Geotechnical Extreme Events Reconnaissance
Turning Disaster into Knowledge

Investigating Liquefaction Effects in Christchurch, New Zealand

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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

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Graduate Students & Post-Docs:

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Collaboration with:

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- EQC (NZ Earthquake Commission)
- MBIE (NZ government)
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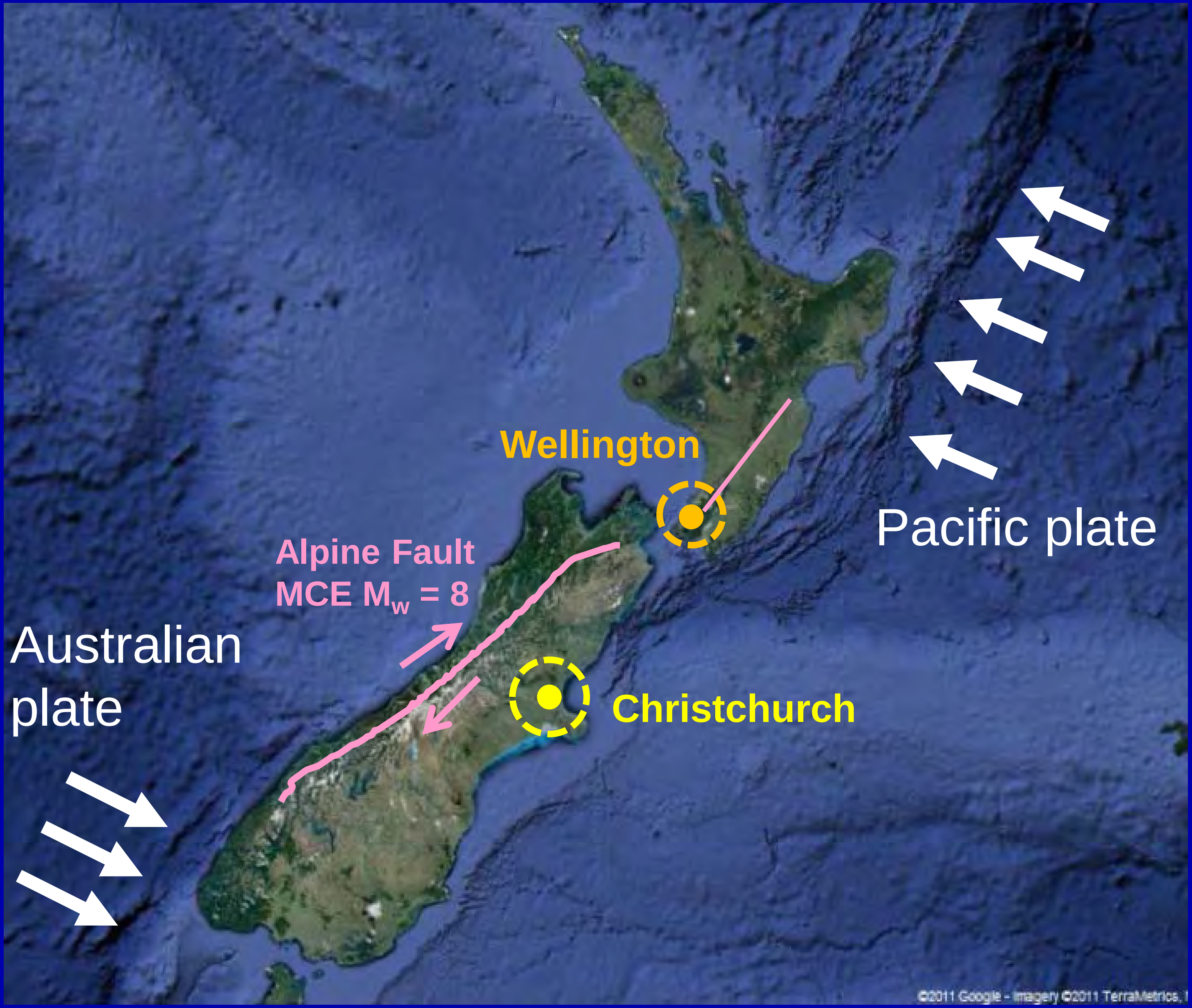
- ECan (Environment Canterbury)

George F. Sowers

OUTLINE

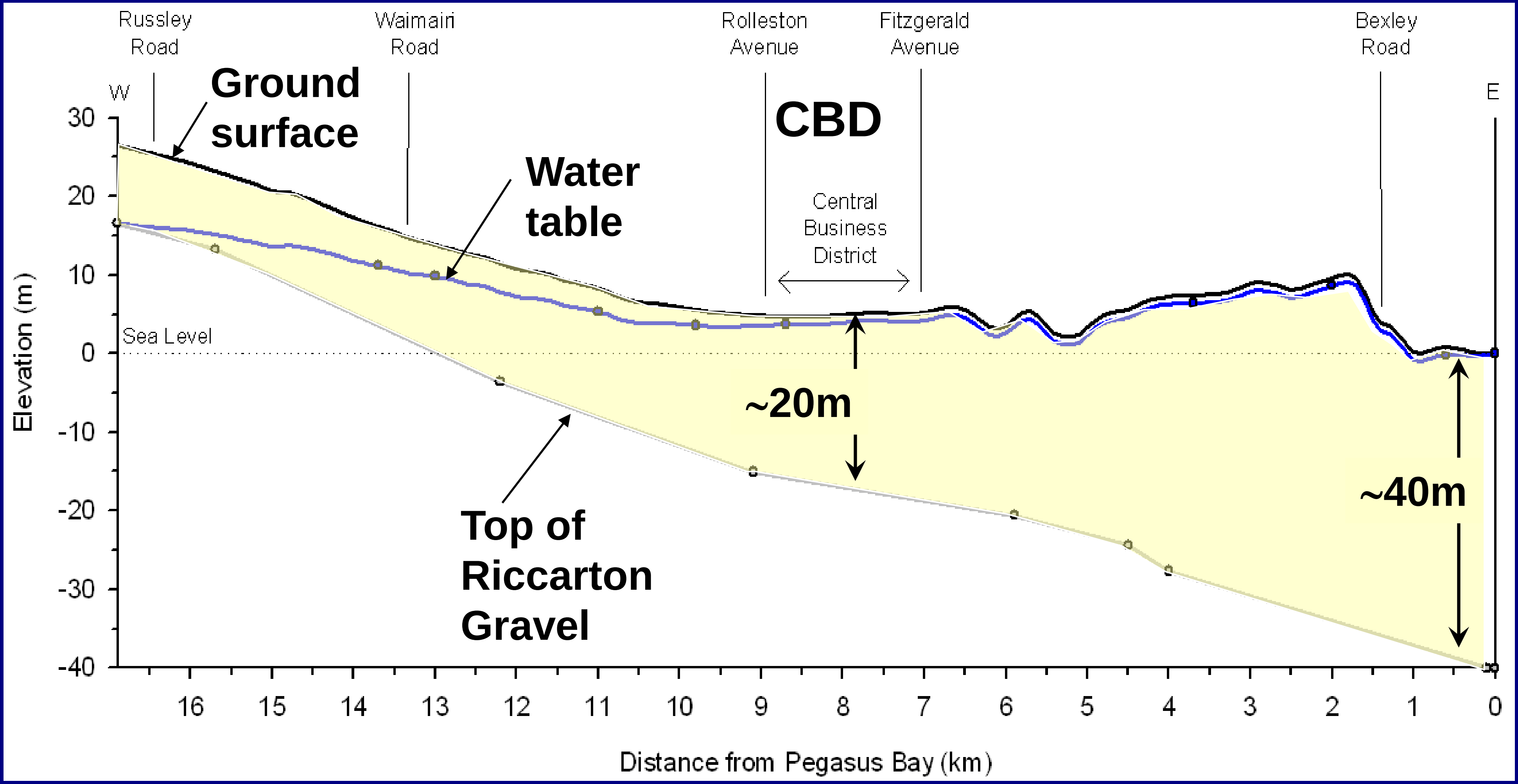
- Christchurch Geologic Setting
- 2010-2011 Canterbury Earthquakes
- Widespread Liquefaction Effects
- Site Investigations
- Evaluation of Liquefaction Effects
- Conclusions

New Zealand


Wellington
Alpine Fault
MCE M_w = 8
Australian plate
Christchurch
Pacific plate
©2011 Google - Imagery ©2011 TerraMetrics

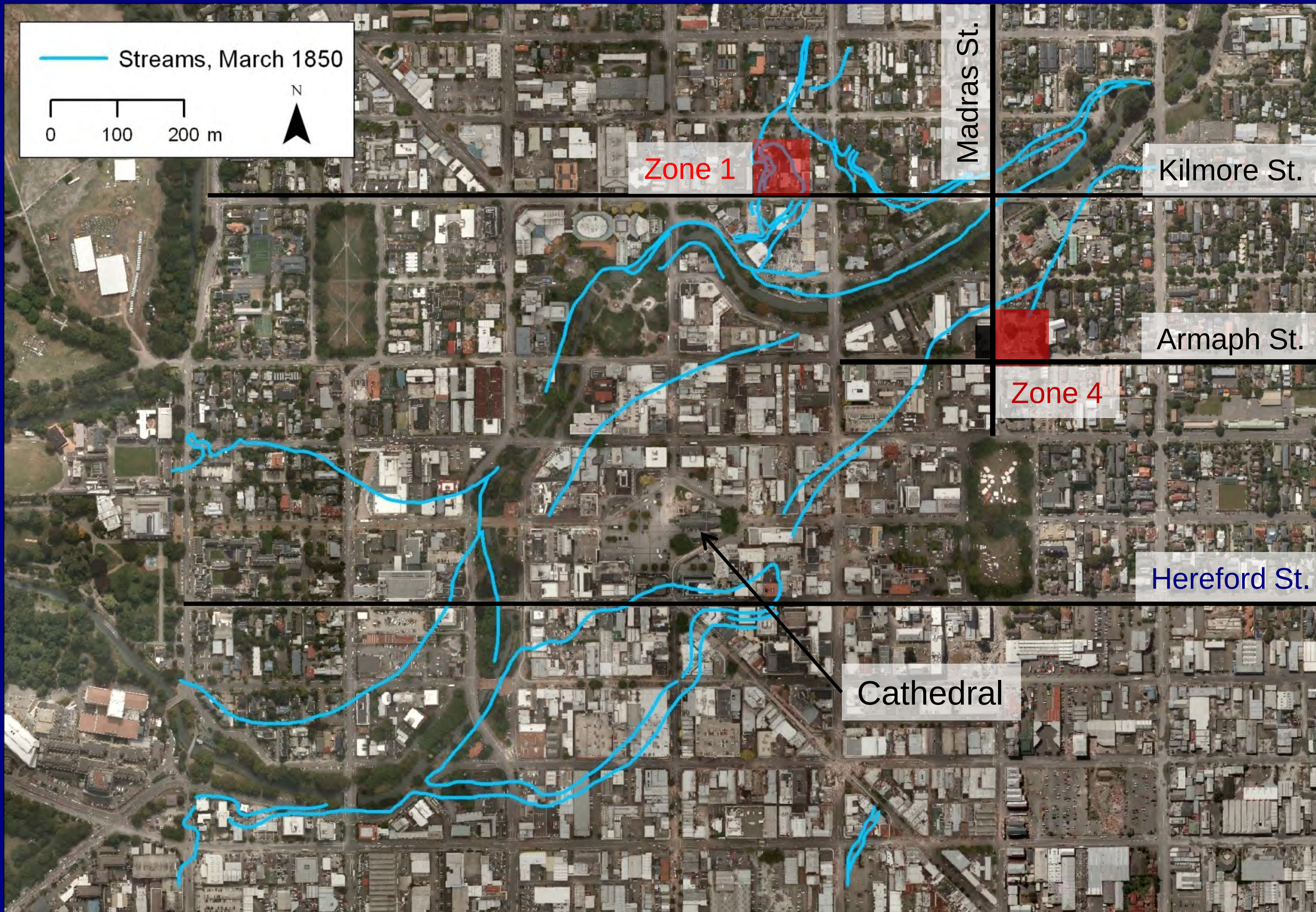
Canterbury Plains

East-West Cross Section through Christchurch



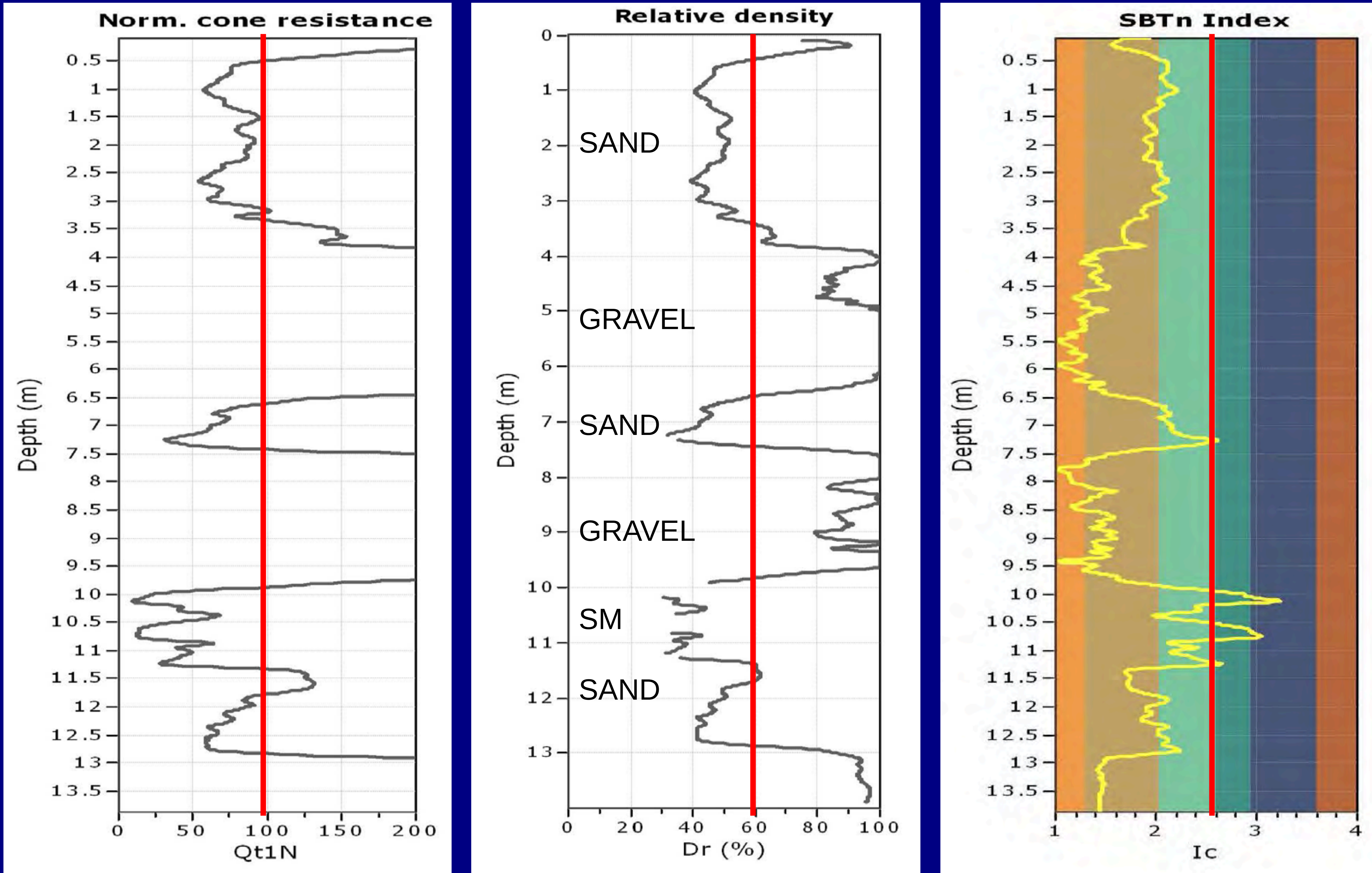
from M. Cubrinovski

Streams in Central Christchurch (from 1850's 'Black Maps')

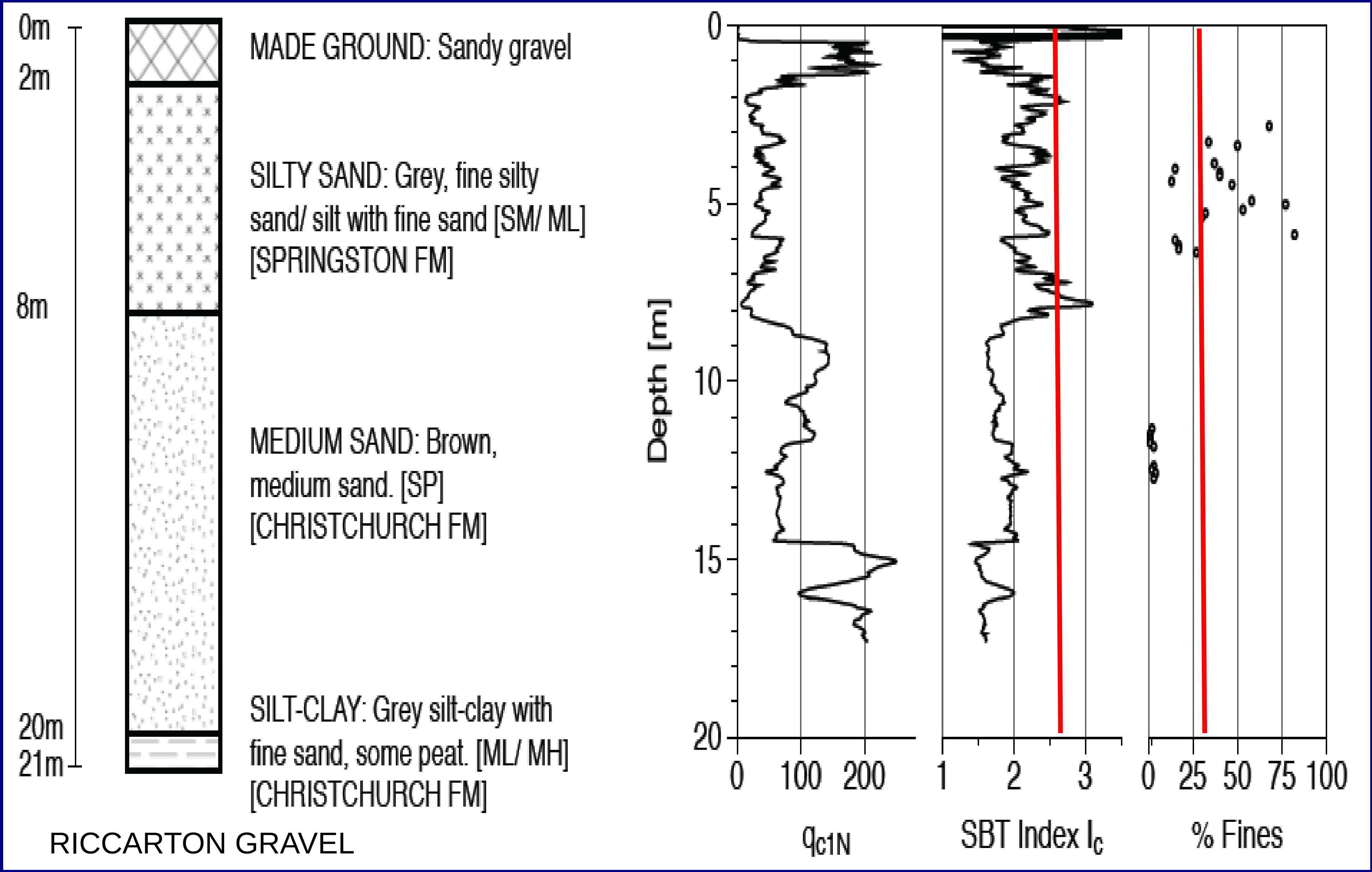


from M. Cubrinovski

Subsurface Profile: Madras & Armagh, Zone 4

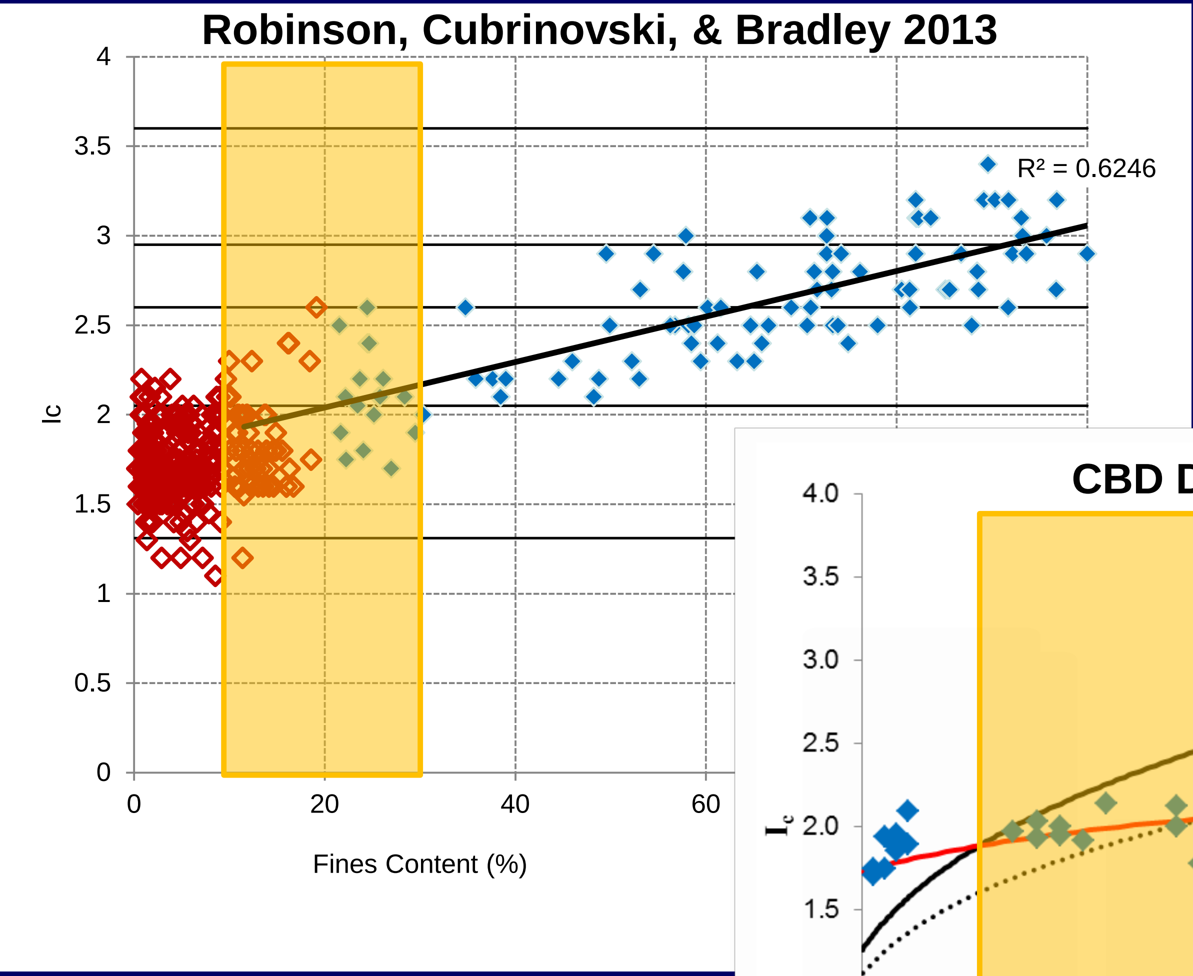


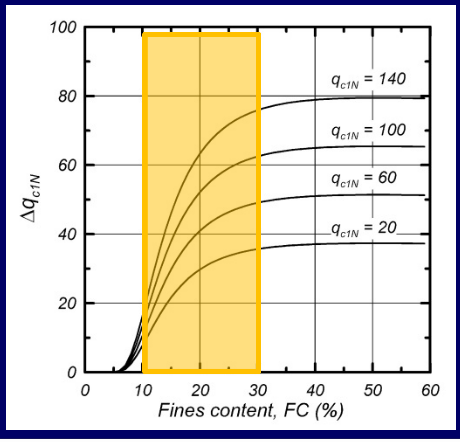
Subsurface Profile at Kilmore St. in Zone 1



