Investigating Liquefaction Effects in Christchurch, New Zealand

Jonathan Bray, Ph.D., P.E., NAE
Faculty Chair in Earthquake Engineering Excellence

with M. Cubrinovski, J. Zupan, C. Markham, C. Beyzaei, R. Luque, M. Riemer, M. Stringer & M. Taylor

University of California - Berkeley & Univ. of Canterbury

Sponsors: National Science Foundation & Earthquake Commission New Zealand
Acknowledgements

Graduate Students & Post-Docs:

- Josh Zupan, Merrick Taylor, Chris Markham, Christine Beyzaei, Kelly Robinson, Anna Winkley, Duncan Henderson, Yasuyo Hosono, Matthew Hughes, Kun Ma, Simona Giorgini, Masoud Moghaddasi, Catherine Tatarniuk, Yusa Muhamed, Jawad Arefi, Patrick Kailey, Kelvin Loh, ...

Collaboration with:

- Tom O’Rourke of Cornell Univ., R. Green of Virginia Tech, B. Bradley of Univ. of Canterbury, K. Stokoe & B. Cox of Univ. of Texas at Austin, L. Wotherspoon of U. of Auckland, S. van Ballegoooy, M. Jacka, R. Wentz & others of Tonkin & Taylor, US-GEER team, Univ. of California, Berkeley, Univ. of Arkansas, JGS team, Kiso-Jiban Cons., McMillan Drilling Ser., Fugro, CERA, NHRP, CCC

Financial support:

- U.S. National Science Foundation
- EQC (NZ Earthquake Commission)
- MBIE (NZ government)
- Natural Hazards Research Platform & UC
- ECan (Environment Canterbury)
George F. Sowers
OUTLINE

- Christchurch Geologic Setting
- 2010-2011 Canterbury Earthquakes
- Widespread Liquefaction Effects
- Site Investigations
- Evaluation of Liquefaction Effects
- Conclusions
Canterbury Plains
East-West Cross Section through Christchurch

- Ground surface
- Water table
- Top of Riccarton Gravel
- CBD

From M. Cubrinovski
Streams in Central Christchurch (from 1850’s ‘Black Maps’)

from M. Cubrinovski
Subsurface Profile at Kilmore St. in Zone 1

MADE GROUND: Sandy gravel

SILTY SAND: Grey, fine silty sand/ silt with fine sand [SM/ ML] [SPRINGSTON FM]

MEDIUM SAND: Brown, medium sand. [SP] [CHRISTCHURCH FM]

SILT-CLAY: Grey silt-clay with fine sand, some peat. [ML/ MH] [CHRISTCHURCH FM]

Taylor et al. 2012

RICCARTON GRAVEL
$I_c$ – Fines Content Correlations

Robinson, Cubrinovski, & Bradley 2013

CBD Data from Taylor 2014 & Zupan 2014

Idriss & Boulanger 2008
Grain-Size Composition of Soils

Sand ejecta samples from areas in Christchurch

- Clean fine sands and non-plastic silty sands
- Does soil ‘know’ that the #200 sieve exists?

(Courtesy of M. Pender, Univ. of Auckland)
Particle Shape of Soils

Soil sample Site 3 Natural Soil Panel 1 at -1.76m R.L at 50x magnification.

Soil sample Site 4 Natural Soil Panel 2 at -1.94m R.L at 50x magnification.

EQC funded work by Tonkin & Taylor & Others
2010-2011 Canterbury Earthquakes

- 185 fatalities in the 22 FEB 2011 Christchurch M 6.2 Earthquake
- Central Business District (CBD) destroyed
- 20,000 residential properties severely affected & 8,000 abandoned
- 700 km of waste water pipes with loss/limited service
- Total economic loss: ~ NZ$30B (25% of its GDP)
2010-2011 Canterbury Earthquake Sequence

- **Mw = 7.1**
  - 4 Sept 10

- **Mw = 6.2**
  - 22 Feb 11

- **Mw = 5.9**
  - 23 Dec 11

- **Mw = 6.0**
  - 13 June 11

GNS Science
Seismic Demand in CBD

13 JUN 11
$D_{5-95} = 11\ s$

22 FEB 11
$D_{5-95} = 10\ s$

26 DEC 10
$D_{5-95} = 4\ s$

4 SEP 10
$D_{5-95} = 25\ s$

SIR = $I_{a\ 5-75}/D_{5-75}$

REHS 092 Recordings (GeoNet)
Canterbury EQs: Widespread Liquefaction

Cubrinovski et al. 2011
Liquefaction from 3+ EQs (Cubrinovski 2011)

Base Map – 22 Feb 2011 – M$_w$ = 6.2
White Areas – 4 Sep 2010 – M$_w$ = 7.1
Black Areas – 13 Jun 2011 – M$_w$ = 6.0
Repeated Liquefaction Events

