm, } V = 10 \text{ cm} \)

Offset on lower channel:
\( H = 120 \text{ cm, } V = 20 \text{ cm} \)

OSL age 21.6 ± 1.5 ka

OSL age 28.4 ± 2.4 ka

Hornblow et al., Tectonophysics, 2014
Coulomb ‘static’ stress evolution for rupture initiating on CCF

CCF on Darf NW

CCF on GF

Darf NW on H

Keystone fault vs. dominoes

Courtesy: Abigail Jimenez, Sandy Steacy
Liquefaction
Geologic expressions of liquefaction

Quigley et al Tectonophysics
Avonside Liquefaction Laboratory: severe and recurrent liquefaction
11 episodes in Christchurch during 2010-2011 CES

Definition of liquefaction-triggering PGA, improved understanding of recurrent liquefaction, and development of new empirical equations with predictive capacity

Paleoliquefaction investigations
Predicting site responses under future seismic loading
Delineating hazardous areas

Bastin et al., GSAB, 2015
Rockfall
Recurrent rockfall and cliff collapse during the 2010-2011 Canterbury earthquake sequence

Massey et al., Eq Spectra, 2014 Mackey and Quigley, Geology, 2014; Quigley et al., Tectonophysics, 2016
Rockfall and boulder roll

Mackey, B., and Quigley, M., (2014) Strong proximal earthquakes revealed by cosmogenic $^3$He dating of prehistoric rockfalls, Christchurch, New Zealand, *Geology*
Cliff collapse, fatalities, and near misses
Empirically-defined calculations of seismologic thresholds for rockfall triggering for different rockmass fragility

Mackey and Quigley, Geology, 2014
Paleo-rockfall deposits

Mackey and Quigley, 2014 Geology; Borella et al. in review, Nat Geosci
Cosmogenic $^3$He dating of paleo-boulder surfaces as proxy for emplacement age

Mackey, B., and Quigley, M., (2014)
Strong proximal earthquakes revealed by cosmogenic $^3$He dating of prehistoric rockfalls, Christchurch, New Zealand, *Geology*
OSL, IRSL and $^{14}$C dating of colluvium underlying and aggraded upslope of boulders

Sohbati et al 2016; Borella et al., 2016
Comparison of paleo- and contemporary rockfall distributions

Borella, J., Quigley, M., Vick, . (in review) Anthropocene rockfalls exceed limits of prehistoric predecessors, PNAS
Modelling of paleo- and contemporary rockfall distributions

Borella, J., Quigley, M., Vick, . (in review) Anthropocene rockfalls exceed limits of prehistoric predecessors, PNAS
Paleoseismology and land use planning
Bad decisions and implementation of operational earthquake forecasting

Post Darfield, pre 22 Feb 2011 earthquake

Post Dec 2011

Canterbury region long-term probabilities

<table>
<thead>
<tr>
<th>Magnitude range</th>
<th>Expected range</th>
<th>Expected average</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0 - 5.4</td>
<td>0 - 5</td>
<td>1.9</td>
<td>85%</td>
</tr>
<tr>
<td>5.5 - 5.9</td>
<td>0 - 3</td>
<td>0.9</td>
<td>45%</td>
</tr>
<tr>
<td>6.0 - 6.4</td>
<td>0 - 1</td>
<td>0.2</td>
<td>15%</td>
</tr>
<tr>
<td>6.5 - 6.9</td>
<td>0 - 1</td>
<td>0.07</td>
<td>7%</td>
</tr>
<tr>
<td>7.0 - 7.9</td>
<td>0 - 1</td>
<td>0.02</td>
<td>2%</td>
</tr>
</tbody>
</table>

This table was last updated.
Fault zone land use policy: the race against recovery

Paleoseismologic investigations (RI, SR)

Policy making and rebuilding

TIME

Avoidance

Greendale Fault: Fault Avoidance Zones
- Fault Avoidance Zone - well defined
- Fault Avoidance Zone - distributed
- Fault Avoidance Zone - uncertain
Liquefaction: ‘red zone’ criteria

- significant and extensive area wide land damage;
- success of engineering solutions may be uncertain in terms of design, its success and possible commencement, given the ongoing seismicity;
- any repair would be disruptive and protracted for landowners.

Probabilistic assessment of liquefaction in the next 50 years based on earthquake forecasting models and liquefaction triggering thresholds.
Independent paleoseismic tests of earthquake forecasts:

Targeted paleoliquefaction studies based on susceptibility (site conditions)

RED = multiple liquefaction episodes in last 2 kyr

GREEN = no evidence for liquefaction
Microzonation of susceptible areas for land use planning – possible?

Difference between river and nearest downslope freeface azimuth

Threshold for avoiding worst land damage
Rockfall: ‘red zone’ criteria and societal tolerance

\[ R_{(LoL)} = P(H) \times P(S:H) \times P(T:S) \times V(D:T), \]

Massey et al. 2014
Delineation of seismic sources capable of rockfall generation using empirical thresholds and GMPEs: The tension between statistical forecasts and geology

Mackey, B., and Quigley, M., (2014) Strong proximal earthquakes revealed by cosmogenic $^3$He dating of prehistoric rockfalls, Christchurch, New Zealand, Geology
Limitations to paleoseismic data

• Applicability of one study site to another unstudied site
• Distinguishing clustered from single events
• Coarse temporal resolution of geology compared to rebuilding / engineering timeframes
• Easily comprehended geologic uncertainties compared to statistic uncertainties
“Dr. Quigley could not dismiss outright the possibility of future strong earthquakes, and said even though we find very little evidence for that from a geologic perspective we cannot completely discount that possibility.”
Where to from here?
Predicting the impacts of future earthquakes under different site conditions and seismic characteristics

Quigley et al., 2016
APPLIED EARTH SCIENCE FOR INSURANCE CLAIMS:

Geologic controls on ground deformation and building damage and pre-CES seismicity
Conclusions

• The 2010-2011 CES is one of the best recorded earthquake sequences in history; combination of seismologic and geodetic data with field observations provides empirical evidence of triggering thresholds for earthquake effects

• Every environmental effect observed during the 2010-2011 CES had a paleoseismic predecessor of similar severity and extent; these were all identified retrospectively

• The recurrence intervals and severity of different effects vary as a function of phenomenon, seismologic thresholds and age

• Paleoseismic data could have been better utilized prior to development, but it is challenging to implement many paleoseismic datasets into land use planning during the recovery and rebuild phase

• Science has richly informed short-term policy in this instance; will it do so in the future?
Additional reading


Duffy, B., Quigley, M., et al. (2013) Fault kinematics and surface deformation across a releasing bend during the 2010 MW7.1 Darfield, New Zealand, earthquake revealed by differential LiDAR and cadastral surveying, *GSA Bulletin 125 (3-4) p. 420-431*