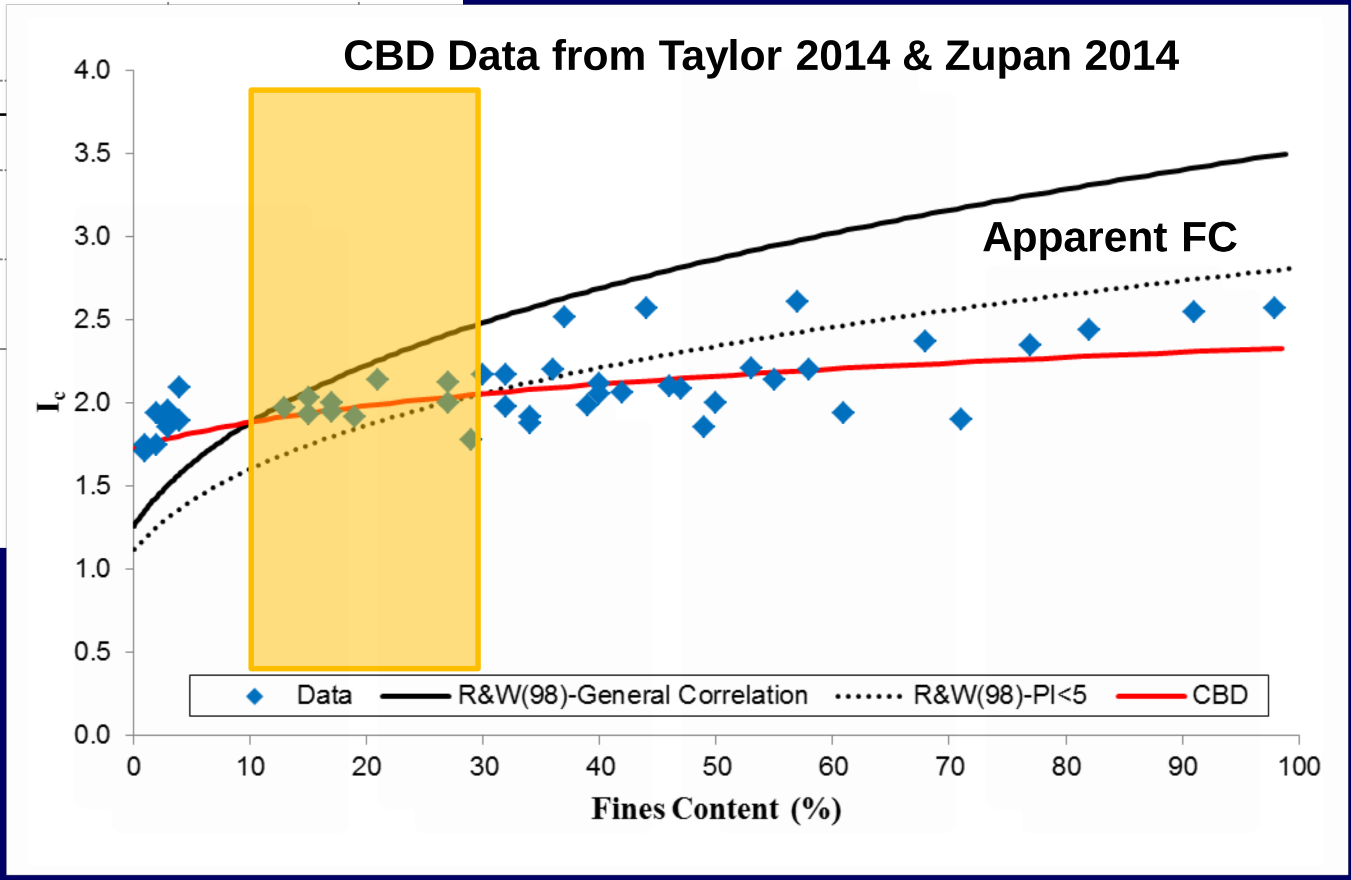
Taylor et al. 2012

I_c – Fines Content Correlations



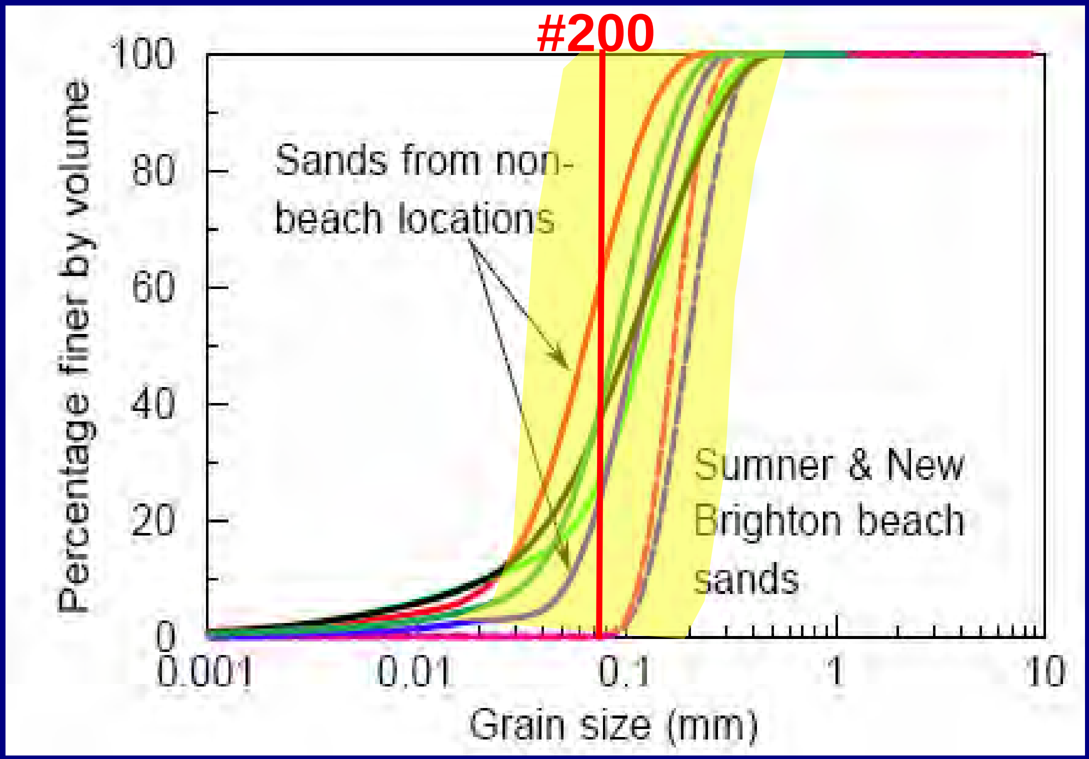


Idriss & Boulanger 2008



Grain-Size Composition of Soils

Sand ejecta samples from areas in Christchurch

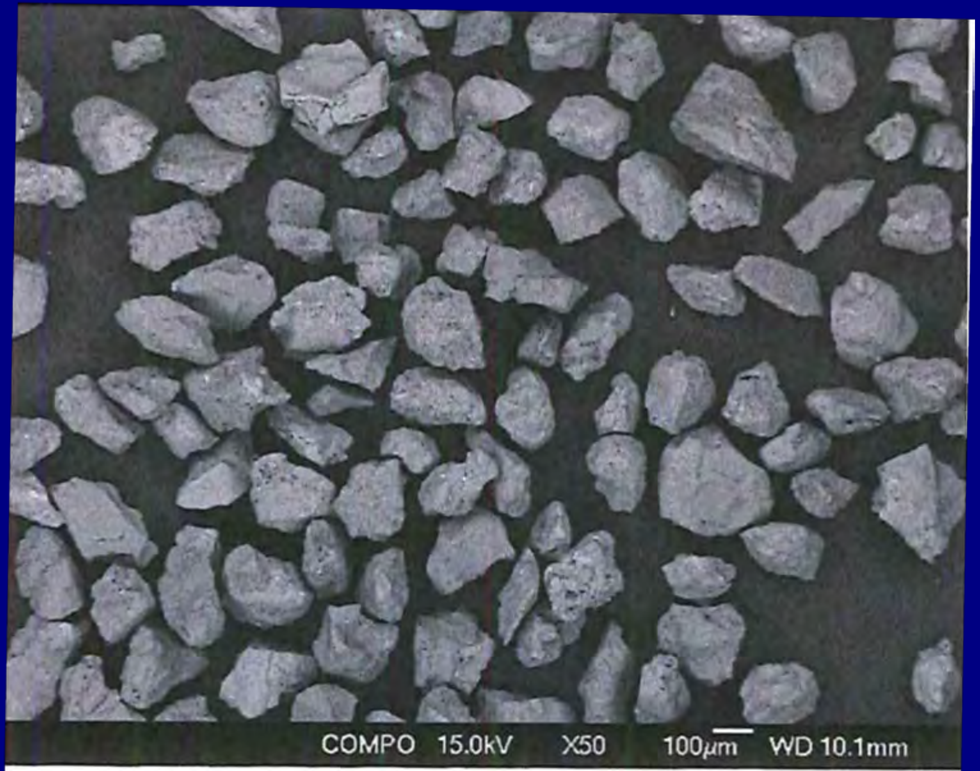


(Courtesy of M. Pender, Univ. of Auckland)

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

Particle Shape of Soils

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



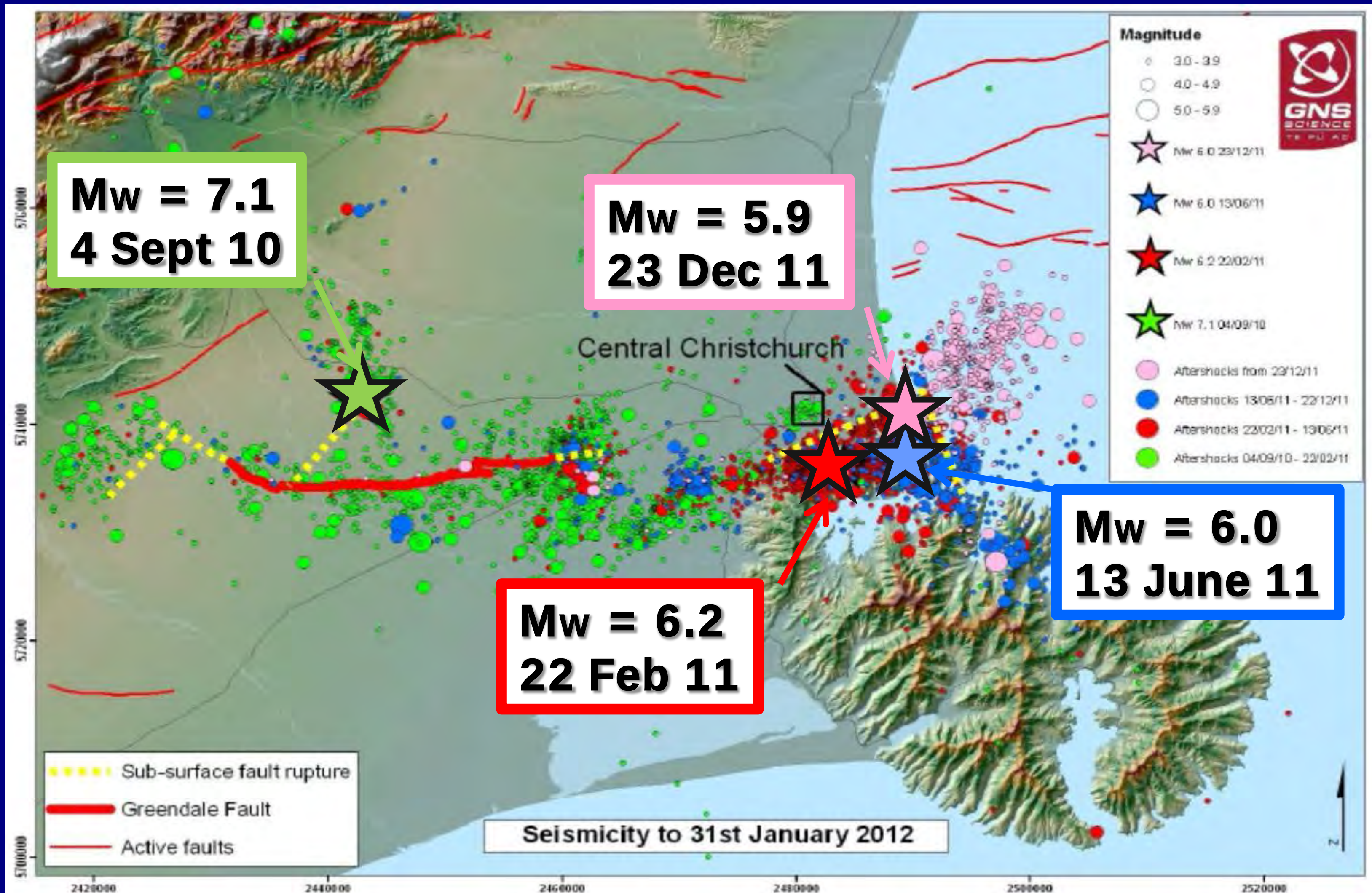
Soil sample Site 4 Natural Soil Panel 2 at -1.94m R.L at 50x magnification.

EQC funded work by Tonkin & Taylor & Others

2010-2011 Canterbury Earthquakes

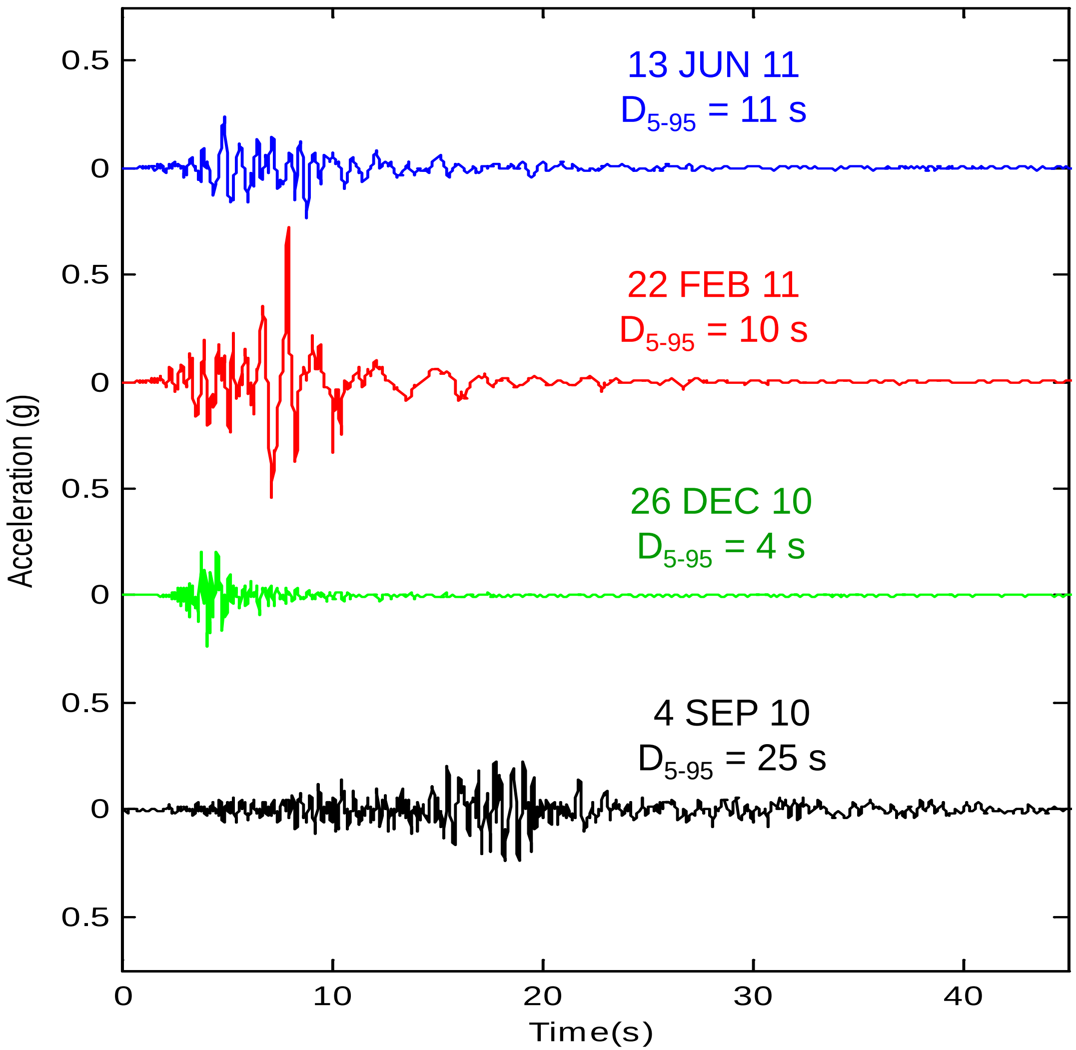
- 185 fatalities in the 22 FEB 2011 Christchurch M 6.2 Earthquake
- Central Business District (CBD) destroyed
- 20,000 residential properties severely affected & 8,000 abandoned
- 700 km of waste water pipes with loss/limited service
- Total economic loss: ~ NZ$30B (25% of its GDP)

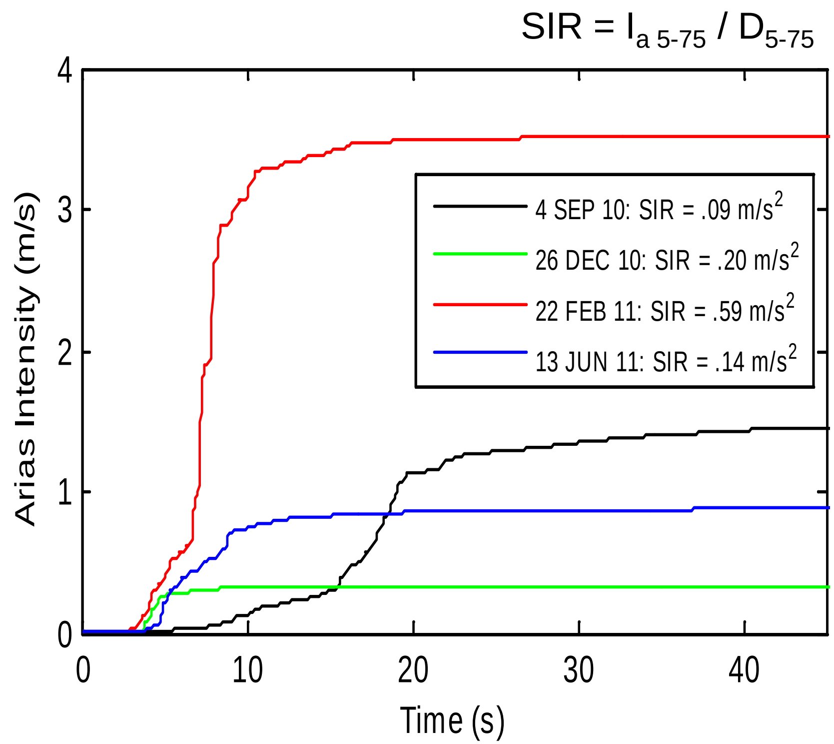
2010-2011 Canterbury Earthquake Sequence



GNS Science

Seismic Demand in CBD



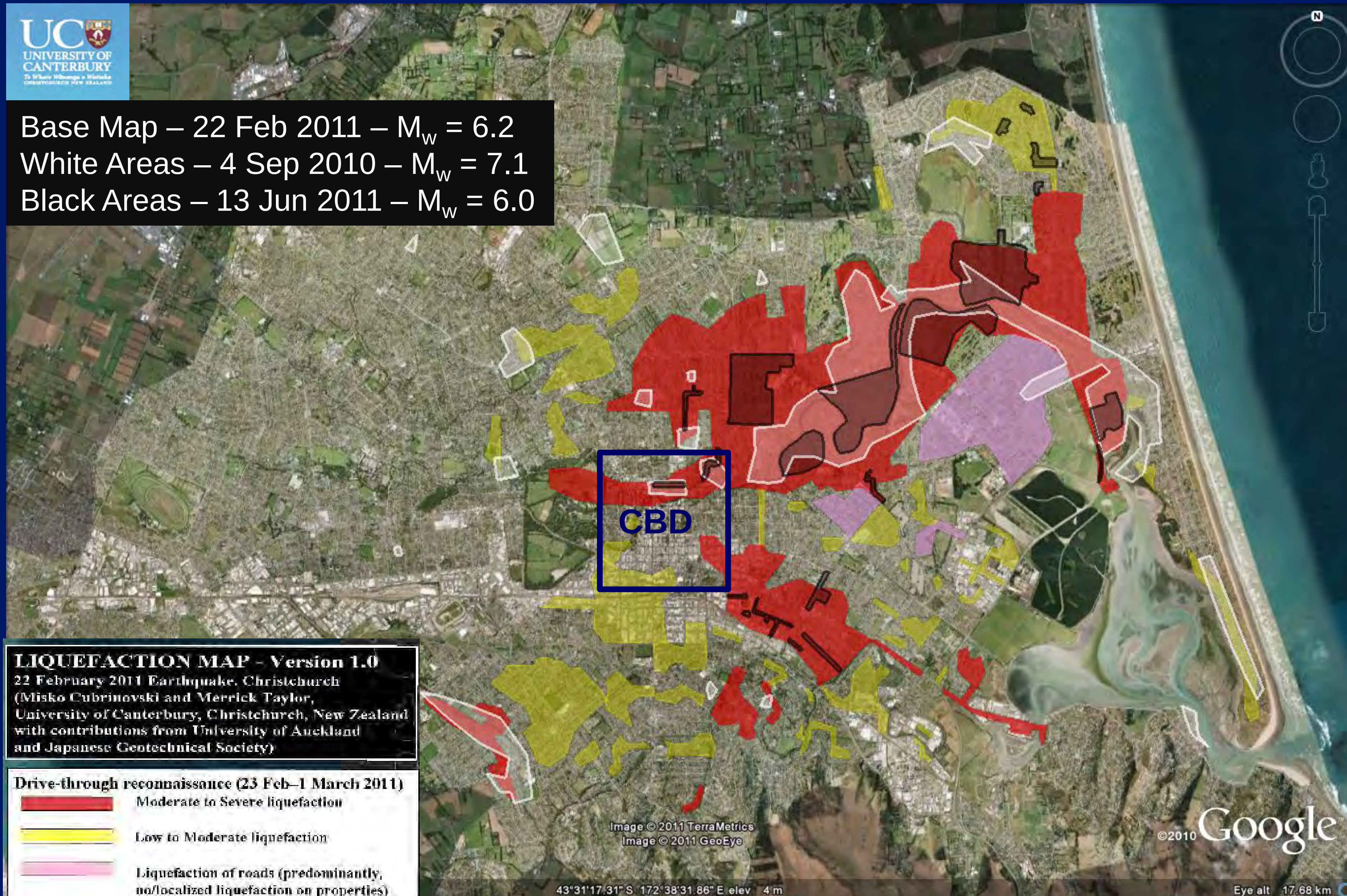


REHS 092 Recordings (GeoNet)