4 Sept 2010

22 Feb 2011

16 April 2011

13 June 2011: Part 1

13 June 2011: Part 2

(Mark Quigley: Avonside)
Age of Christchurch Soils

from M. Cubrinovski
Liquefaction Effects in Christchurch

From M. Cubrinovski
Seismic Performance of Buried Utilities

22 February 2011 Mains Faults

22 February 2011 Liquefaction
- Moderate to Severe
- Low to Moderate
- Road Liquefaction
- Trace

Pipe Materials
- Polyethylene
- Polyvinyl Chloride
- Other

from M. Cubrinovski
Effects of Liquefaction on Water Mains

No failure of HDPE pipes installed after 2010 Darfield EQ

from M. Cubrinovski

from T. O’Rourke
Liquefaction in Christchurch

(van Ballegooy et al. 2014)
CPT Investigations at Shallow Gravel Sites

CPT Z2-8 in July 2011: refusal at only 3.4 m

CPT Z2-16 in March 2013: advanced to 9 m with pre-collaring
CPT Investigations at Shallow Gravel Sites

Pre-Collaring System (developed by I. Haycock, McMillan Drilling Services)
CPT Investigations at Shallow Gravel Sites

CPT Z2-30 in April 2013: advanced through gravel with 20 ton truck

qc = 60+ MPa

DENSE GP

Depth (m)

Fugro
Capturing Liquefaction Effects

Liquefaction Potential Index  \( (\text{Iwasaki et al. 1982}) \)

\[
LPI = \int_0^{20} F_1 W(z) \, dz
\]

\[
W(z) = 10 - 0.5z
\]

\[
F_1 = 1 - FS \text{ for } FS < 1.0, \quad F_1 = 0 \text{ for } FS \geq 1.0,
\]

\( z = \text{depth (m) below the ground surface} \)

Liquefaction Severity Number  \( (\text{van Ballegooy et al. 2014}) \)

\[
LSN = 1000 \int \frac{\varepsilon_v}{z} \, dz
\]

\( \varepsilon_v = \text{post-liquefaction volumetric reconsolidation strain (decimal)} \)

\( z = \text{depth (m) below the ground surface} > 0.0 \)
Post-Liquefaction Volumetric Strain ($\varepsilon_v$)

Clean sands

$\gamma_{\text{max}} = 1.5 \epsilon_{1\text{max}}$

$LSN = 1000 \int \frac{\varepsilon_v}{z} \, dz$

Ishihara & Yoshimine 1992
Post-Liquefaction Volumetric Strain ($\varepsilon_v$)

\[ LSN = 1000 \int \frac{\varepsilon_v}{z} \, dz \]
Capturing Liquefaction Effects

\[ LSN = 1000 \int \frac{\varepsilon_y}{z} \, dz \]

\( LSN \) considers when \( FS > 1 \)

\( LSN \) limited by \( \max \varepsilon_y \)

\( LSN \) affected by \( D_r \)

\( LSN \) heavily weights shallow layers

\[ LPI = \int_0^{2.0} F_1 W(z) \, dz \]

van Ballegooy et al. 2014
Capturing Liquefaction Effects

van Ballegoooy et al. 2014
Liquefaction in Christchurch

Ground Surface Observations
- No cracking or observed sand ejection
- Minor cracking, no observed sand ejection
- Minor to moderate sand ejection
- Severe sand ejection, no lateral spreading
- Sand ejection and moderate lateral spreading
- Sand ejection and severe lateral spreading

(van Ballegooey et al. 2014)
Liquefaction of Silty Sands

CPT at Christchurch site where no liquefaction effects were observed

(from R. Wentz, Wentz-Pacific)
Liquefaction of Silty Sands

Evaluation of 4 CPTs at site where no liquefaction effects were observed

(from R. Wentz, Wentz-Pacific)
Observations of Liquefaction Ejecta

van Ballegoooy et al.
Tonkin & Taylor for the EQC
Central Business District of Christchurch

Strong Motion Station

Liquefaction 22 FEB 2011

UCB/UC Study Zones
## Seismic Demand in CBD

<table>
<thead>
<tr>
<th>Event</th>
<th>Median CSR&lt;sub&gt;M7.5&lt;/sub&gt;</th>
<th>Level of Liquefaction in CBD</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 SEP 10 M&lt;sub&gt;w&lt;/sub&gt; = 7.1</td>
<td>0.12 (0.10 – 0.17)</td>
<td>Low</td>
</tr>
<tr>
<td>26 DEC 10 M&lt;sub&gt;w&lt;/sub&gt; = 4.8</td>
<td>0.07</td>
<td>None</td>
</tr>
<tr>
<td>22 FEB 11 M&lt;sub&gt;w&lt;/sub&gt; = 6.2</td>
<td>0.20 (0.16 – 0.28)</td>
<td>Severe</td>
</tr>
<tr>
<td>13 JUN 11 M&lt;sub&gt;w&lt;/sub&gt; = 6.0</td>
<td>0.09 (0.08 – 0.15)</td>
<td>Low</td>
</tr>
<tr>
<td>23 DEC 11 M&lt;sub&gt;w&lt;/sub&gt; = 5.9</td>
<td>0.10</td>
<td>Low</td>
</tr>
</tbody>
</table>

