LESSONS LEARNED FROM DISASTERS

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Geotechnical Extreme Events Reconnaissance
Turning Disaster into Knowledge



POST-EVENT RECONNAISSANCE IS IMPORTANT

Geotechnical Engineering is an experience-driven field

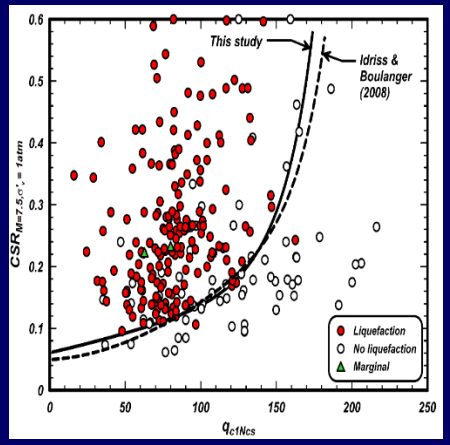
Response of natural soil deposits cannot be easily replicated

Field observations shape our understanding

Provide the data that form our empirical design procedures



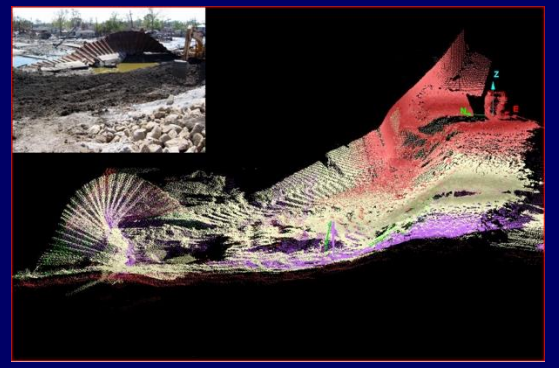
Lateral Spread
1964 Niigata EQ
(H.B. Seed)



Liquefaction Triggering
(Boulanger & Idriss 2014)



Tsunami Damage
(Fritz & Borrero 2005)



I-Wall & Levee Lidar
2005 Katrina Hurricane
(Seed et al. 2005)



2008 Hurricane Gustave
(Wooten et al. 2009)

GEER: Geotechnical Earthquake Engineering Reconnaissance ➡ ***Geotechnical Extreme Events Reconnaissance***

2023 M7.8 Turkey EQ

(Moug et al. 2023)