Canterbury EQs: Widespread Liquefaction

Cubrinovski et al. 2011

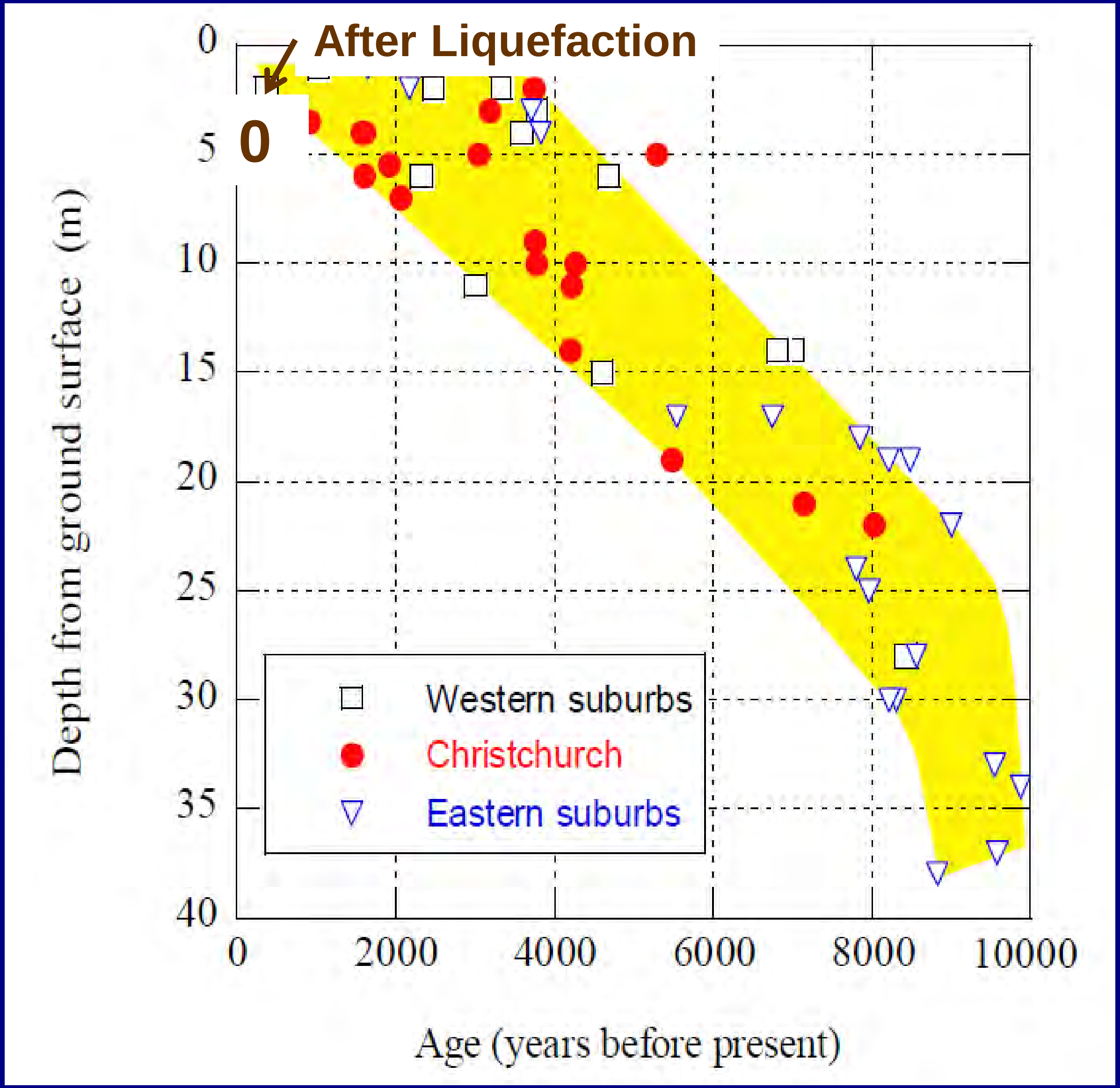
Liquefaction from 3+ EQs (Cubrinovski 2011)



Repeated Liquefaction Events

(Mark Quigley: Avonside)

Age of Christchurch Soils



from M. Cubrinovski

Liquefaction Effects in Christchurch

From M. Cubrinovski

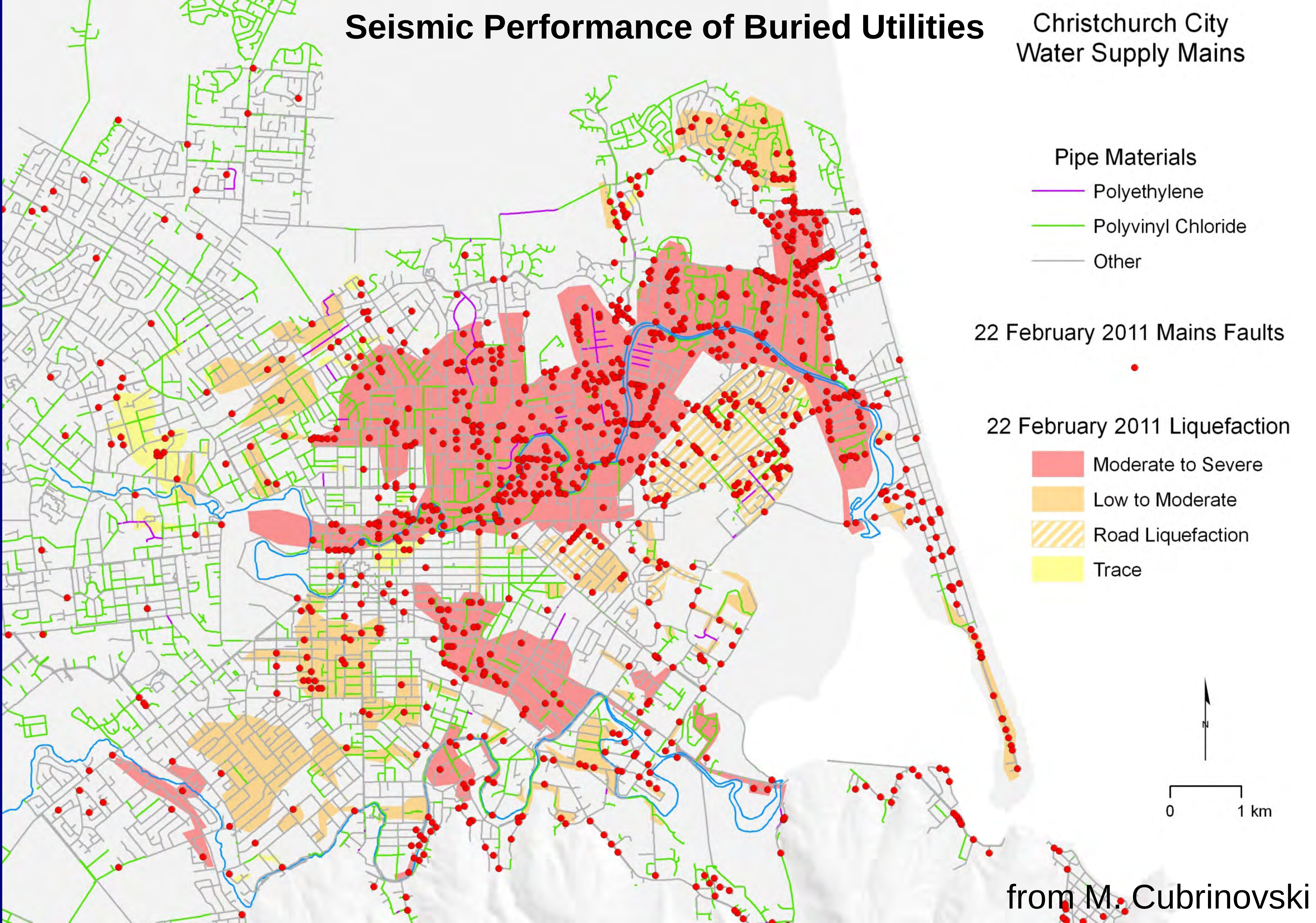
Effects of Lateral Spreading

from M. Cubrinovski

Performance of House Foundations

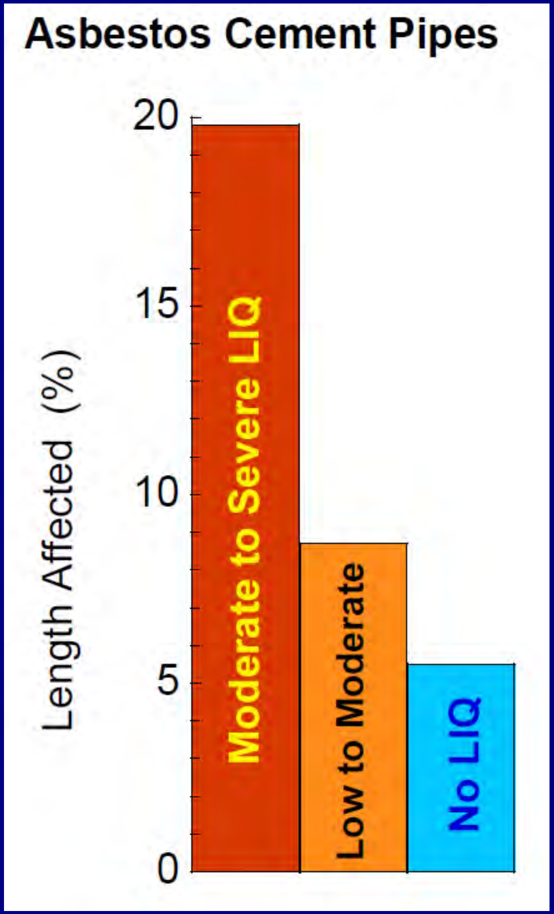
from M. Cubrinovski

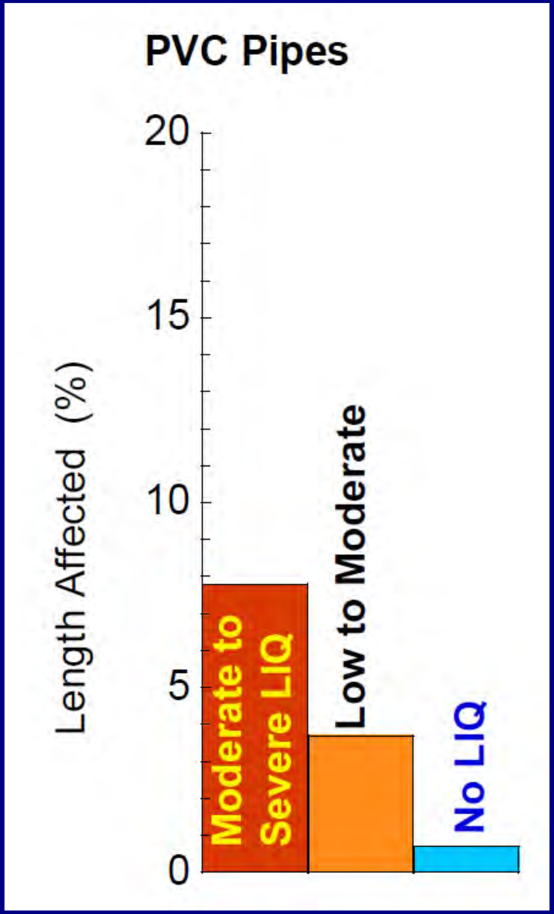
Seismic Performance of Buried Utilities

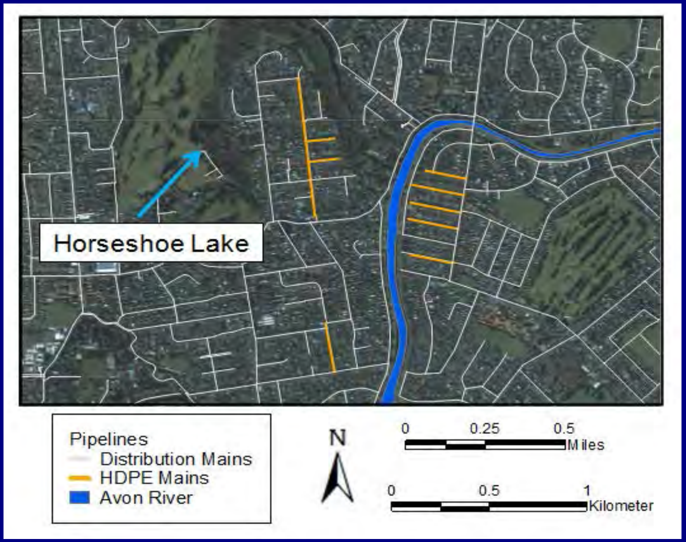


from M. Cubrinovski

Effects of Liquefaction on Water Mains





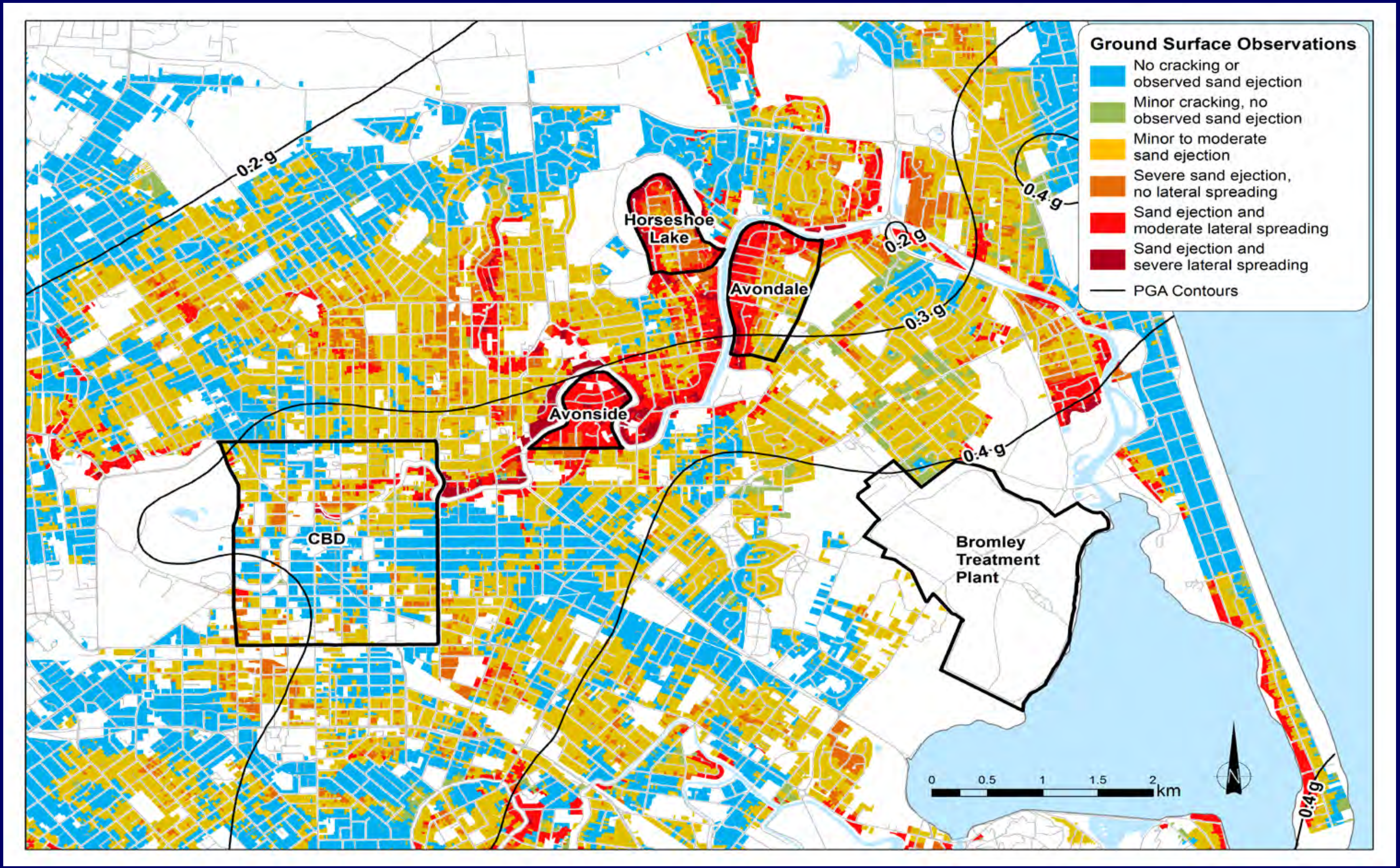


No failure of HDPE pipes installed after 2010 Darfield EQ

from M. Cubrinovski

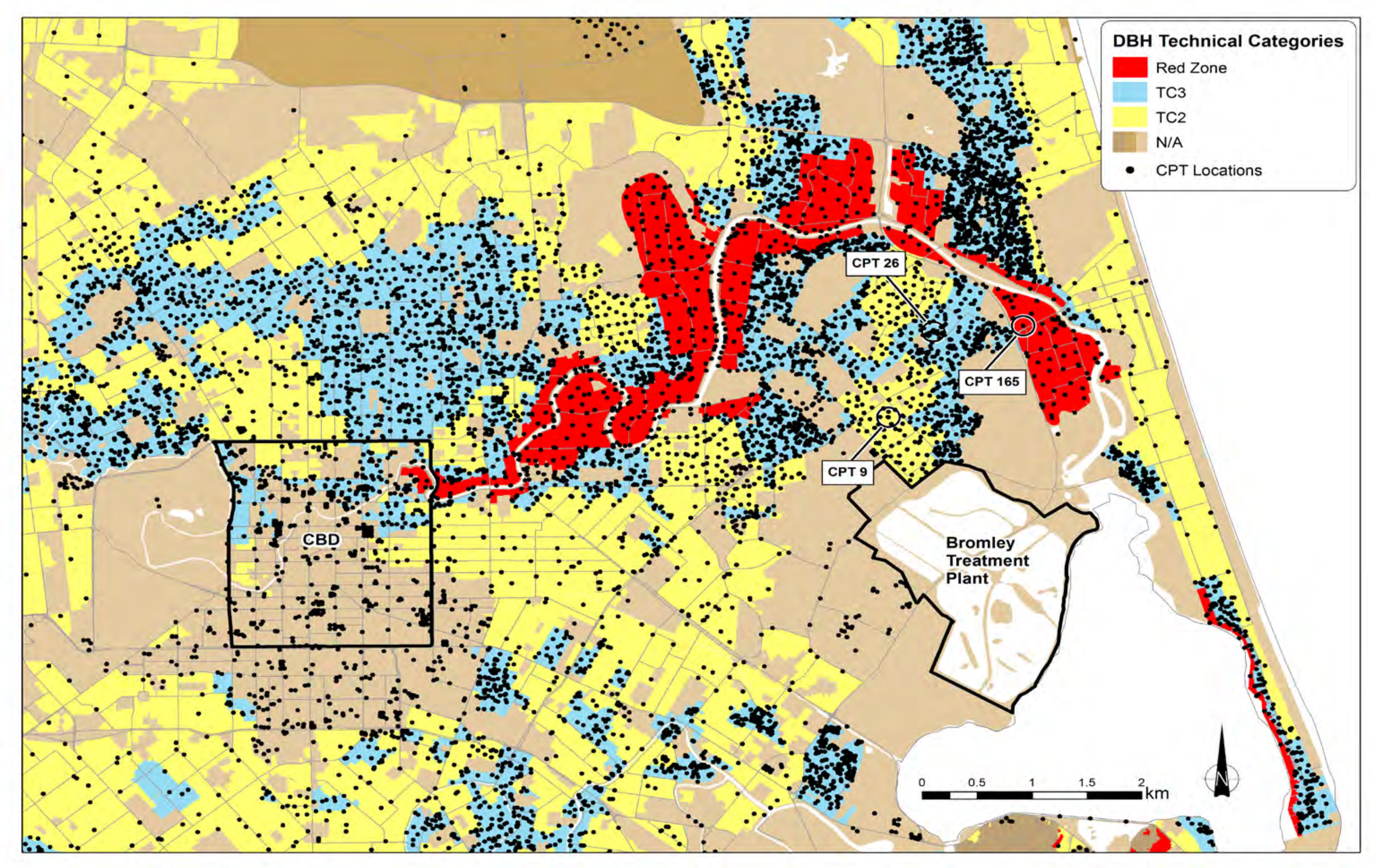
from T. O'Rourke

Liquefaction in Christchurch



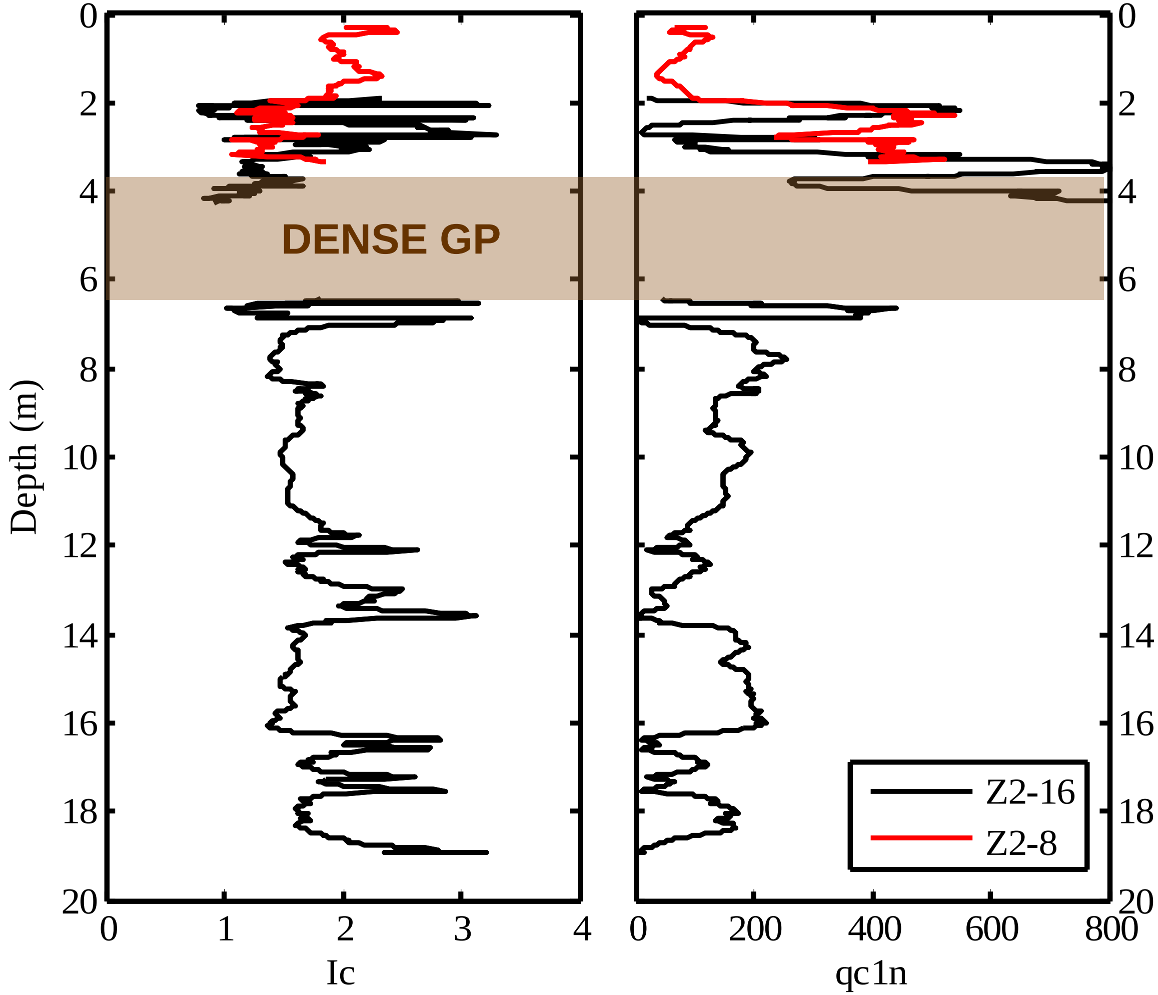
(van Ballegooy et al. 2014)