**CSR<sub>M7.5</sub>** = 0.65 (PGA/g) / MSF  
**MSF** = 6.9 exp(-M<sub>w</sub>/4) – 0.058 ≤ 1.8  
Median PGA from recordings; 16% - 84% PGA from Bradley and Hughes (2012)
Liquefaction Effects on Structures

- Tilting and Sliding of Buildings
  - 15 cm
  - 1.8°

- Settlement of Ground next to Piled Bldg.
  - 30 cm

- Cracking due to Differential Settlement
  - β = 1/70

- Tilt of Tall Buildings
Central Business District of Christchurch

CBD STUDY ZONES:
107 UCB-UC CPTs
13 UCB-UC BHs
34 CGD CPTs
8 CGD BHs
Variability in Shallow Soils
Car Park on Corner of Armagh and Madras Streets

CTUC Building

Severe Liquefaction

UC Berkeley / Univ. of Canterbury CPTs by McMillan Drilling Services
Variability in Shallow Soils
Car Park on Corner of Armagh and Madras Streets

No-to-Minor Liquefaction || Severe Liquefaction

Elevation (m)

Horizontal Scale

Liquefiable SM/ML

Liquefiable SP/SM

qt (MPa)
CTUC Building
Liquefaction-Induced Differential Settlement Induces Distress

Building Settlement (cm)
Maximum Angular Distortion $\approx 1/50$

GEER: Bray, Cubrinovski et al.
CTUC Building

Severe Liquefaction Zone

Datum Building

Z4-6 (14.30m)

Z4-4 (13.98m)

Z4-5 (24.92m)

Adjacent Building

Z4-7 (18.28m)

Z4-28 (24.62m)

Z4-10 (17.28m)

Z4-18

Z4-19

Z4-8

Armagh Street

Madras Street

Armagh and Madras Parking Lot
CTUC Building: Christchurch EQ

CTUC Building Settlement

Actual Settlement

~40 cm
~15 cm
~15 cm
~10 cm
~5 cm

CTUC Building: Sensitivity of Results

SA Building
Liquefaction-Induced Differential Settlement

GEER: Bray, Cubrinovski et al.
SA Building
Liquefaction-Induced Differential Settlement

Z8-7 (10.14m)
Z8-14 (9.04m)
Z8-11 (7.3m)
Z8-15 (21.23m)
Z8-6 (17.86m)

10-20cm
25cm

Adjacent Building

Peterborough Street

2011 Christchurch EQ

Scale is approximate
SA Building: Christchurch EQ

SA Building: Sensitivity of Results

PWC Building
Liquefaction-Induced Differential Settlement and Tilt

21 stories on basement mat
PWC Building

Cyclic Triaxial Test Results

CSR = σ_d/(2σ_c)

FC = 4 to 8%
FC = 22 to 26%

Cycles to ε_{ax-S.A.} = 3%

Upper Soil--Field
Lower Soil--Field

CTUC Building Shallow Soils

Ph.D. Students: C. Markham & C. Beyzaei
“Undisturbed” Soil Sampling & Testing

D&M Thin-Walled Piston Sampler

Careful Handling

Cut

Extrude

Test
Calibration of Constitutive Model for Numerical Analyses

FTG-7 Building

Ph.D. Students: C. Markham & R. Luque
LIQUEFACTION

- 1906 San Francisco EQ (Lawson et al. 1908)
- 1989 Loma Prieta EQ

EFFECTS

- 1964 Niigata, Japan EQ (from H.B. Seed)
LIQUEFACTION EFFECTS

Flow Liquefaction
(strain-softening \(\Rightarrow\) large strain)

Cyclic Mobility
(strain-hardening \(\Rightarrow\) limited strain)
LIQUEFACTION Factor of Safety (FS)

FS = CRR / CSR

Normalized corrected CPT tip resistance, $q_{c1N}$

CRR

Derived Curve for FC = 35%

Idriss & Boulanger (2004) for Clean Sands

Fines Content, FC
[data points from Moss (2003)]

Liquefaction Effects Observed at Ground Surface

No Liquefaction Effects Observed at Ground Surface

FS = 1.2

Idriss & Boulanger 2008
Liquefaction Flow Slides when $q_{c1Ncs-Sr} < 85$

Equivalent clean sand CPT normalized corrected tip resistance, $q_{c1Ncs-Sr}$

Idriss & Boulanger 2008
CONCLUSIONS

• Liquefaction severely damaged ground, buildings, and buried utilities in Christchurch.

• Loose shallow silty sand layer led to much of the damage in CBD, especially in areas with ejecta.

• Shear-induced deformation is critical mechanism.

• Current analytical procedures do not capture effects of liquefaction well in Christchurch.

• Each EQ was well recorded, so there is an opportunity to refine analytical procedures.
RECOMMENDATIONS

For level ground conditions with no free-face:

Pile foundation with its neutral plane in firm ground below the liquefiable layer will not settle significantly.

Shallow foundation with deep liquefiable layer will largely undergo volumetric reconsolidation that can be estimated using 1D procedures.

Shallow foundation with shallow liquefiable layer can undergo largely shear-induced movements that cannot be estimated using available 1D procedures.

Effective stress analyses based on good earthquake & soil characterization can provide useful insights.