Intense Shaking-Induced Damage
Antakya



Liquefaction Building Tilt & Settlement
Golbasi



Ejecta in Golbasi with PI = 9 – 14

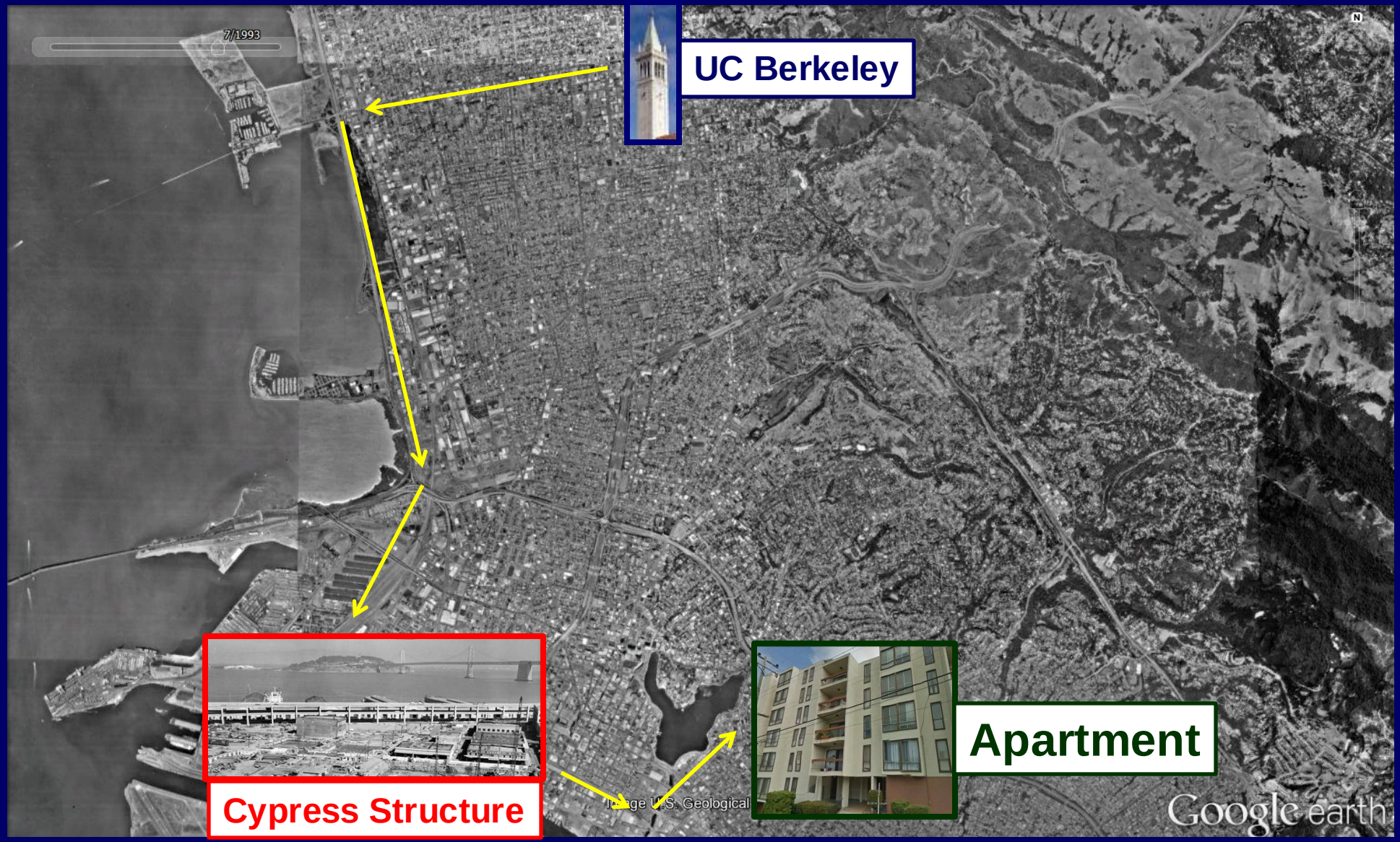






Flooding of Settled Areas in Iskenderun

My Commute in 1989 - Berkeley to Oakland



Cypress Structure Collapse - 1989 Loma Prieta EQ



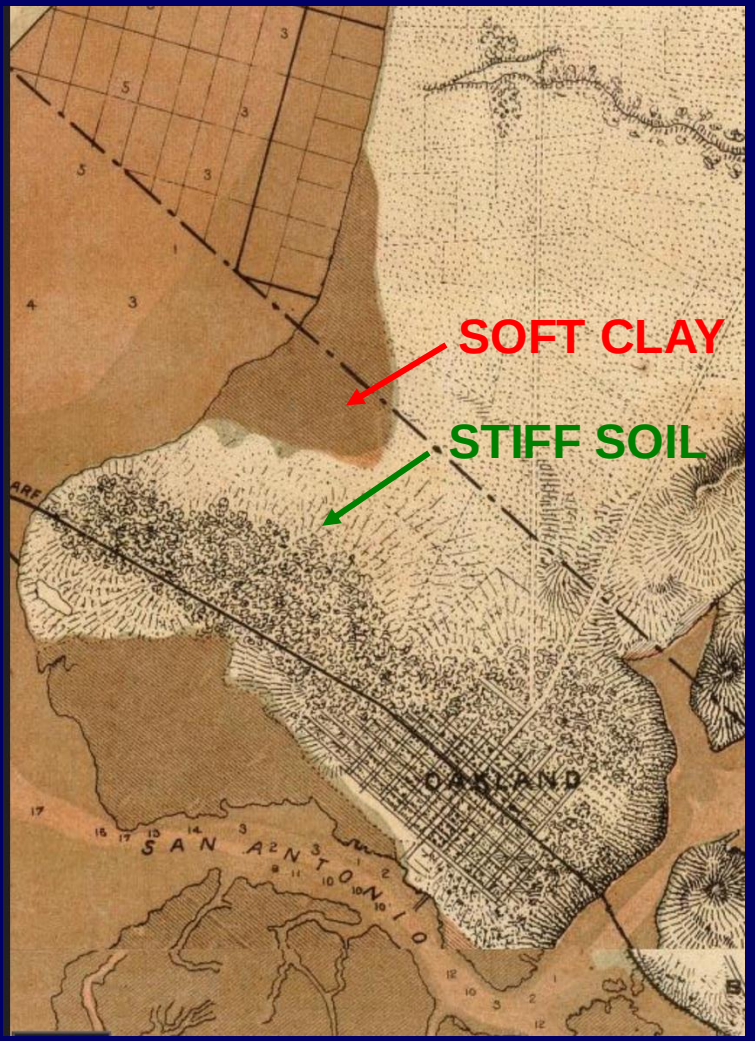