CPT Investigations 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

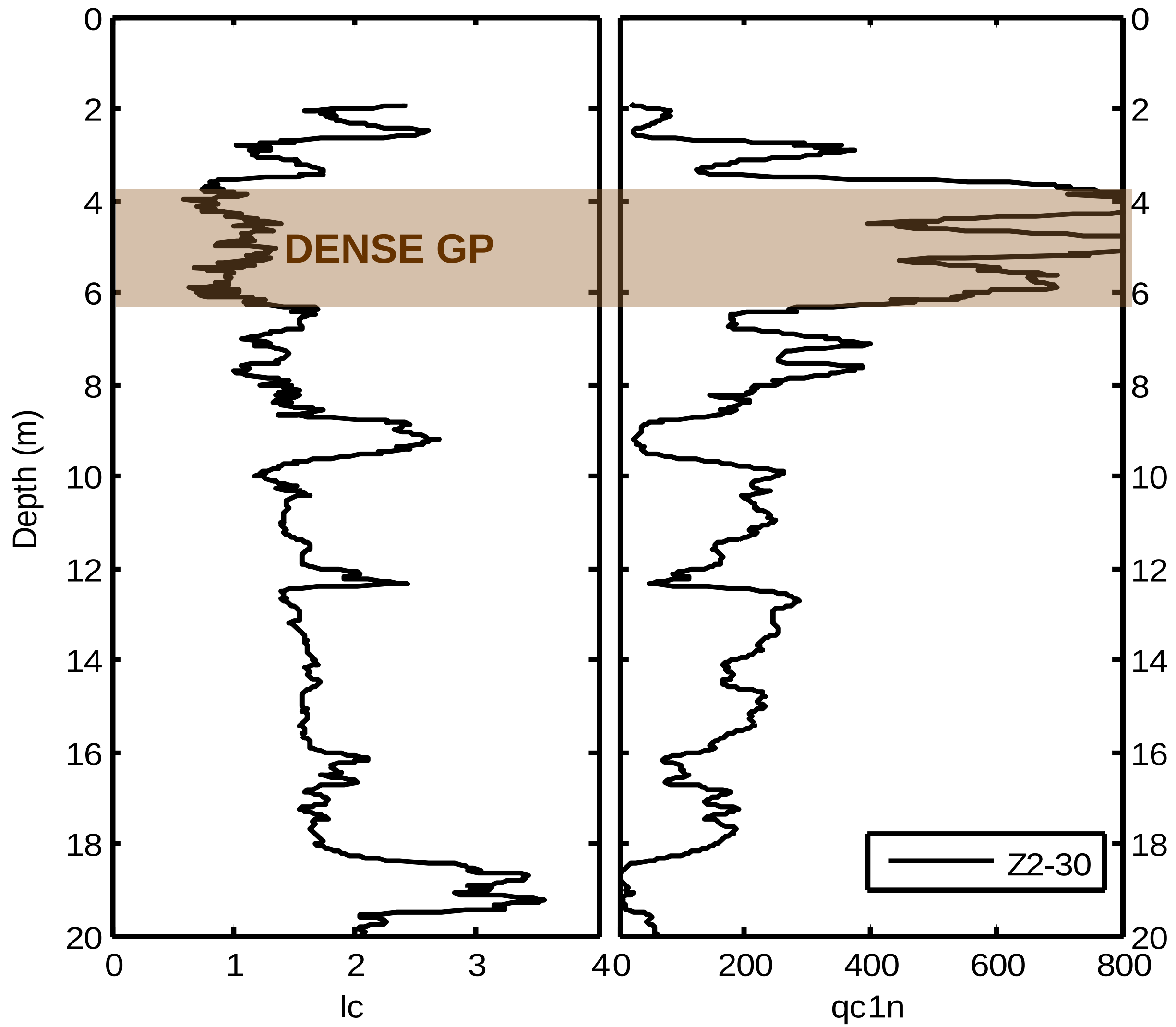
CPT Z2-16 in March 2013: advanced to 9 m with pre-collaring

McMillan
Drilling Services

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

$q_c = 60^+$ MPa

Fugro

Capturing Liquefaction Effects

Liquefaction Potential Index (Iwasaki et al. 1982)

$$LPI = \int_0^{20} F_1 \mathrm{W}(z)\,\mathrm{dz}$$

$W(z) = 10 - 0.5z$

$F_1 = 1 - FS \; for \; FS < 1.0, \; F_1 = 0 \; for \; FS \geq 1.0,$

z = depth (m) below the ground surface

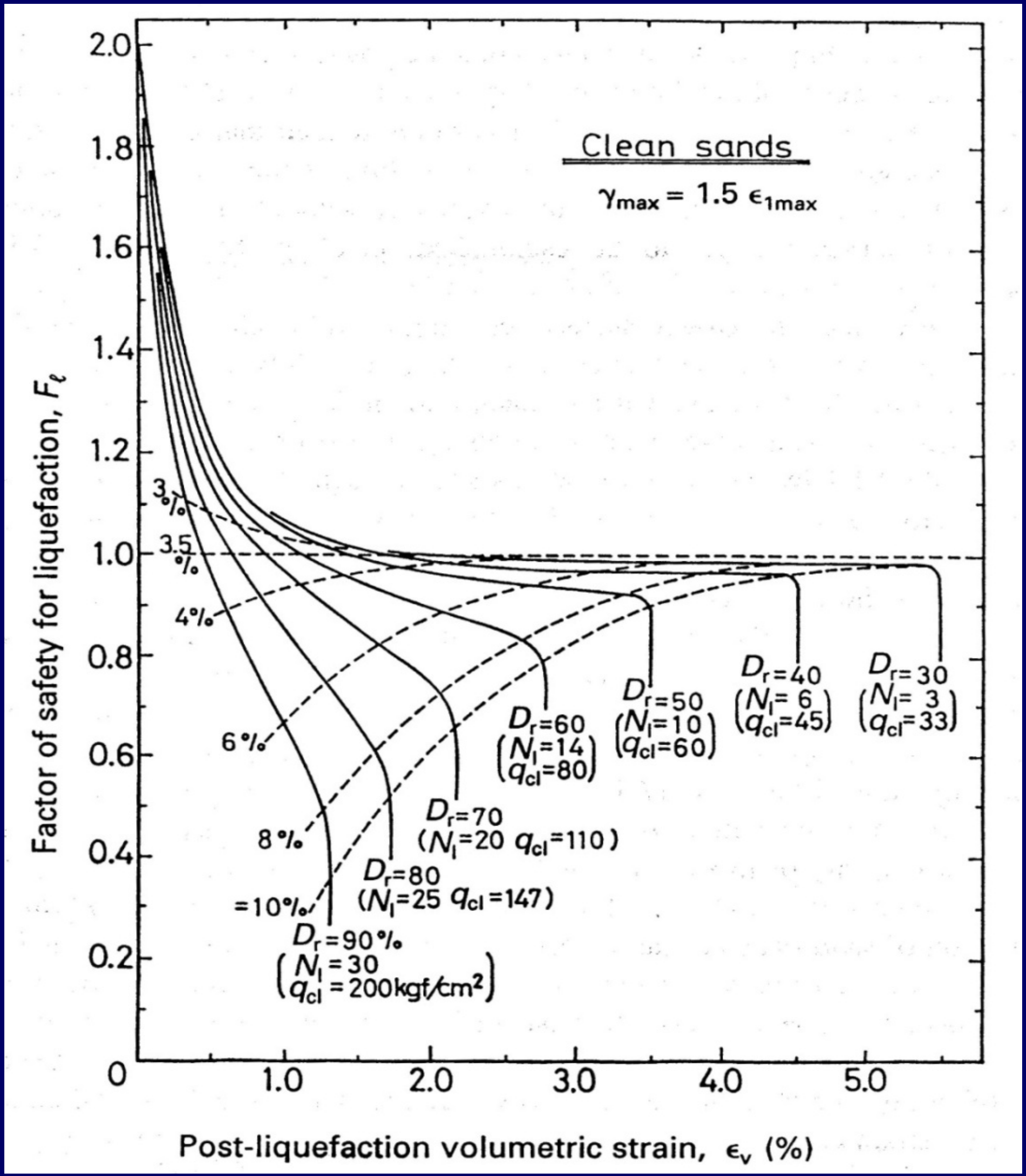
Liquefaction Severity Number (van Ballegooy et al. 2014)

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

ε_v = post-liquefaction volumetric reconsolidation strain (decimal)

z = depth (m) below the ground surface > 0.0

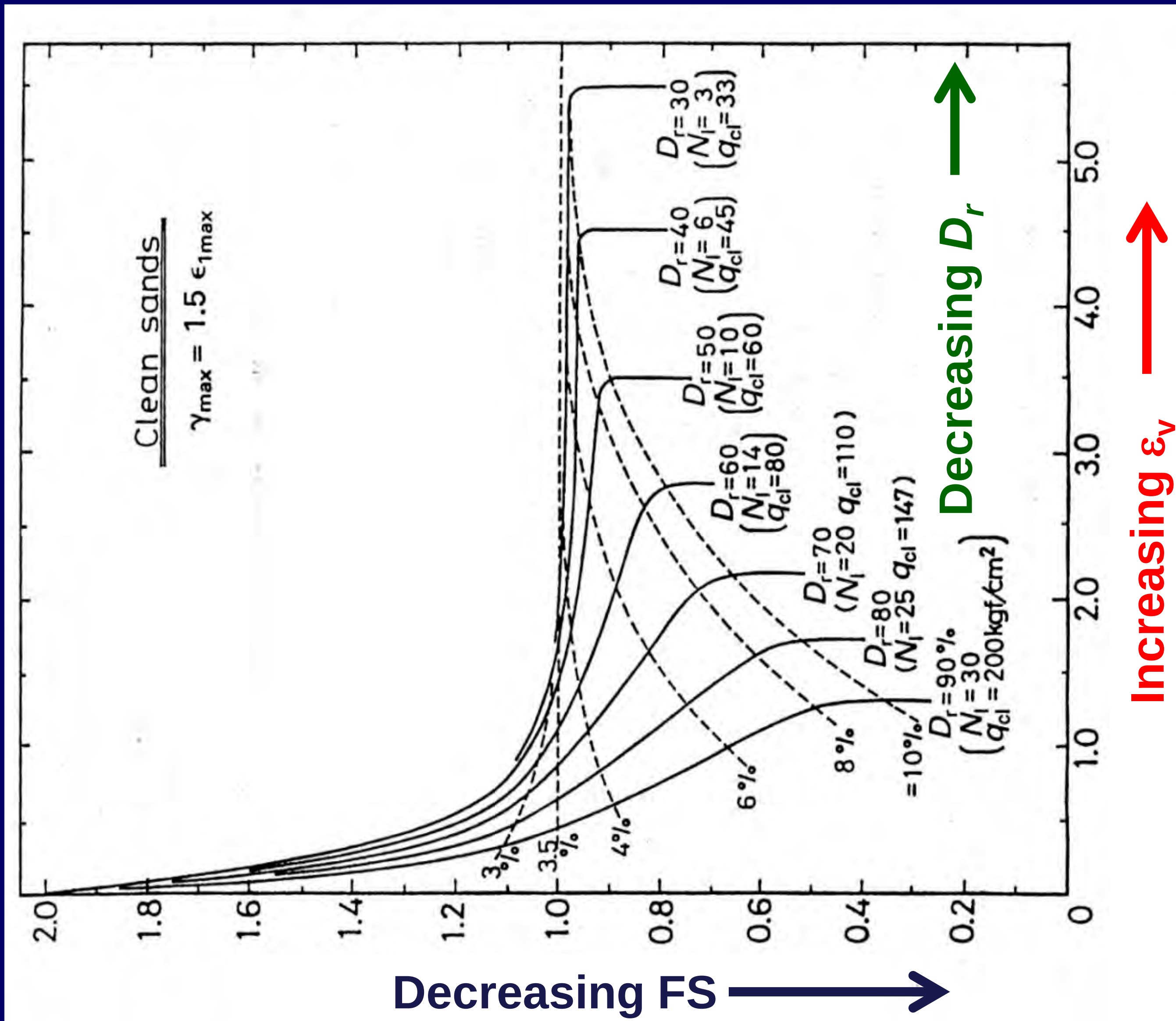
Post-Liquefaction Volumetric Strain (ε_v)



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

Ishihara & Yoshimine 1992

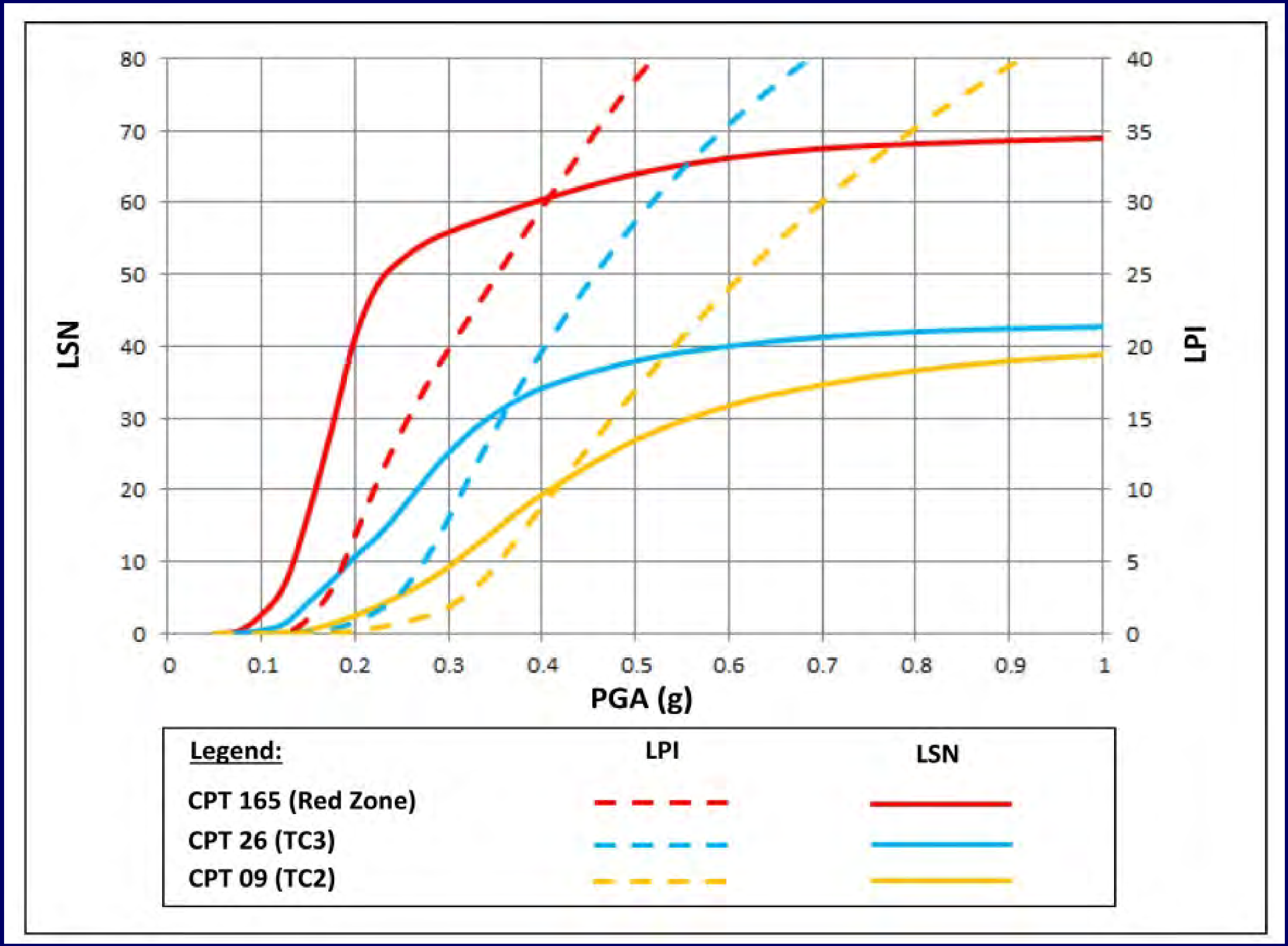
Post-Liquefaction Volumetric Strain (ε_v)



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

Ishihara & Yoshimine 1992

Capturing Liquefaction Effects



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

LSN considers when *FS* > 1

LSN limited by max ε_v

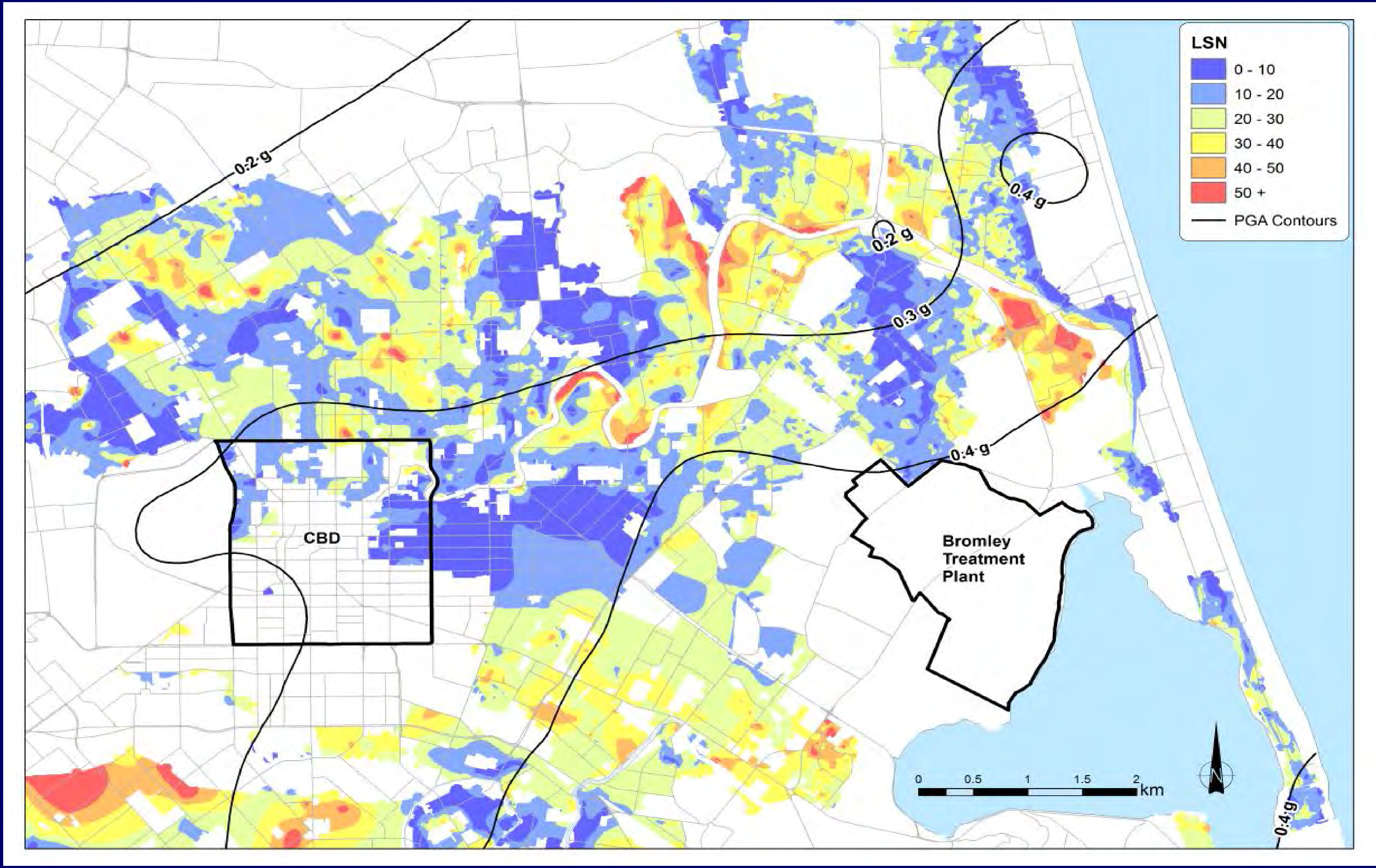
LSN affected by D_r

LSN heavily weights shallow layers

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

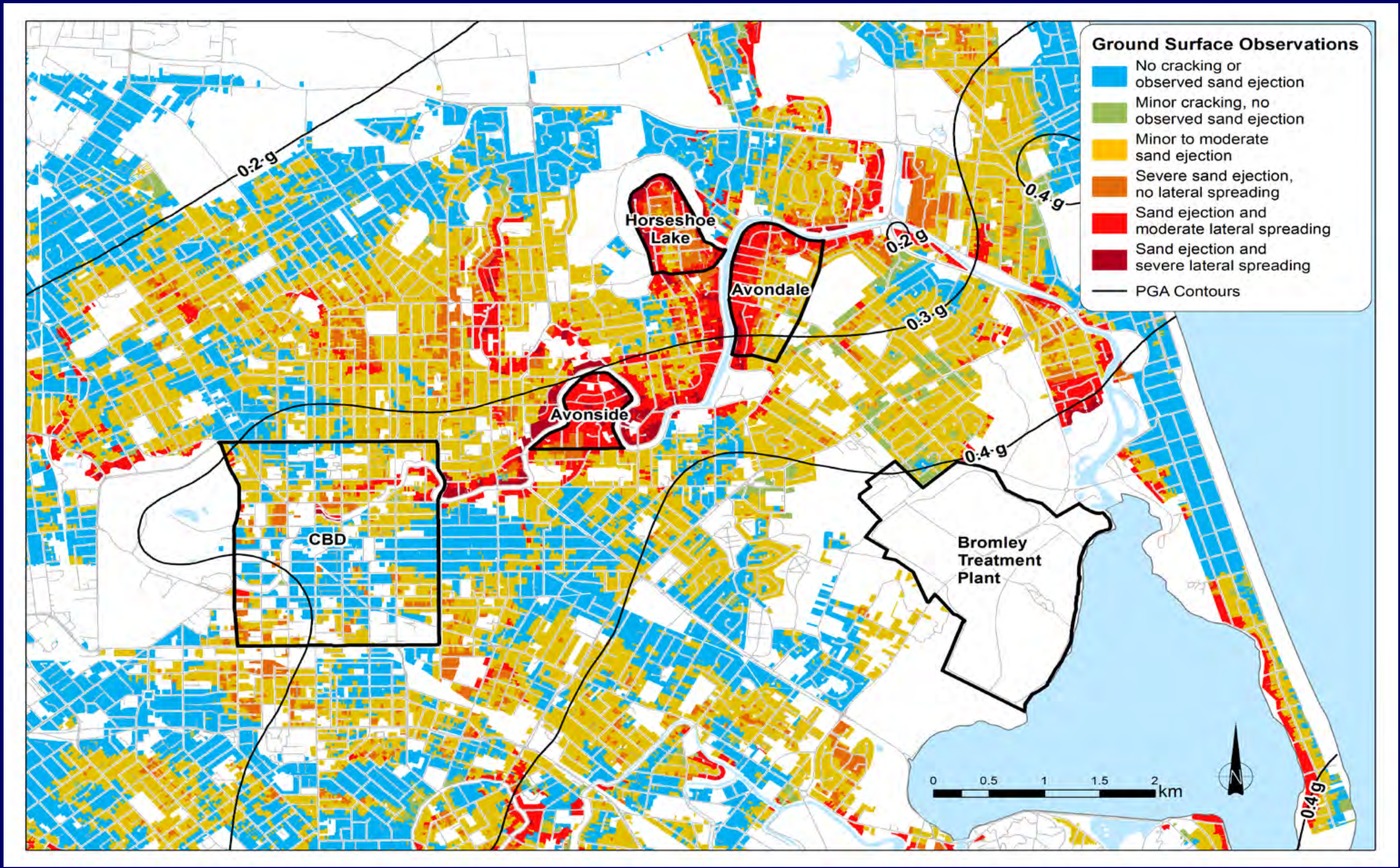
van Ballegooy et al. 2014

Capturing Liquefaction Effects



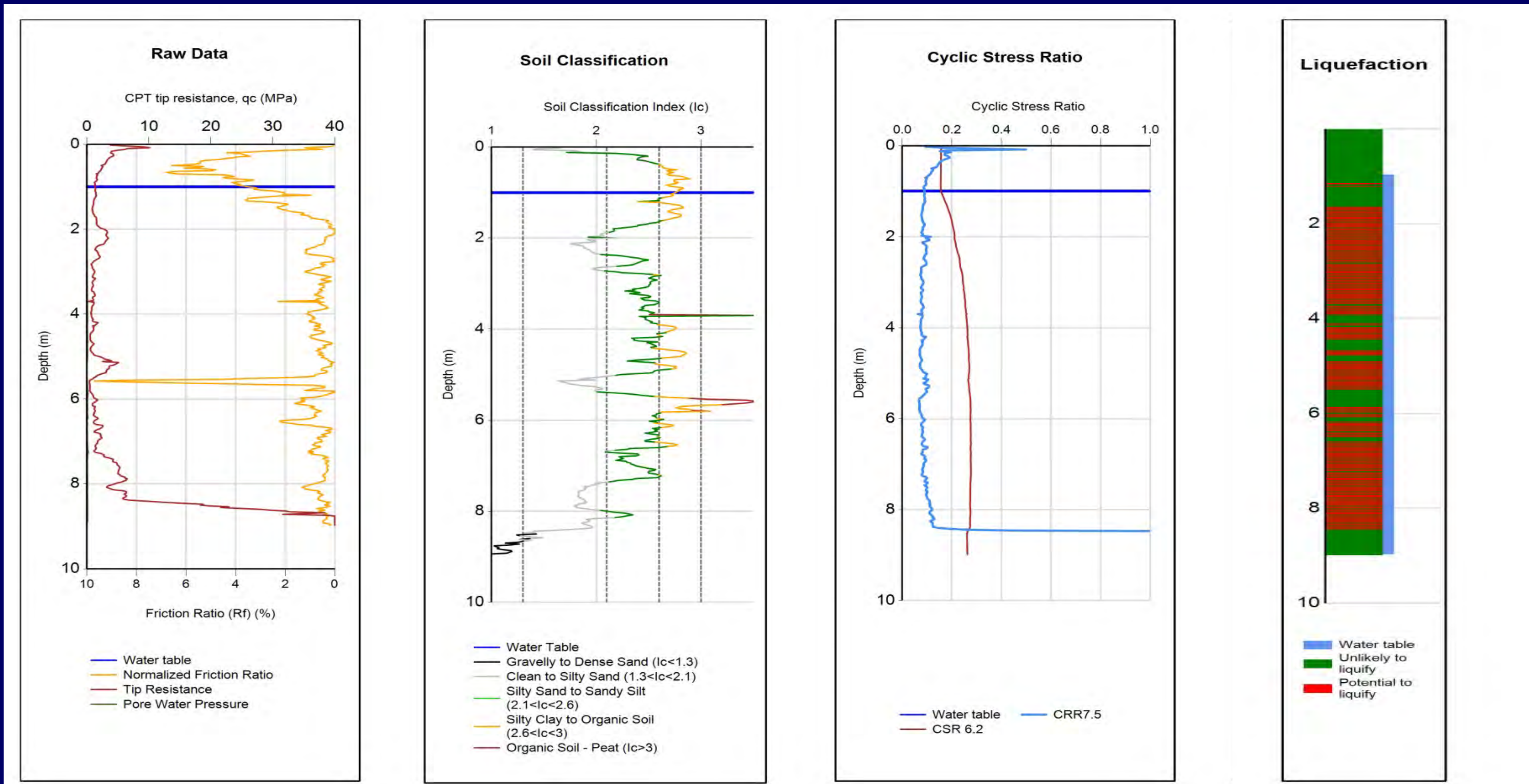
van Ballegooy et al. 2014

Liquefaction in Christchurch



(van Ballegooy et al. 2014)

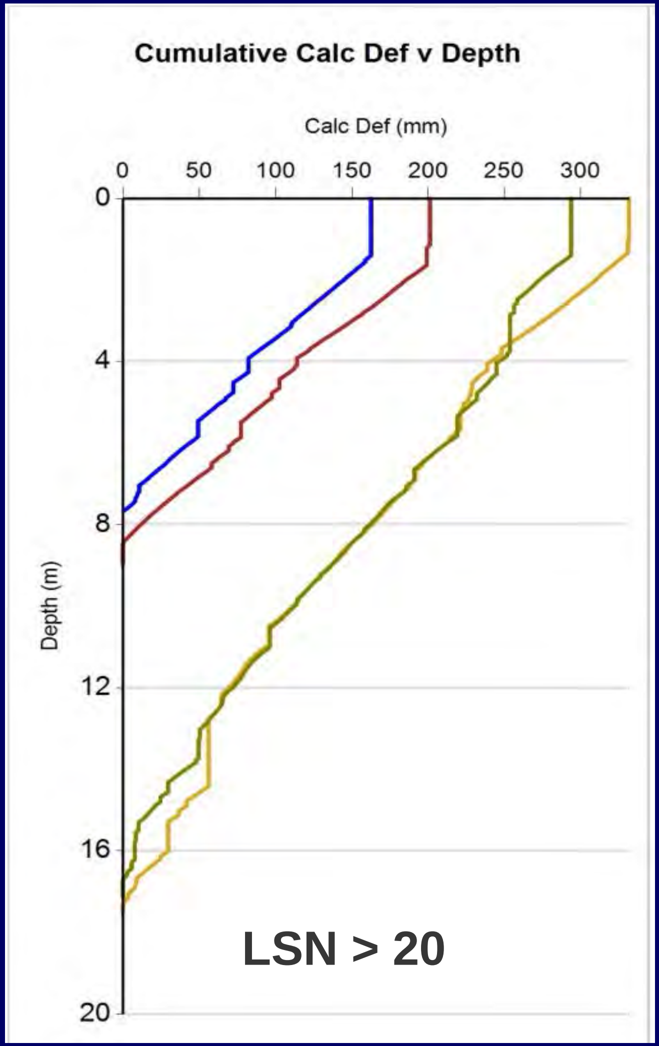
Liquefaction of Silty Sands



CPT at Christchurch site where no liquefaction effects were observed

(from R. Wentz, Wentz-Pacific)

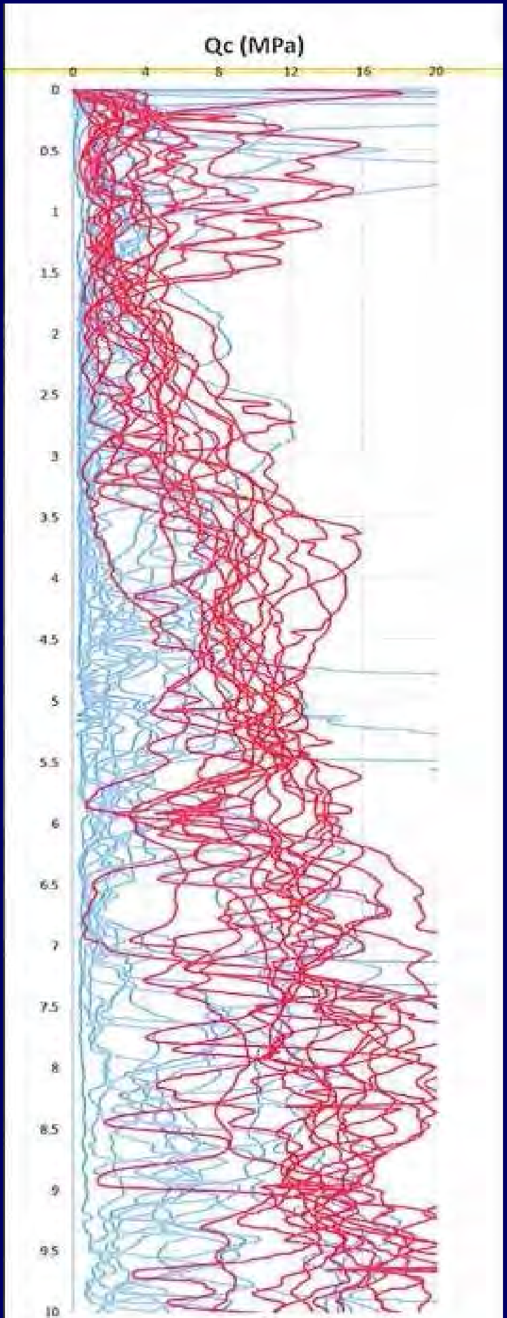
Liquefaction of Silty Sands

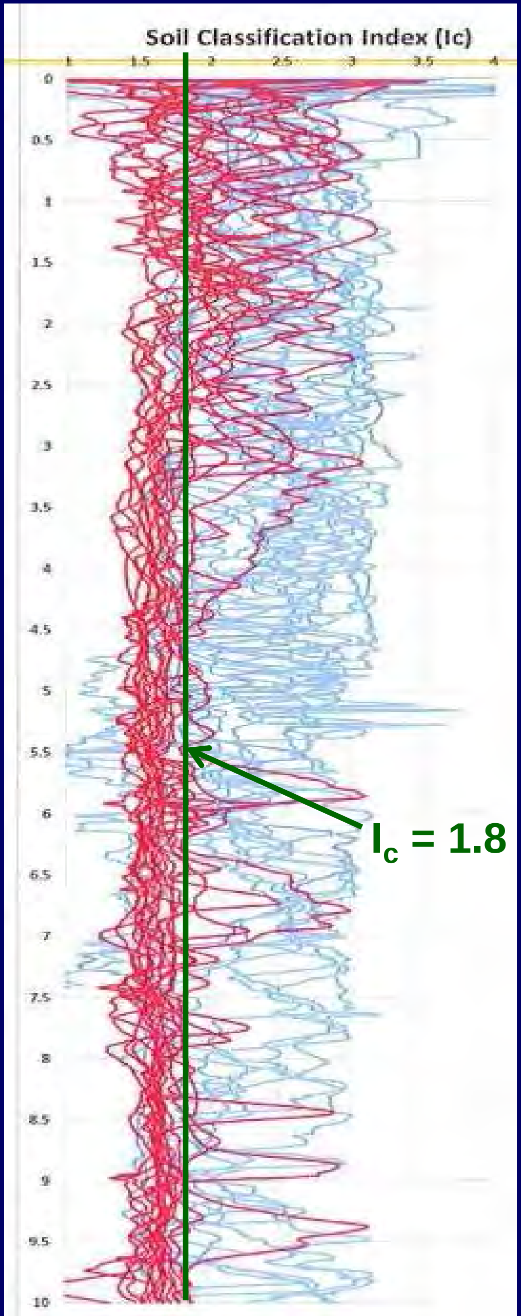


Evaluation of 4 CPTs at site where no liquefaction effects were observed

(from R. Wentz, Wentz-Pacific)

Observations of Liquefaction Ejecta





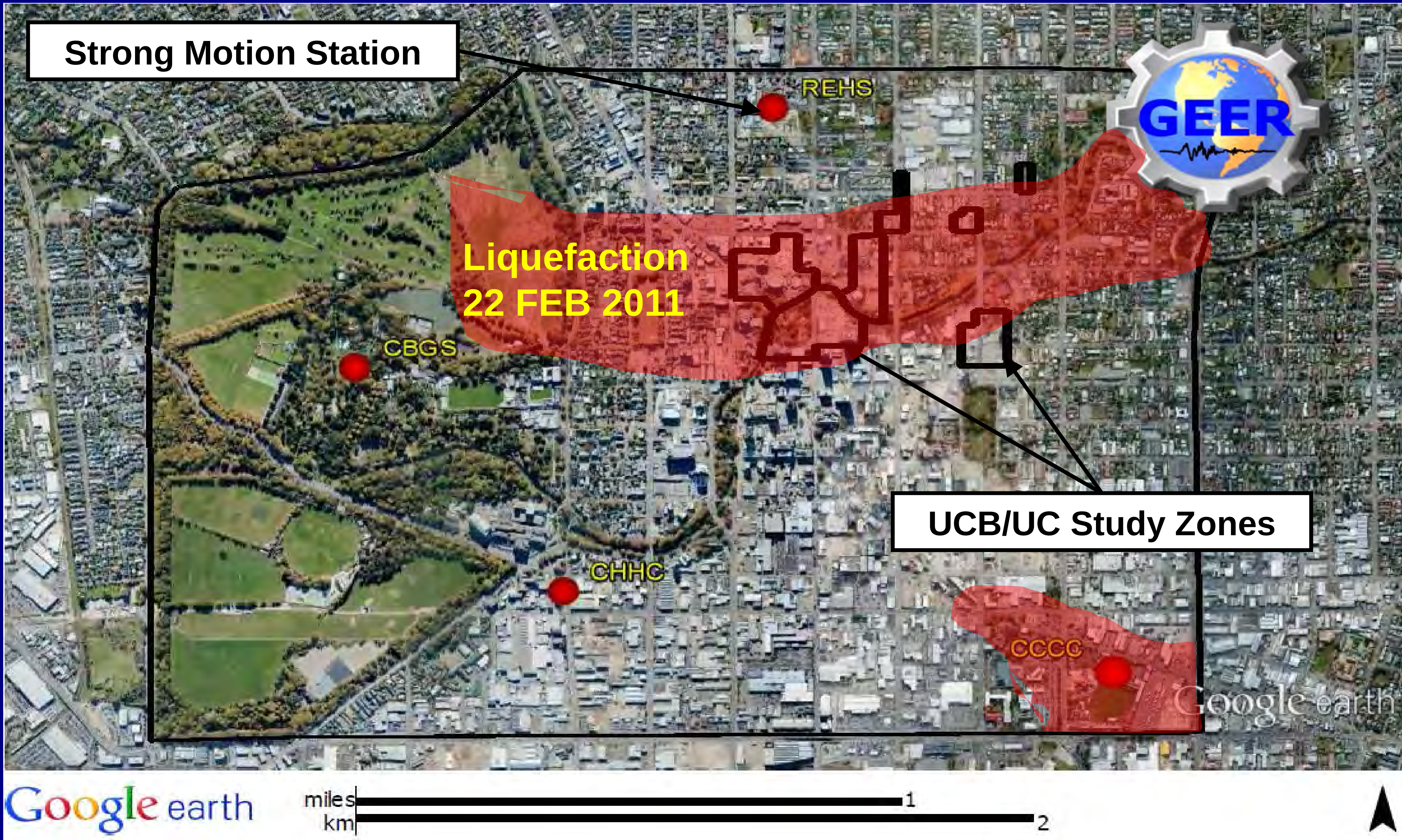
2010 Darfield EQ

Ejecta Observed

No Ejecta

van Ballegooy et al.
Tonkin & Taylor
for the EQC

Central Business District of Christchurch



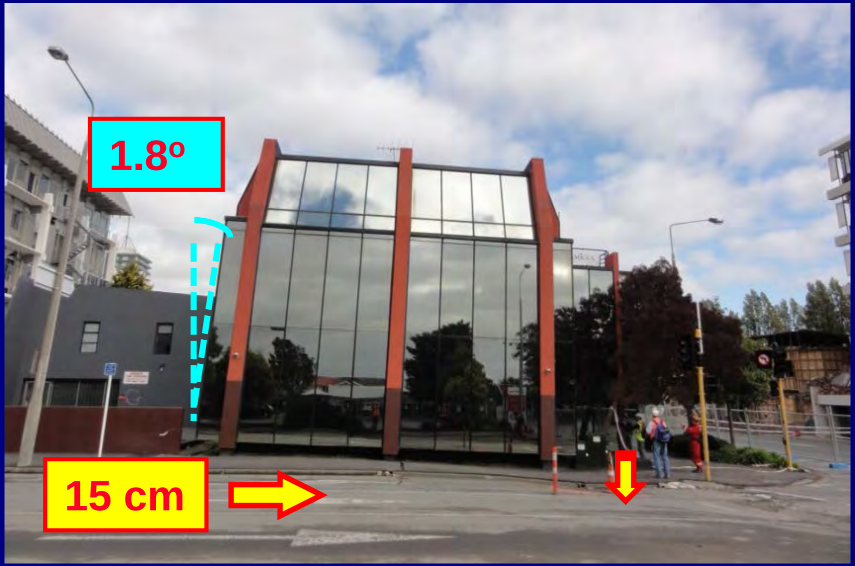
Seismic Demand in CBD

Event	Median $CSR_{M7.5}$ (16% - 84%)	Level of Liquefaction in CBD
4 SEP 10 $M_w = 7.1$	0.12 (0.10 – 0.17)	Low
26 DEC 10 $M_w = 4.8$	0.07	None
22 FEB 11 $\mathbf{M_w = 6.2}$	**0.20** **(0.16 – 0.28)**	**Severe**
13 JUN 11 $M_w = 6.0$	0.09 (0.08 – 0.15)	Low
23 DEC 11 $M_w = 5.9$	0.10	Low

$CSR_{M7.5} = 0.65\,(PGA/g)\,/\,MSF$ **$MSF = 6.9\exp(-M_w/4) - 0.058 \leq 1.8$**

Median PGA from recordings; 16% - 84% PGA from Bradley and Hughes (2012)

Liquefaction Effects on Structures



Tilting and Sliding of Buildings

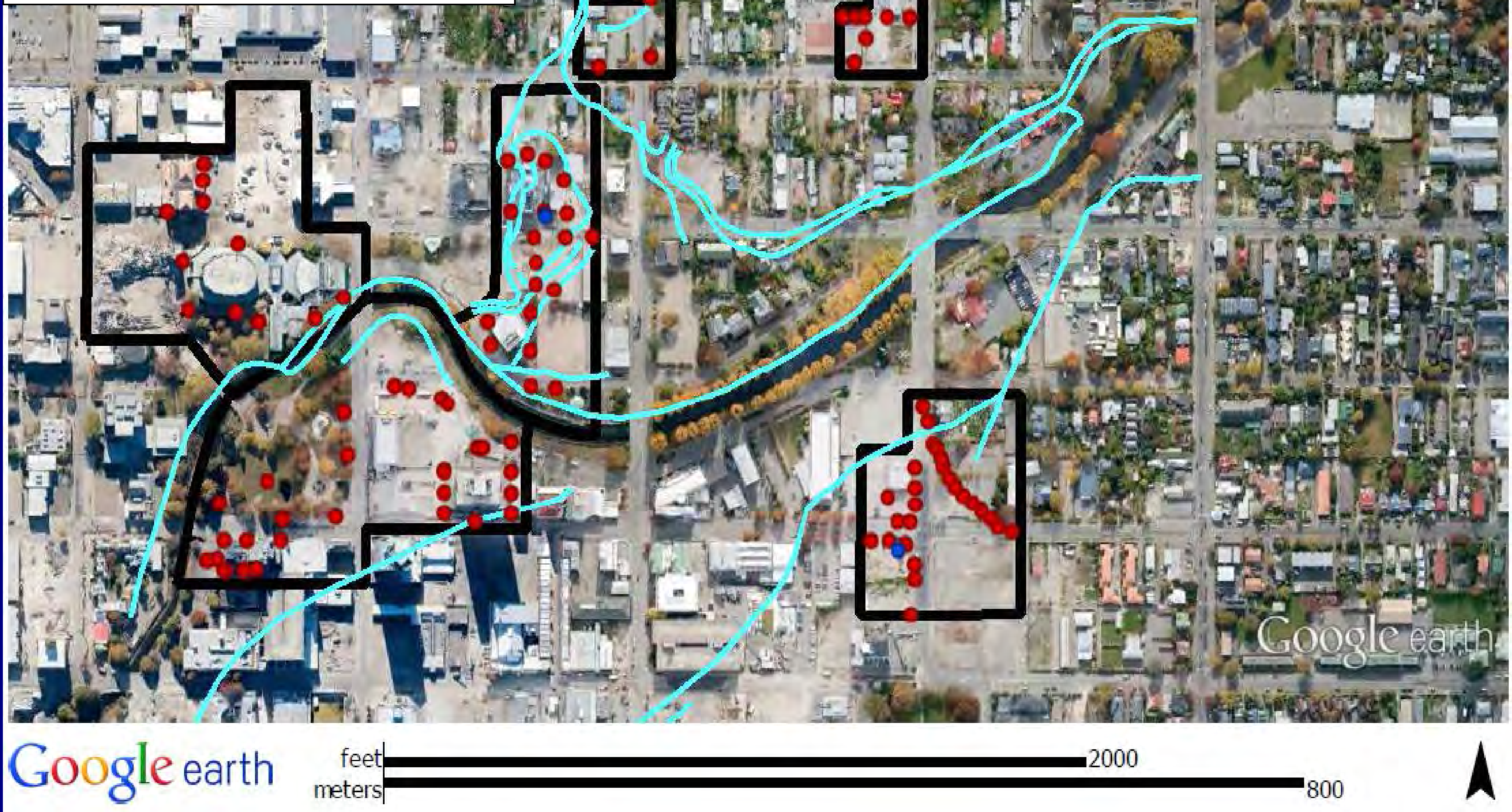
Settlement of Ground next to Piled Bldg.

Cracking due to Differential Settlement

Tilt of Tall Buildings

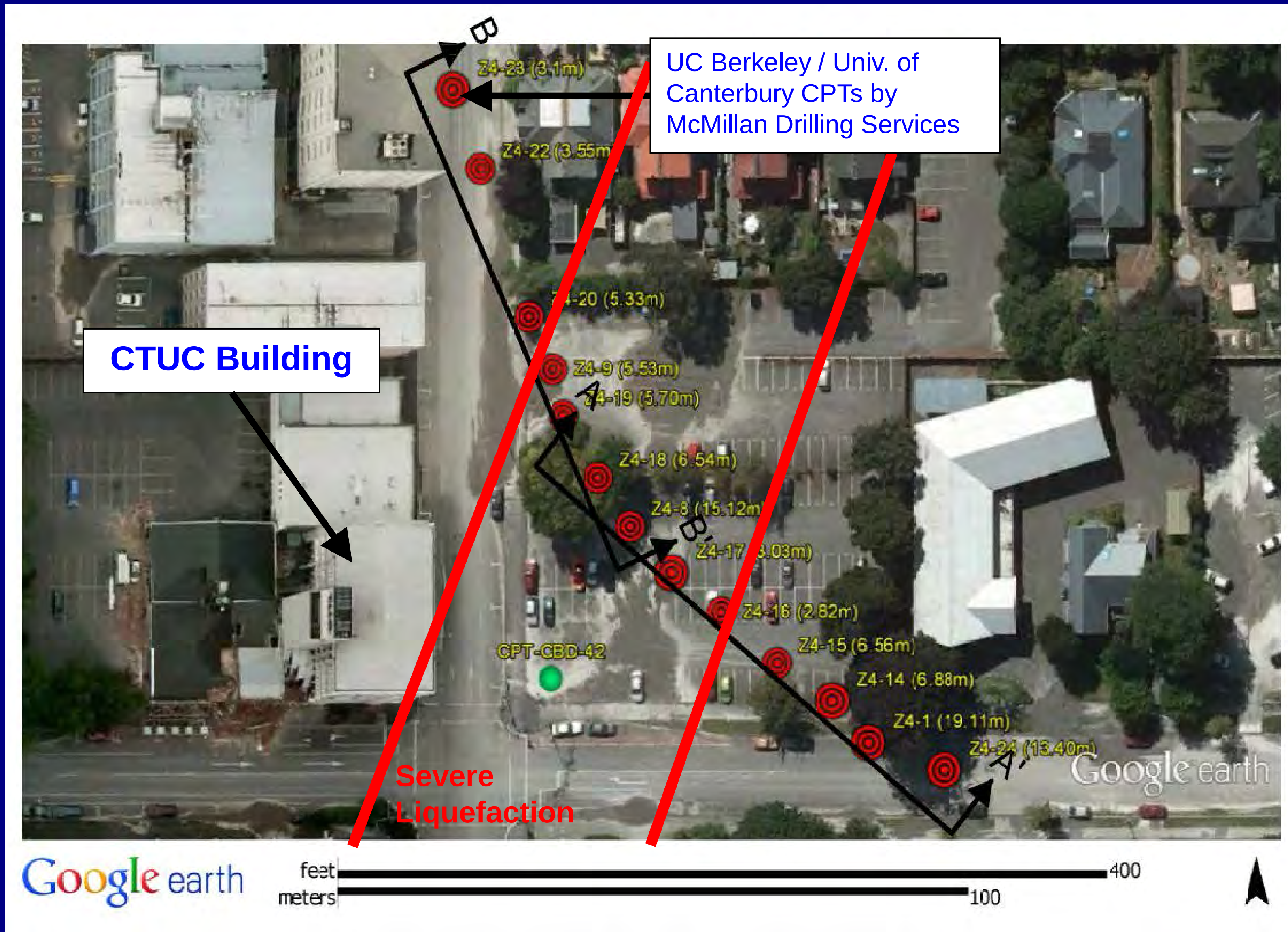
Central Business District of Christchurch