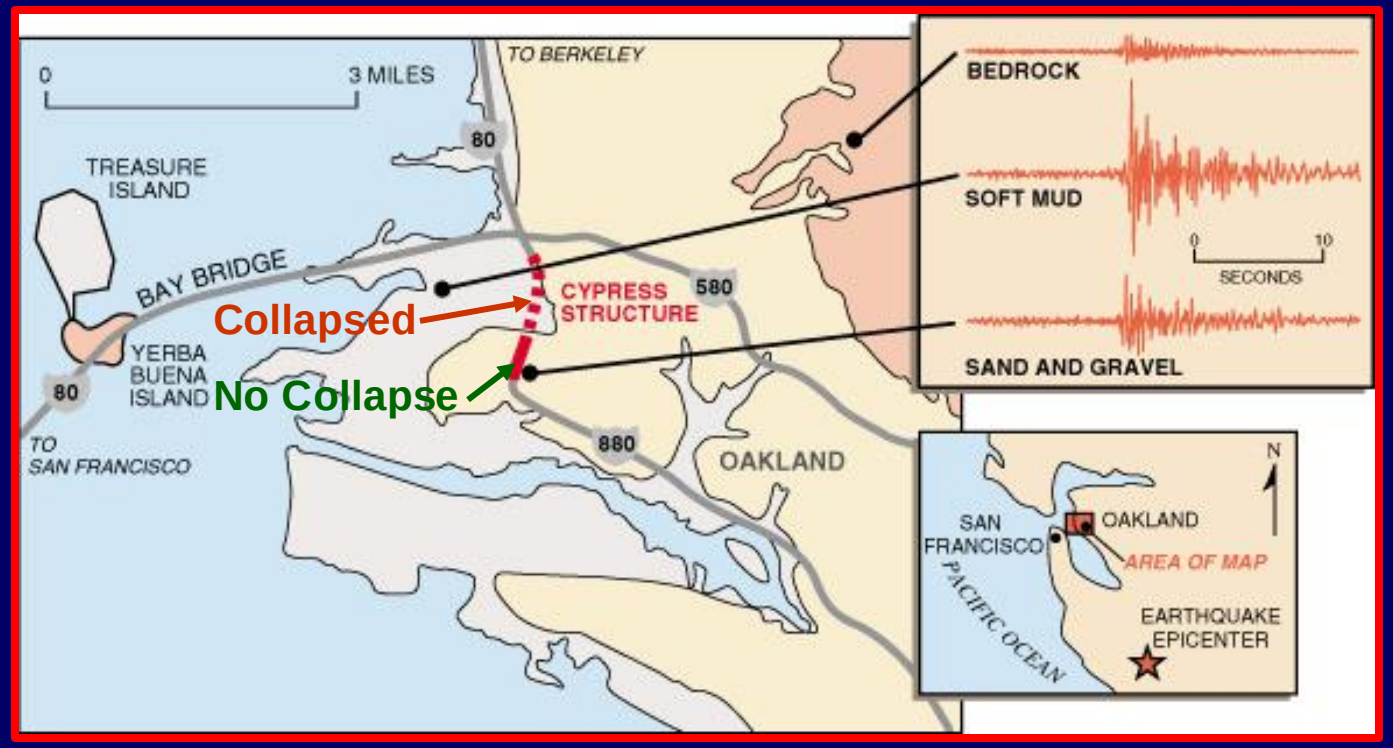


42 people killed from Cypress Structure collapse
overall 63 people killed

Site Effects - Cypress Structure Collapse over Soft Clay Deposit



1874 Map of Salt Marsh Land
SF Board of State Harbor Commissioners



1989 Loma Prieta Aftershocks

USGS Fact Sheet - 176-95 (based on Hough et al. 1990)