CBD STUDY ZONES:
107 UCB-UC CPTs
13 UCB-UC BHs
34 CGD CPTs
8 CGD BHs

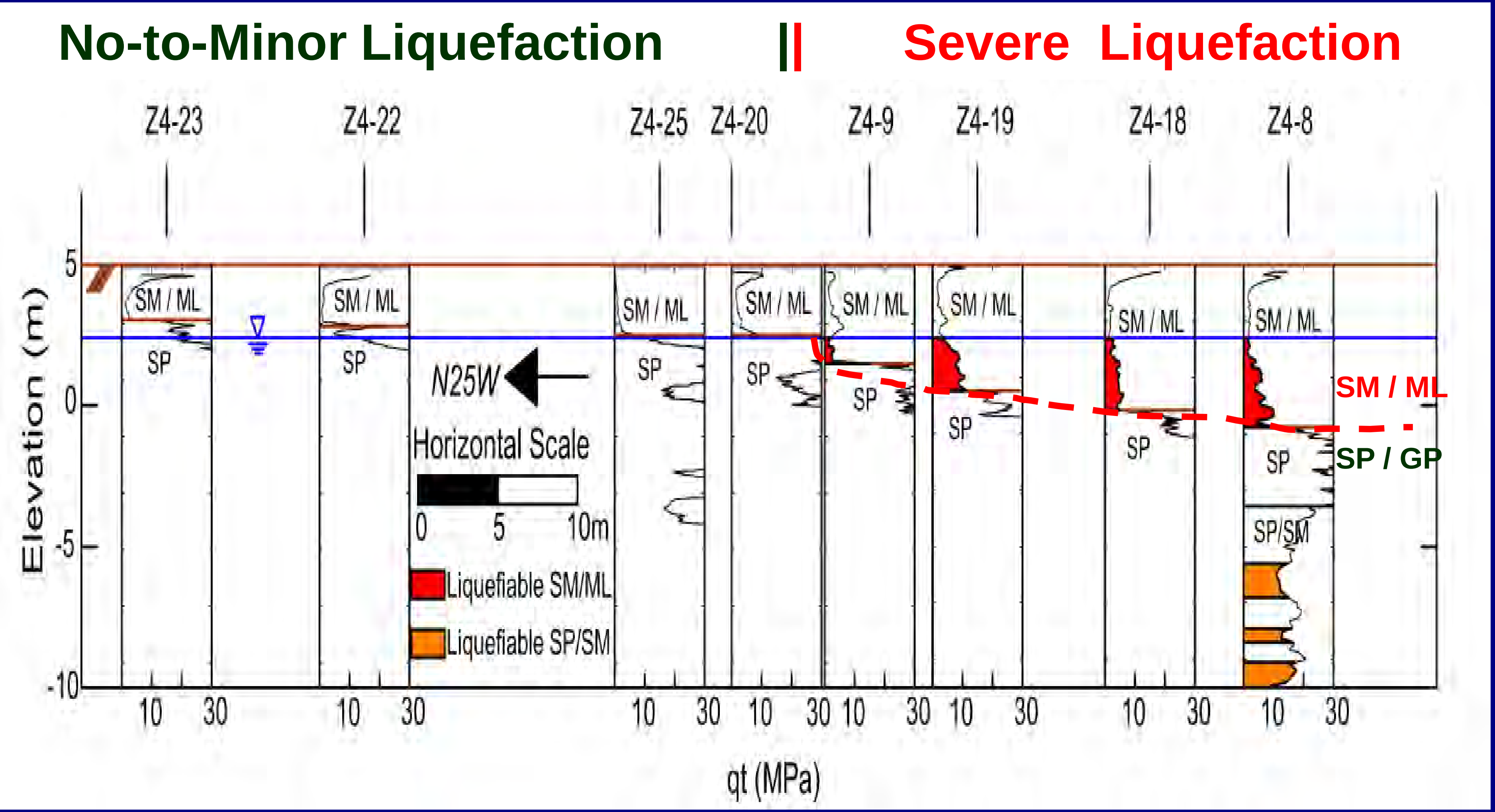


Variability in Shallow Soils

Car Park on Corner of Armagh and Madras Streets

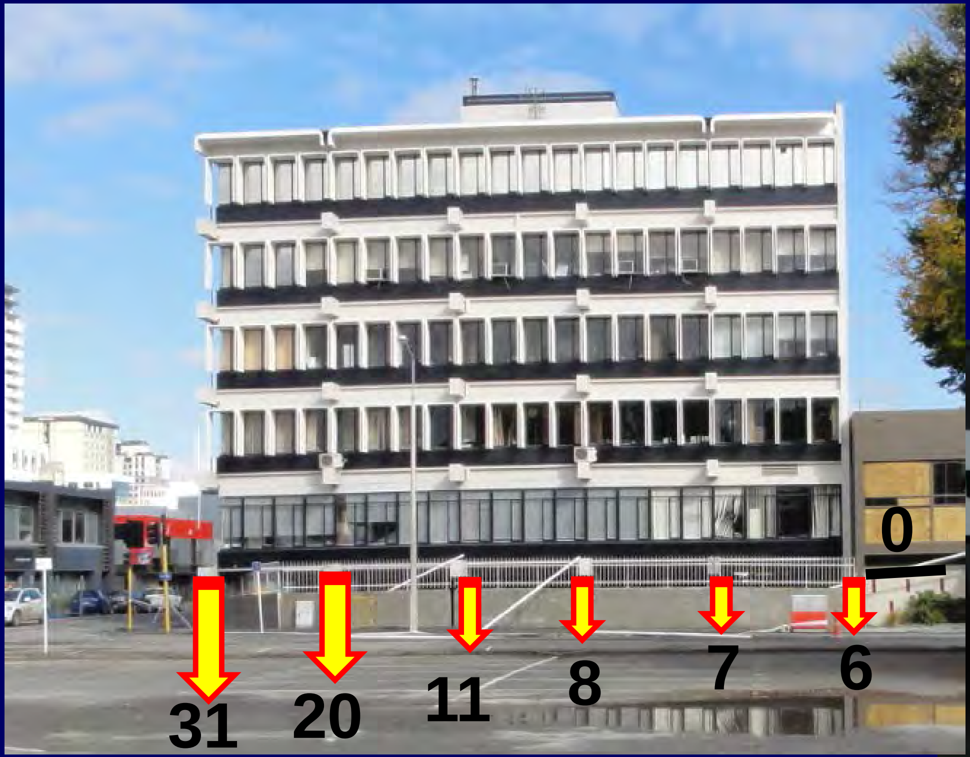


Variability in Shallow Soils
Car Park on Corner of Armagh and Madras Streets



CTUC Building

Liquefaction-Induced Differential Settlement Induces Distress

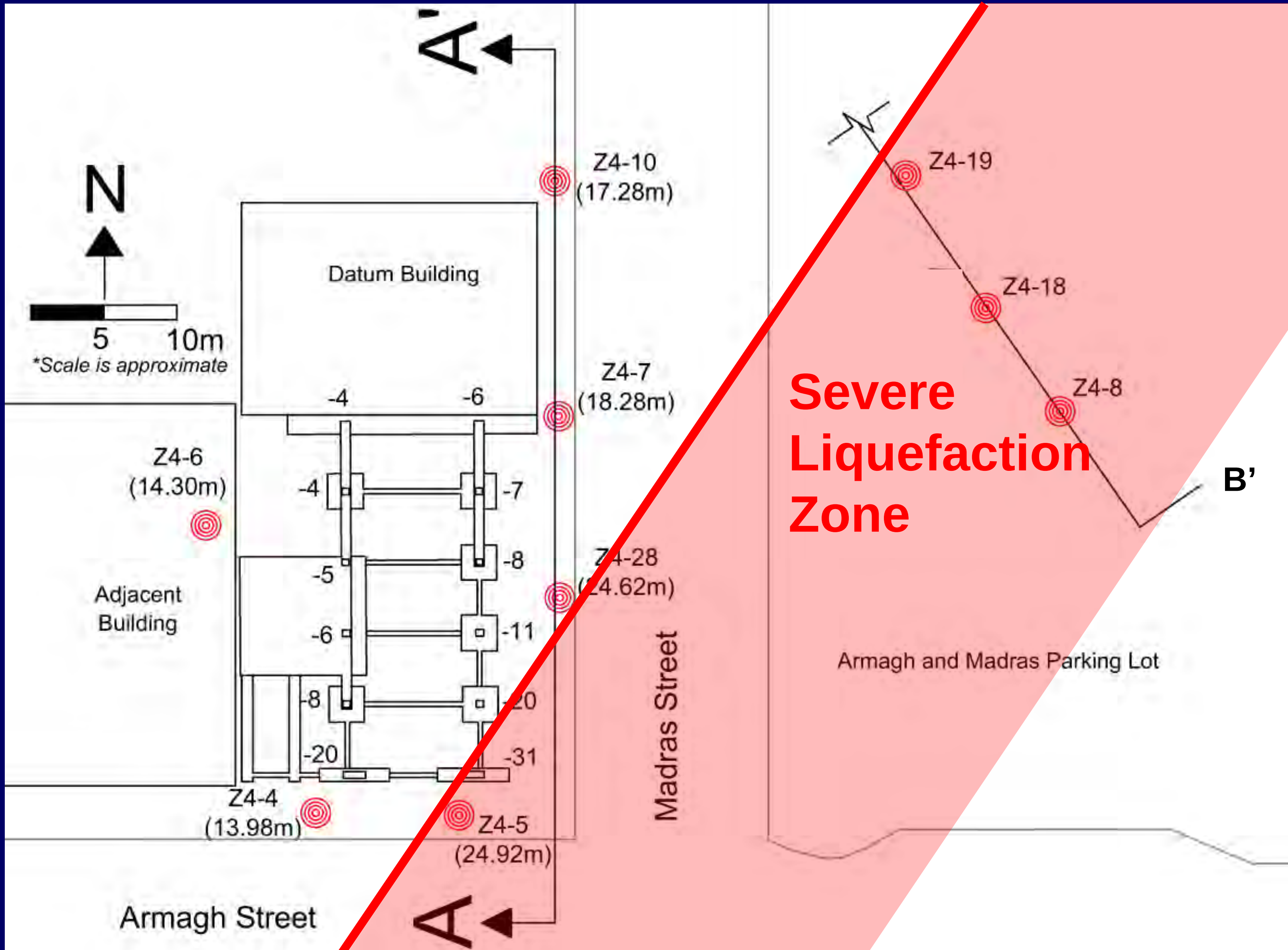


Building Settlement (cm)
Maximum Angular Distortion ≈ 1 / 50

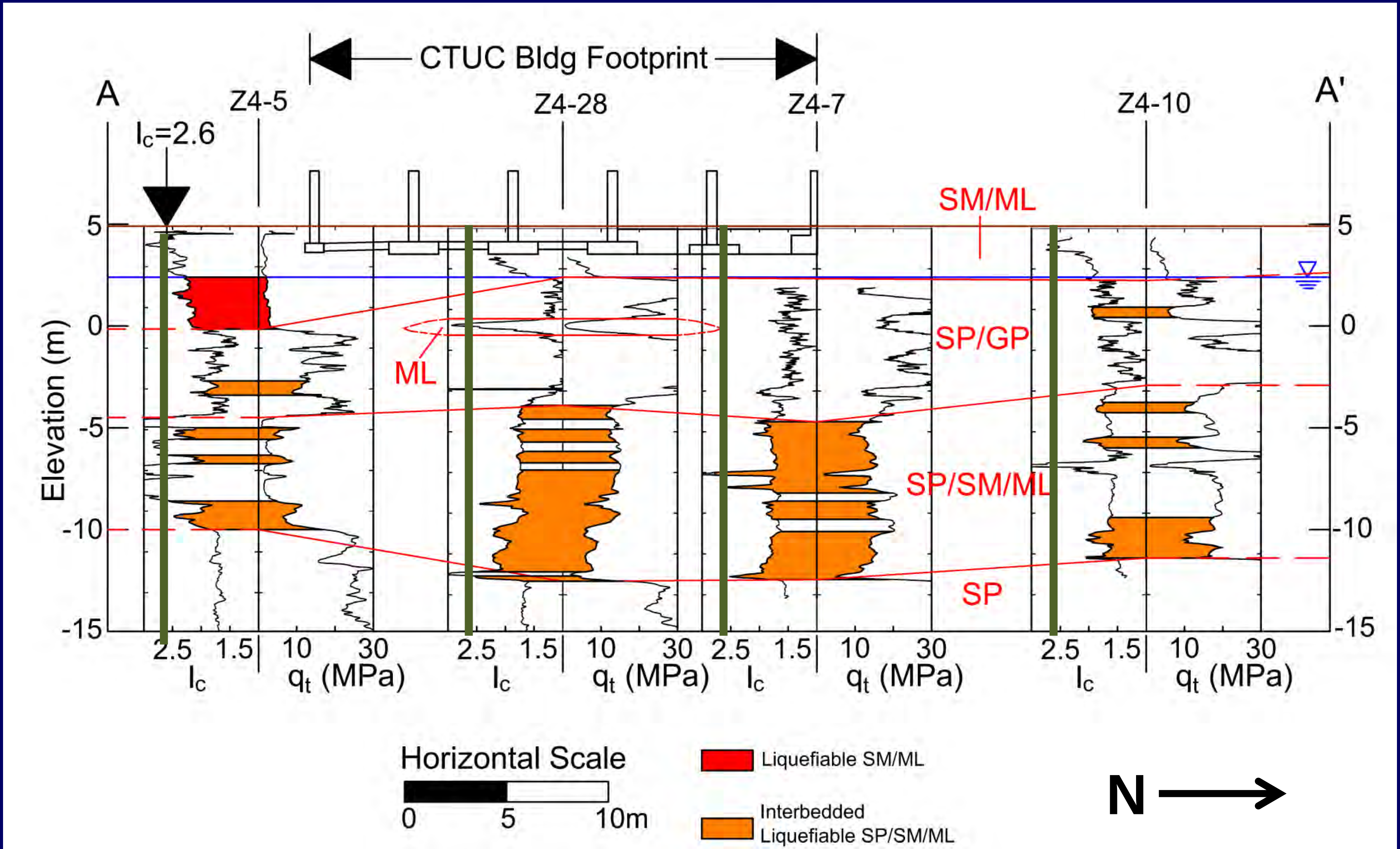
Ejecta

GEER: Bray, Cubrinovski et al.

CTUC Building

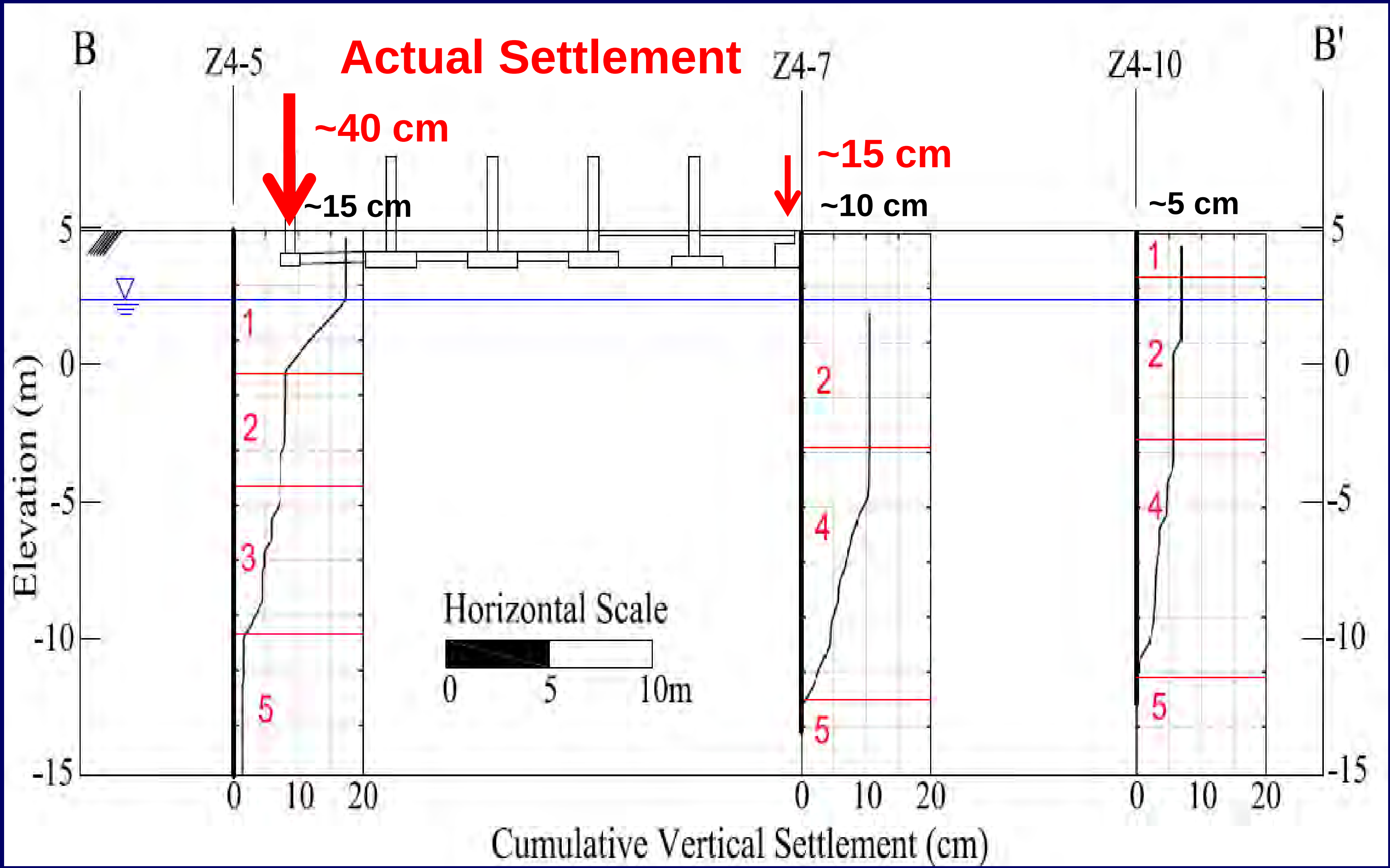


CTUC Building: Christchurch EQ



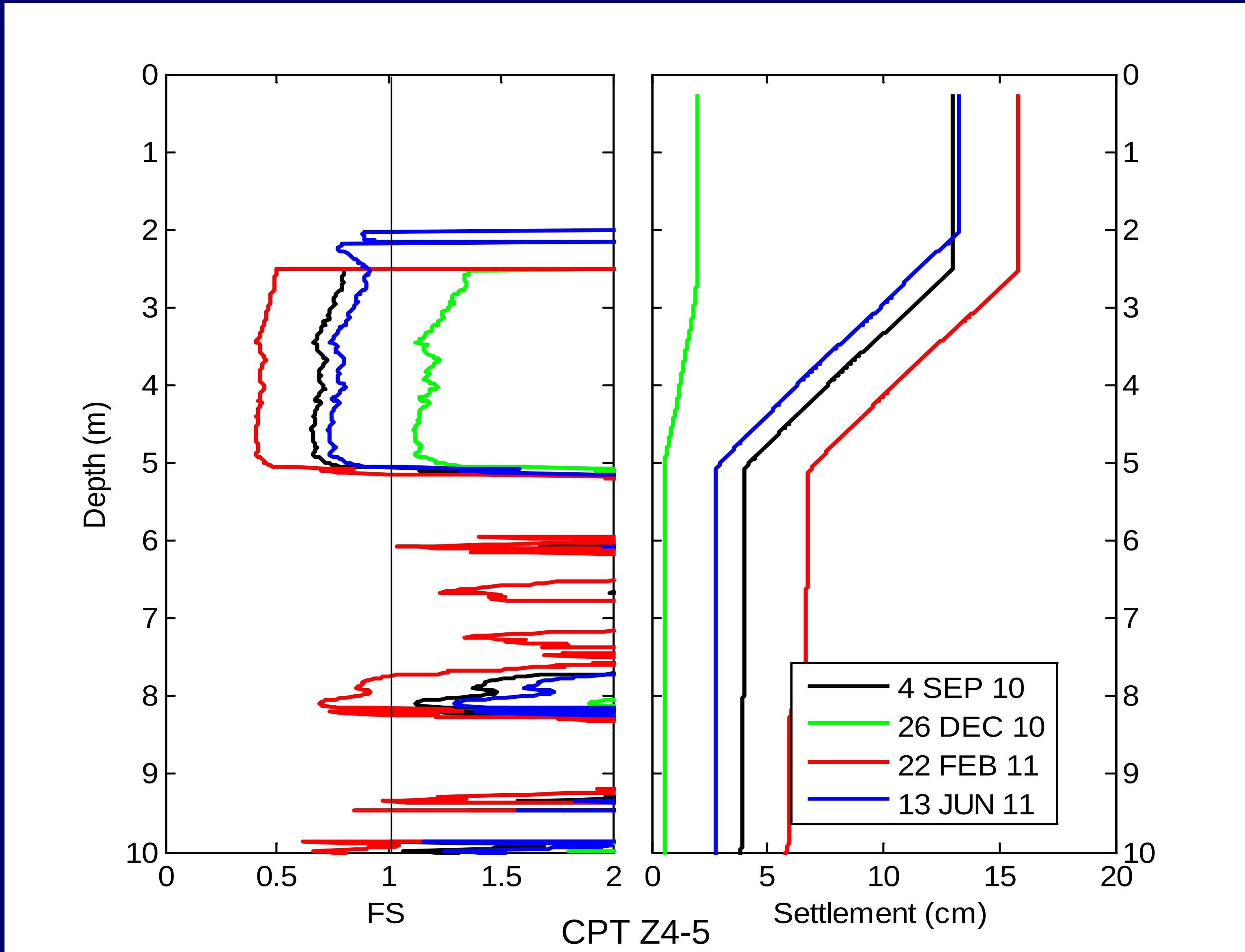
2011 Christchurch EQ: Robertson & Wride (1998)

CTUC Building Settlement



Robertson & Wride (1998) & Zhang, Robertson et al. (2002)

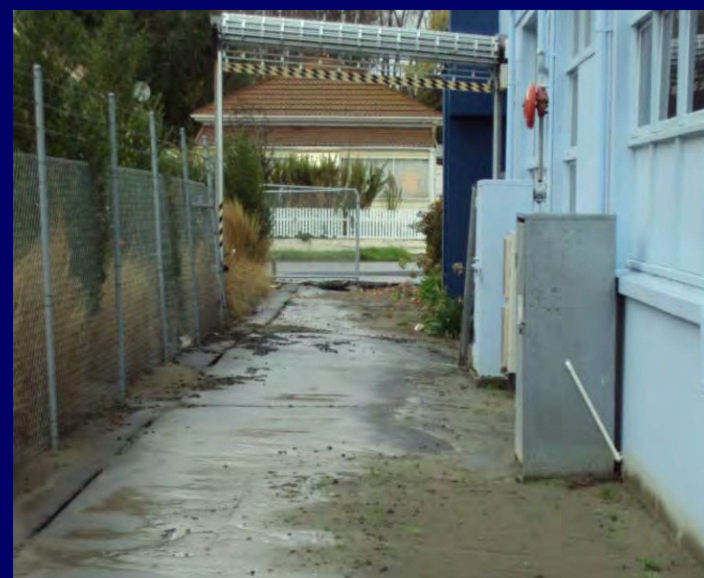
CTUC Building: Sensitivity of Results



Robertson & Wride (1998) & Zhang, Robertson et al. (2002)

SA Building

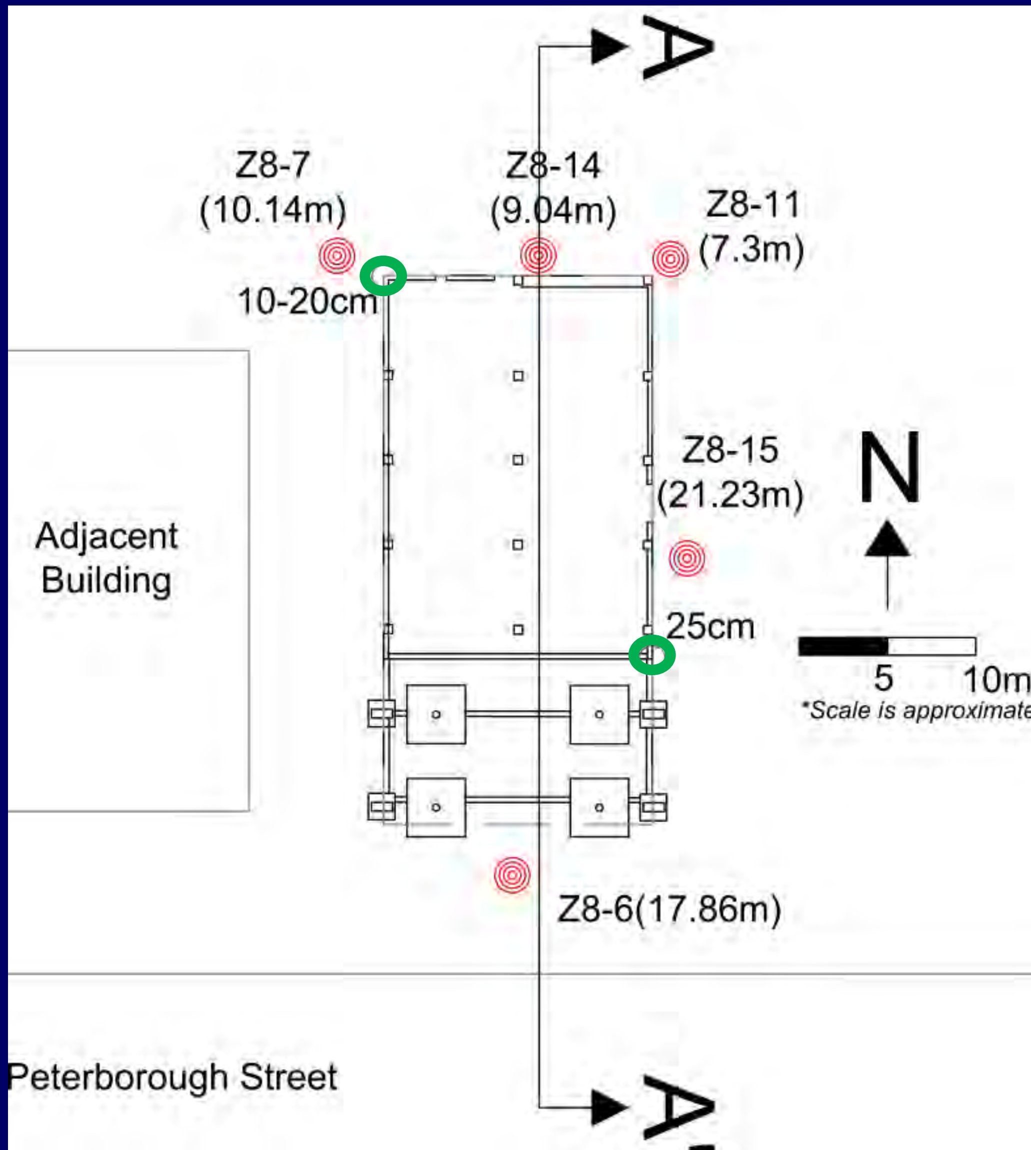
Liquefaction-Induced Differential Settlement



GEER: Bray, Cubrinovski et al.

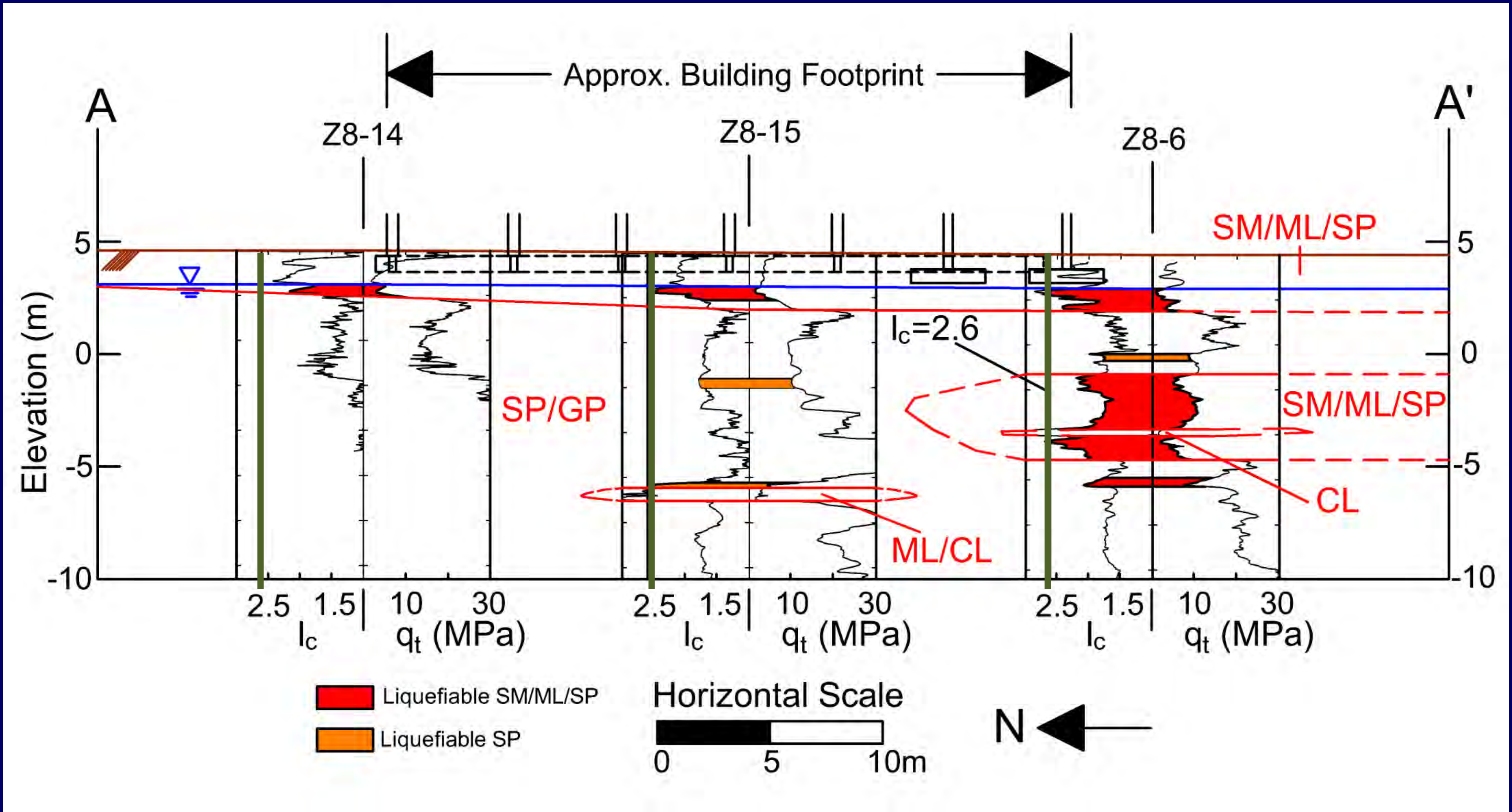
SA Building

Liquefaction-Induced Differential Settlement



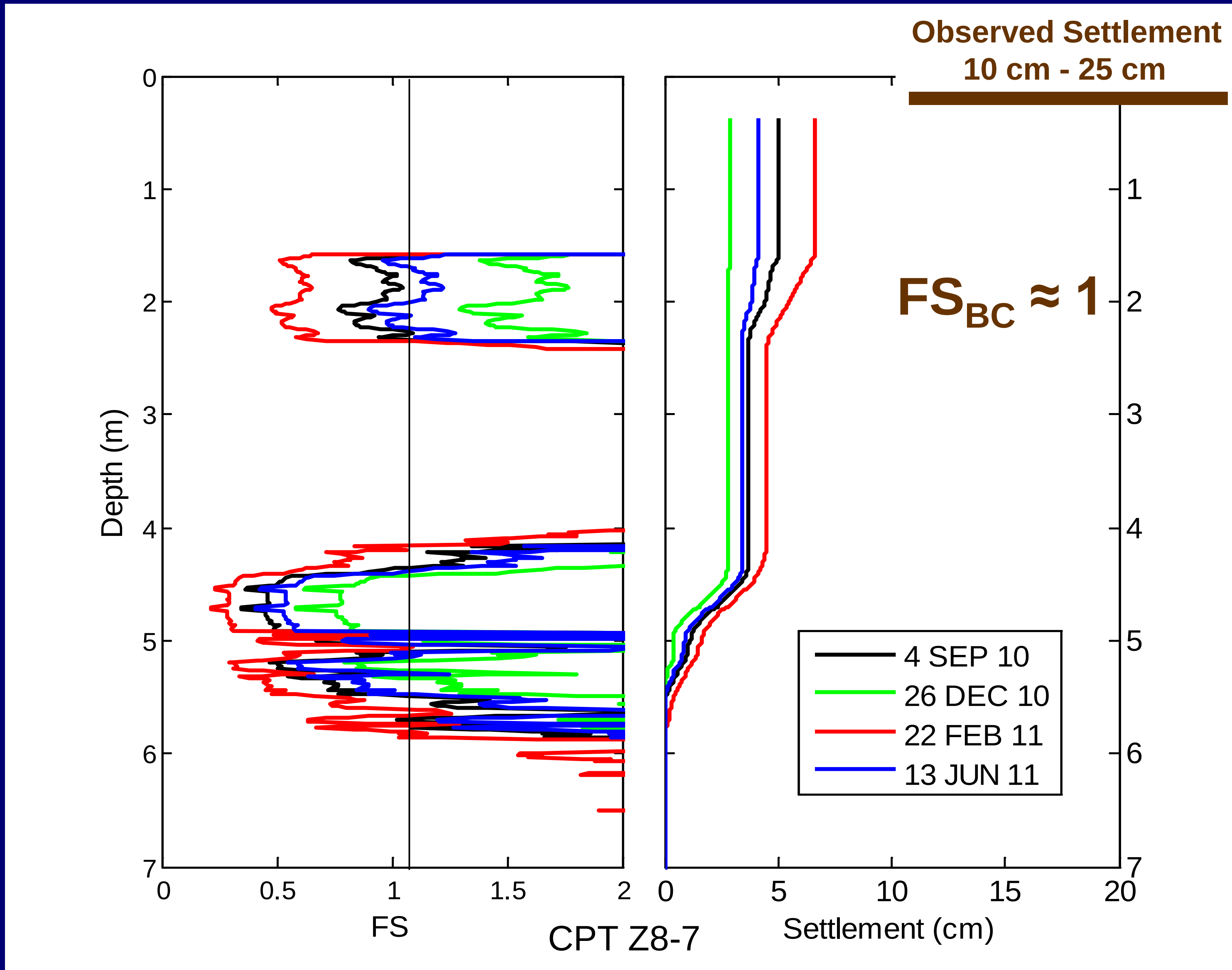
2011 Christchurch EQ

SA Building: Christchurch EQ



2011 Christchurch EQ: Robertson & Wride (1998)

SA Building: Sensitivity of Results

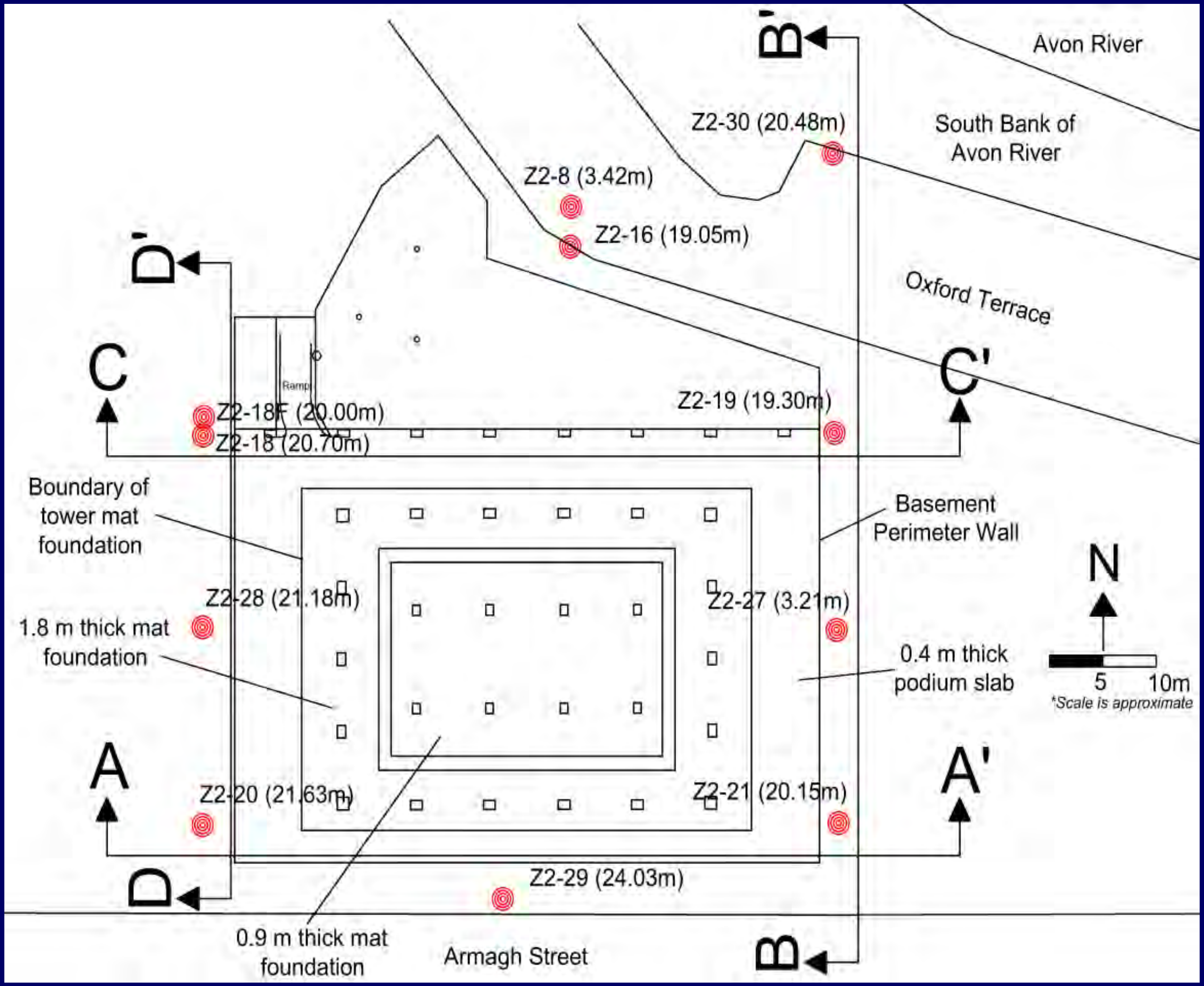


Robertson & Wride (1998) & Zhang, Robertson et al. (2002)

PWC Building

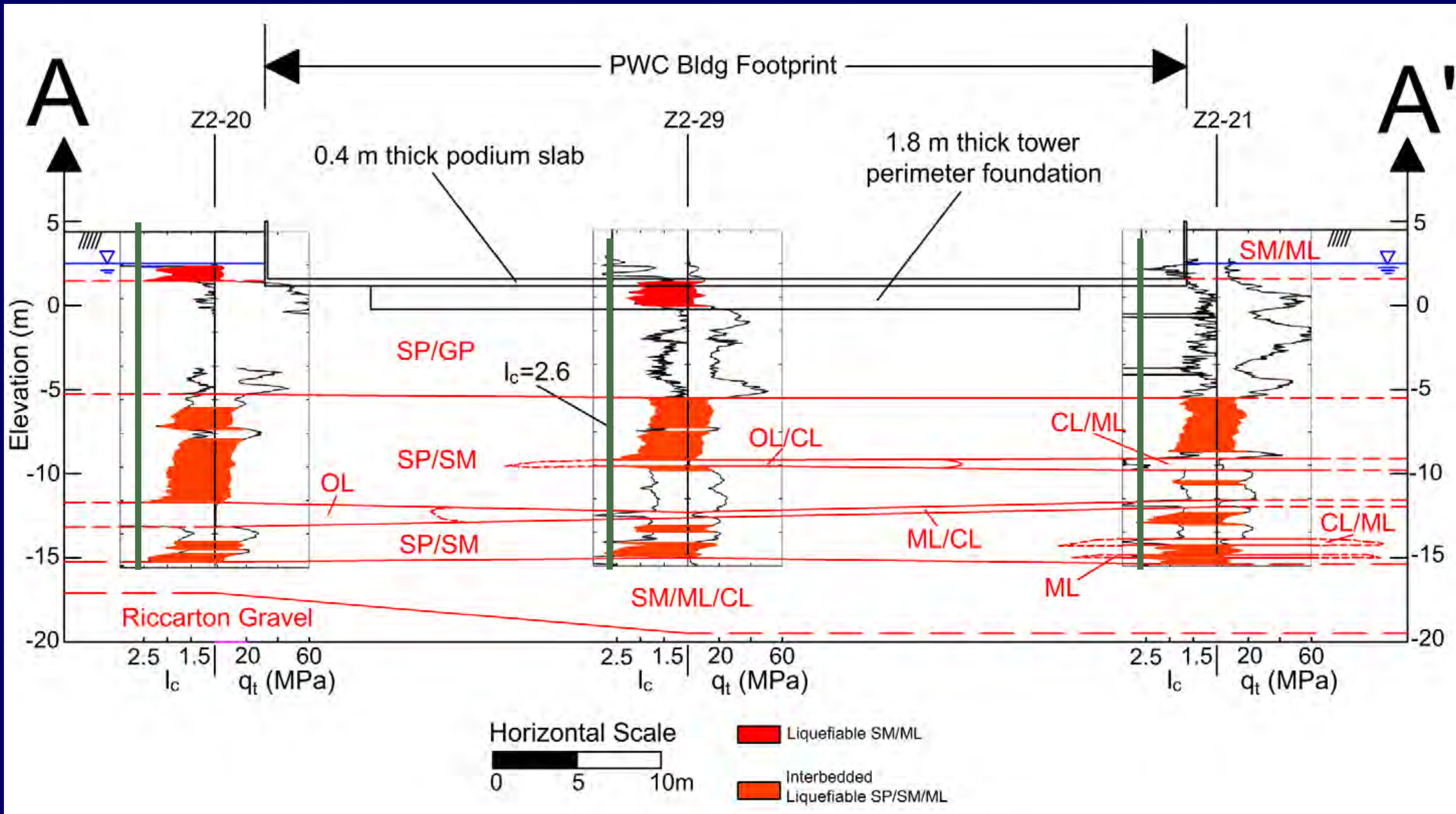
Liquefaction-Induced Differential Settlement and Tilt

21 stories on basement mat



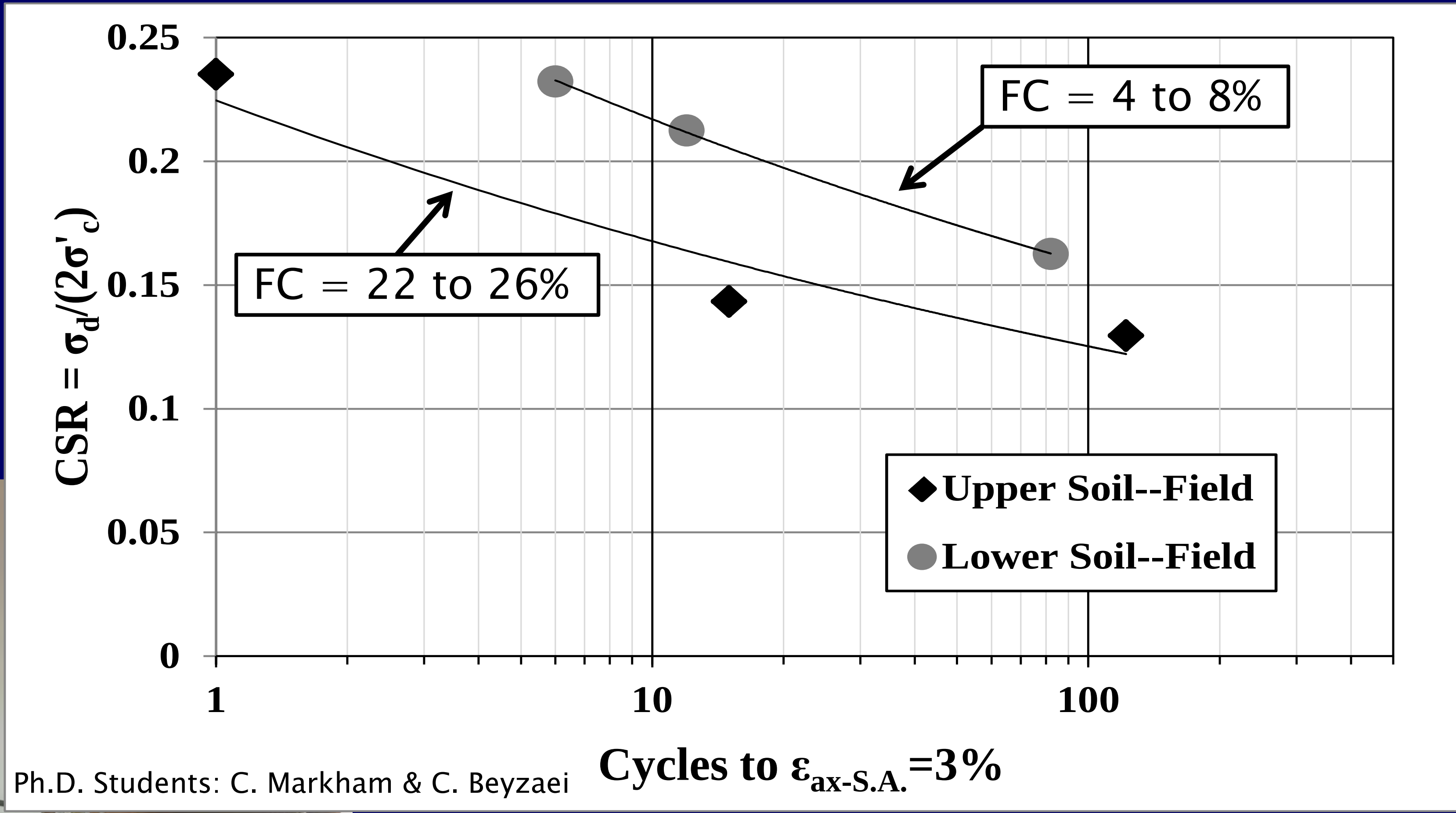
GEER: Bray, Cubrinovski et

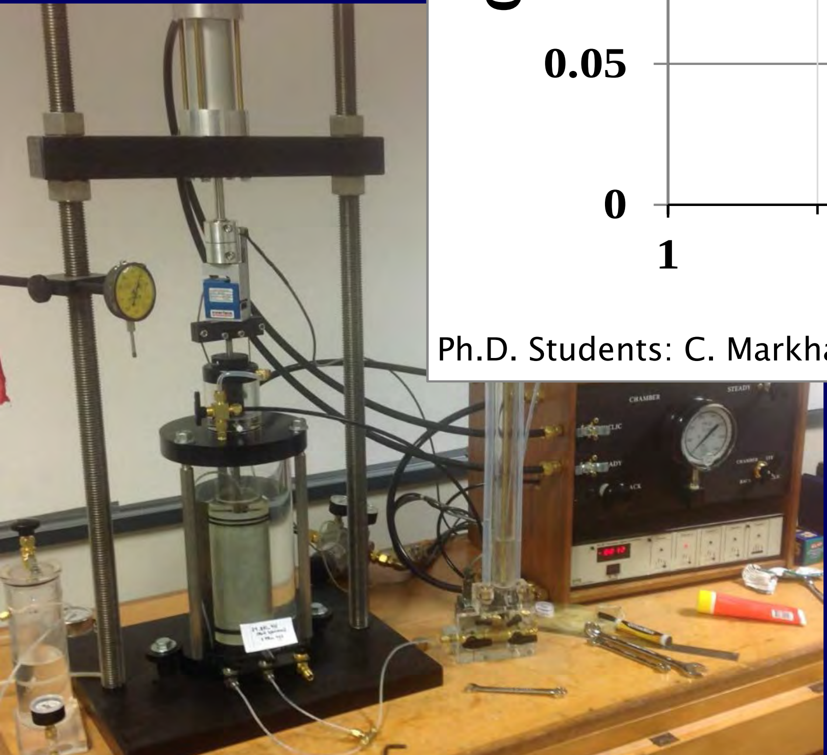
PWC Building



2011 Christchurch EQ: Robertson & Wride (1998)

Cyclic Triaxial Test Results





CTUC Building Shallow Soils

“Undisturbed” Soil Sampling & Testing

D&M Thin- Walled Piston Sampler

Careful Handling

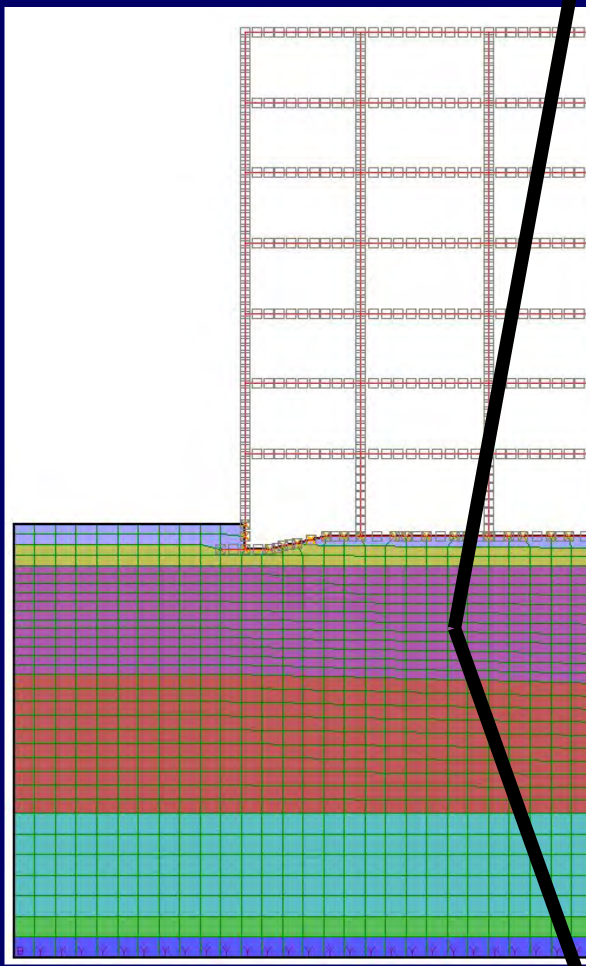
Cut

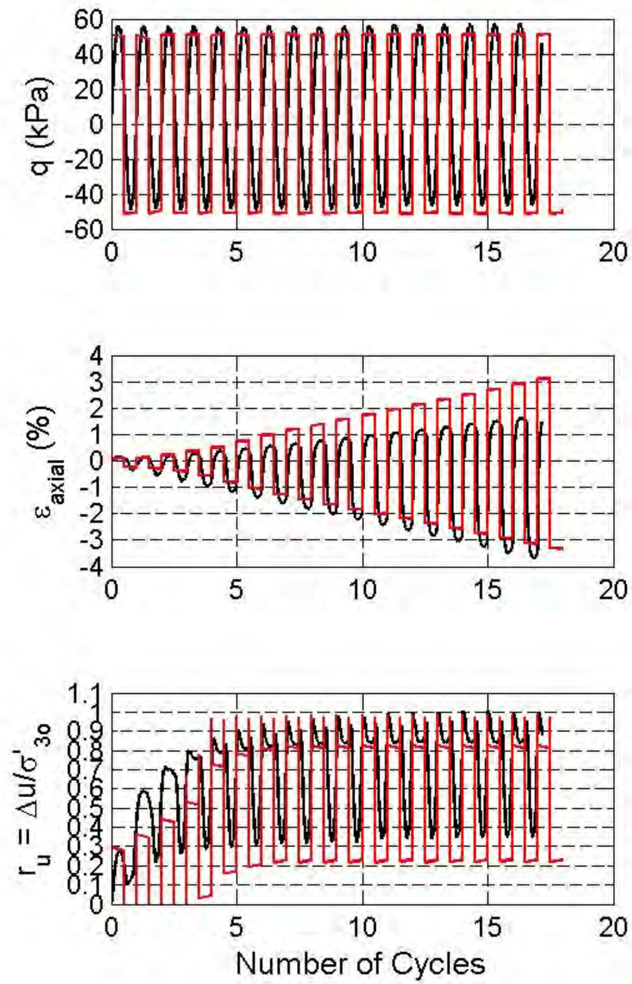
Extrude

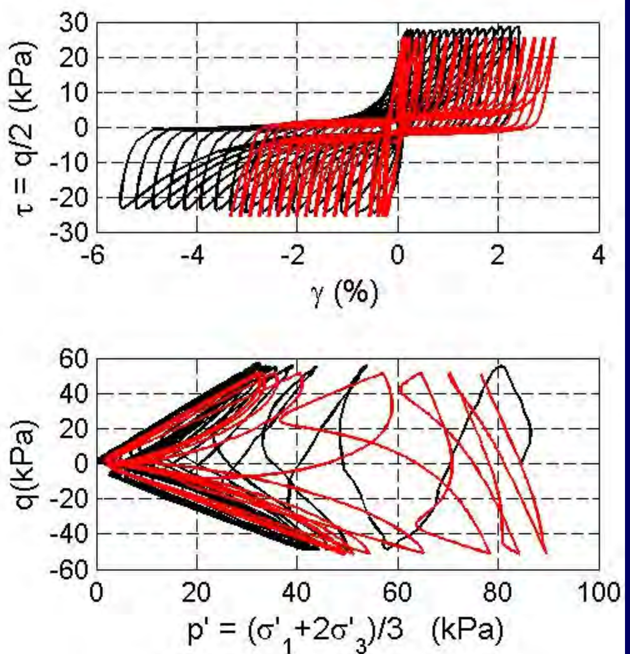
Test

Calibration of Constitutive Model for Numerical Analyses

FTG-7 Building







ICU Static TX Comp. Data vs PM4SAND

Site:	151 Kil. St	ρ_{sat} (kg/m^3):	1758
Borehole:	DM BH2	D_r (%):	47
Sample No.:	4U	G_o :	392
Nearest CPT:	Z1-B3	h_{po} :	3.25
Spec. Depth (m):	5.88	e_{max} :	0.93
Gs:	2.7	e_{min} :	0.59
e_o:	0.77	n_b :	0.5
σ'_{3o} (kPa):	84.7	n_d :	2
PI (%):	--	A_{do}:	3.1812
USCS:	--	z_{max} :	4.396
FC (%):	12	c_z :	250
$N_{3\%\ S.A.}$ (Lab)	14	c_e :	1.8
$N_{3\%\ S.A.}$ (Flac)	16.5	ϕ_{cv} :	33
$N_{5\%\ D.A.}$ (Lab)	16.5	v:	0.3
$N_{5\%\ D.A.}$ (Flac)	14	Q :	9.5
		R :	1

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

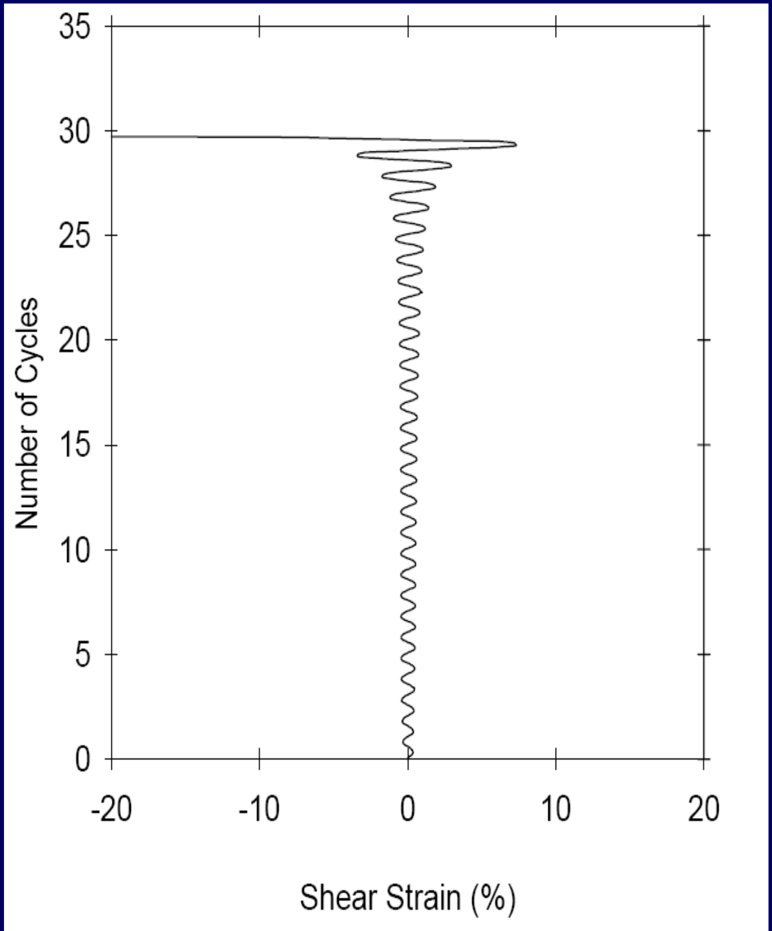
LIQUEFACTION EFFECTS

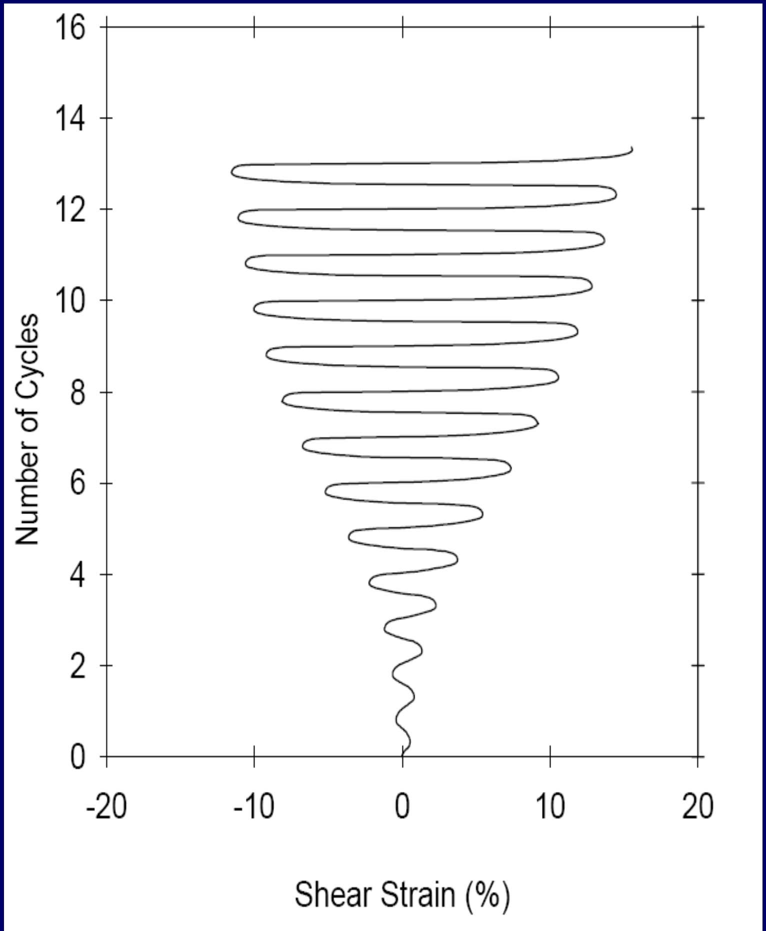
1906 San Francisco EQ (Lawson et al. 1908)

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

1989 Loma Prieta EQ

LIQUEFACTION EFFECTS

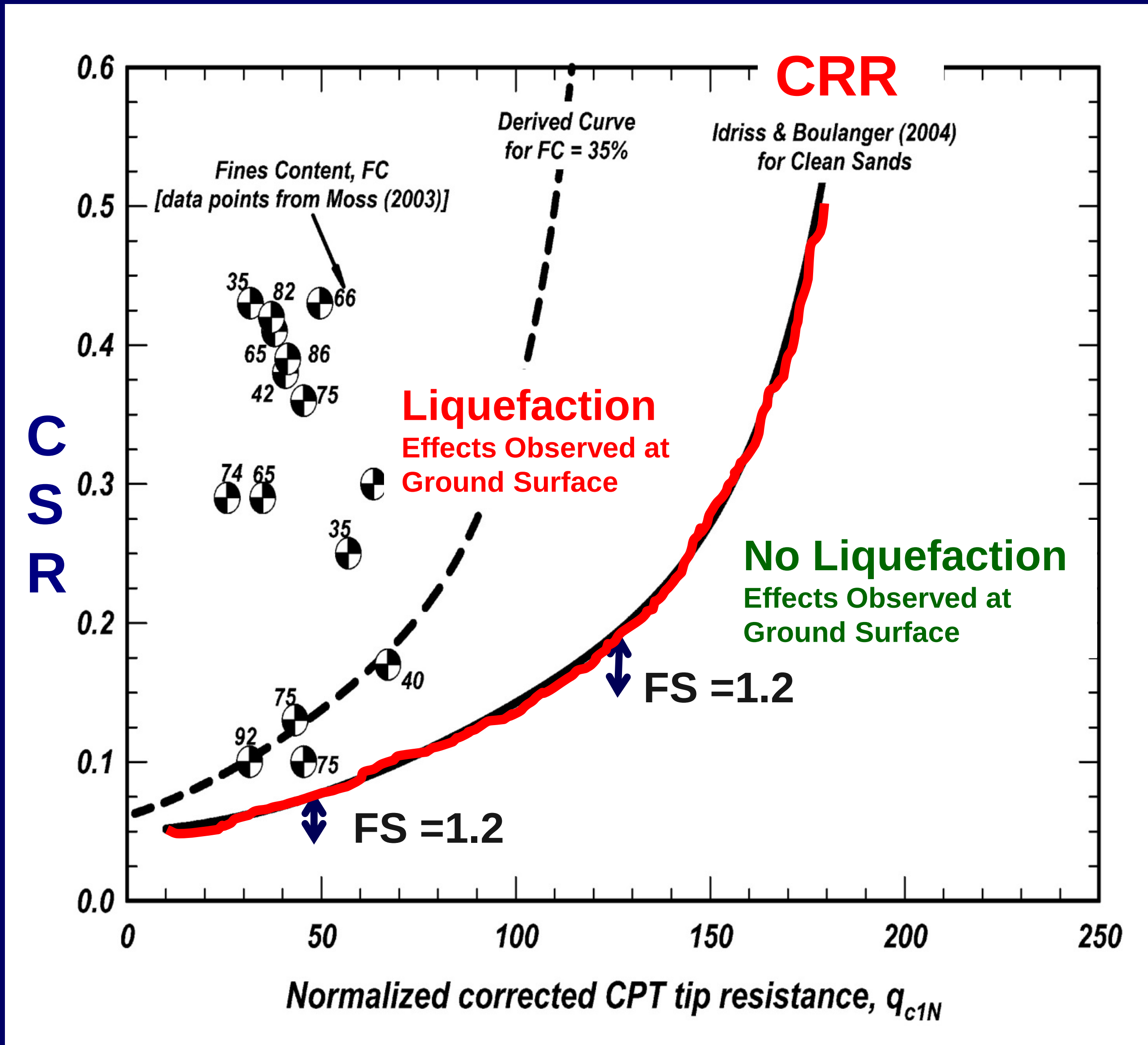




Flow Liquefaction
(strain-softening → large strain)

Cyclic Mobility
(strain-hardening → limited strain)

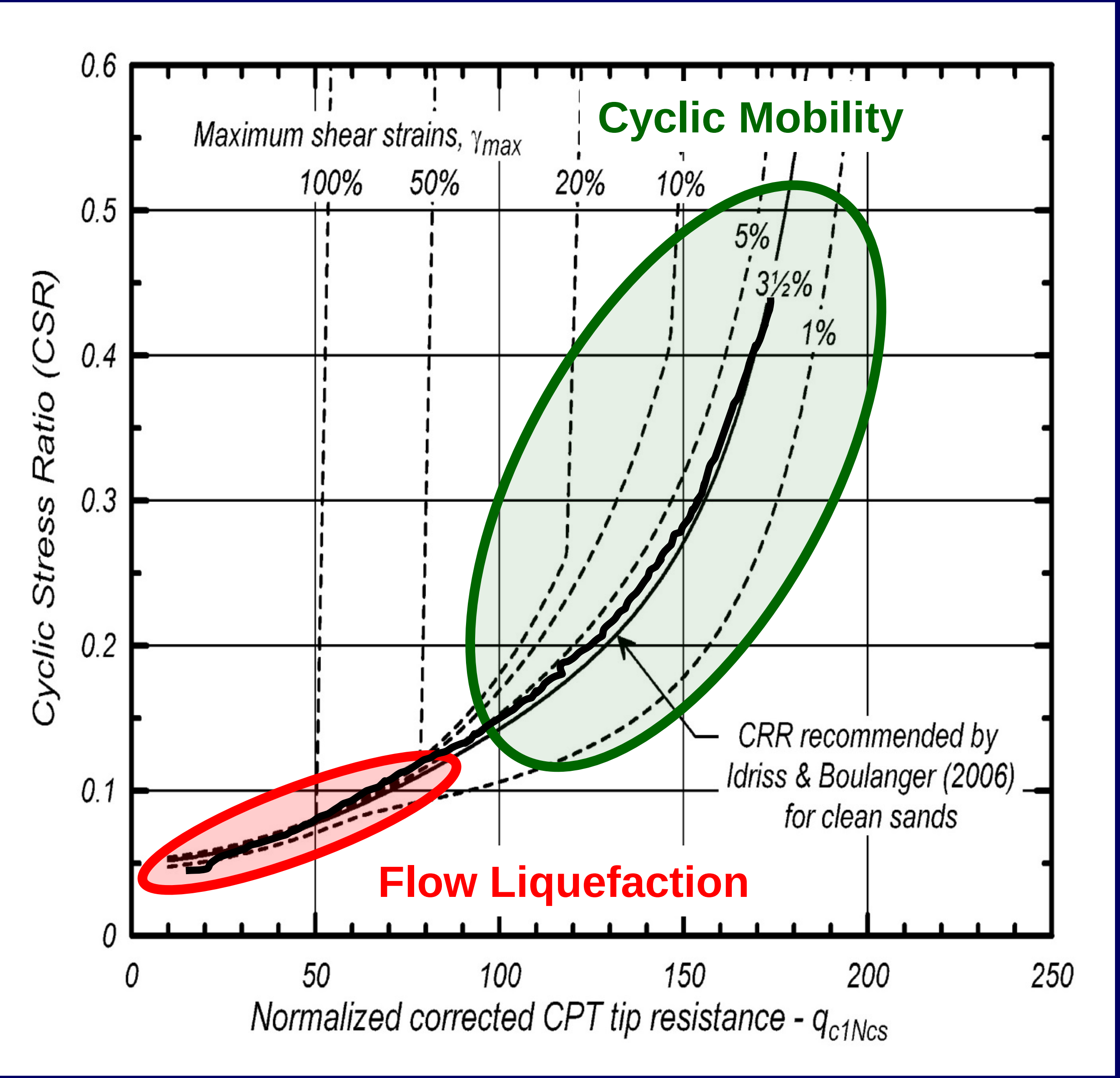
LIQUEFACTION Factor of Safety (FS)



FS = CRR / CSR

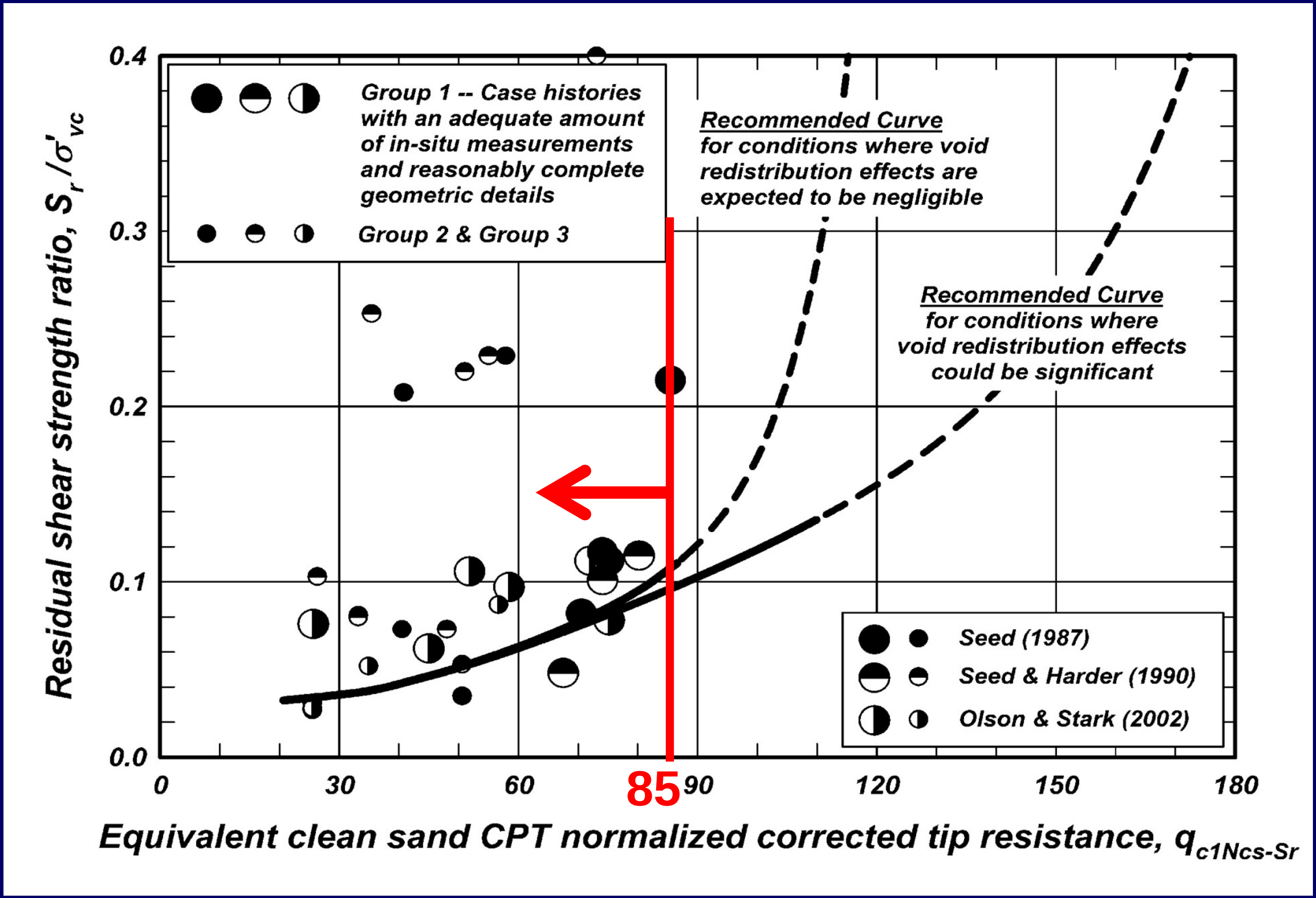
Idriss & Boulanger 2008

LIQUEFACTION EFFECTS



Idriss & Boulanger 2008

Liquefaction Flow Slides when $q_{c1Ncs-Sr} < 85$



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 <u>cannot</u> be estimated using available 1D procedures

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