Bay Bridge Partial Collapse – 1989 Loma Prieta, SF EQ



Struve Slough Bridge Collapse – 1989 Loma Prieta, SF EQ







Damage in San Francisco – 1989 Loma Prieta EQ



1989 LP EQ (Seed et al. 1990)



1906 SF EQ (Lawson et al. 1908)





1994 Northridge, LA EQ









57 people killed

Santa Monica Freeway Damage at La Cienega









1995 Kobe, Japan EQ

Intense Near Fault Ground Shaking









6,434 people killed

Akai et al. 1995

Video in 2-Story Building in Kobe, Japan



NHK Television

Liquefaction-Induced Fires

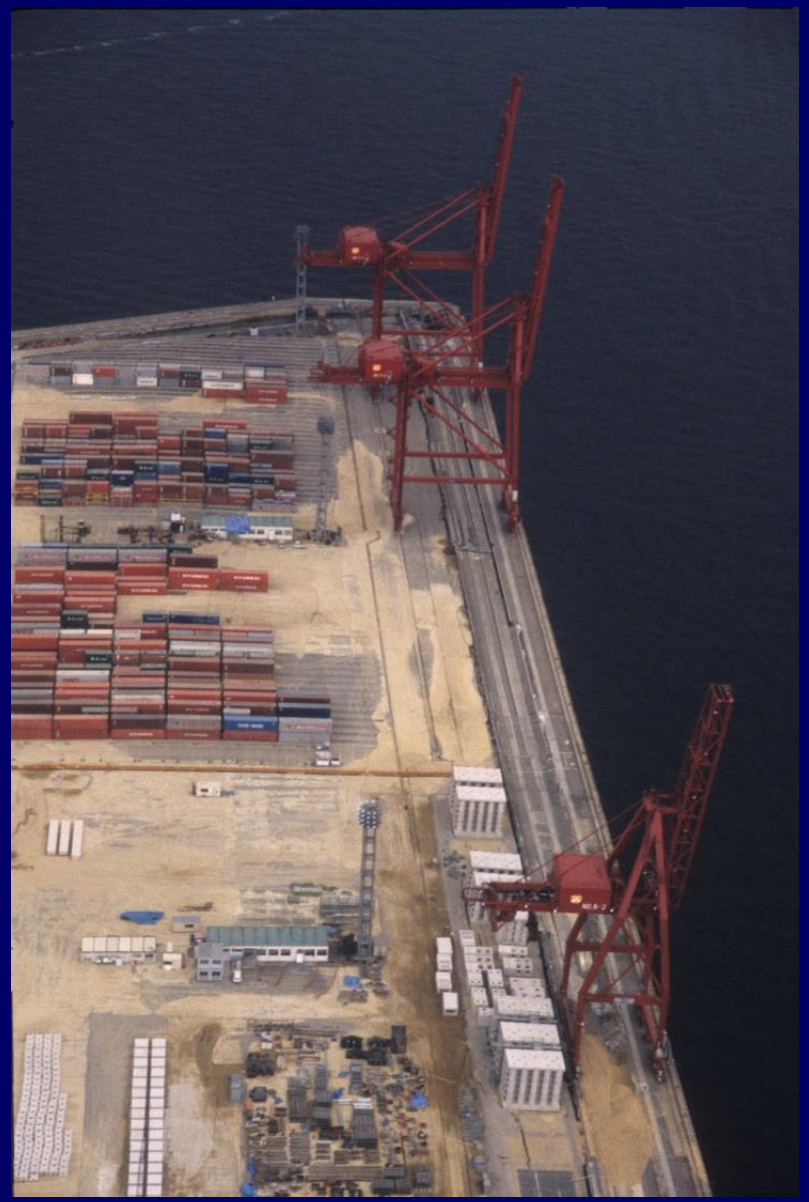






Akai et al. 1995

Liquefaction-Induced Damage to Ports









Akai et al. 1995

Earthquake Damage to Subway





Dakai Subway Station, Kobe, Japan

Akai et al. 1995

Geotechnical Extreme Events Reconnaissance

Turning Disaster into Knowledge

OBJECTIVES

Collect perishable data

Develop and implement new technologies

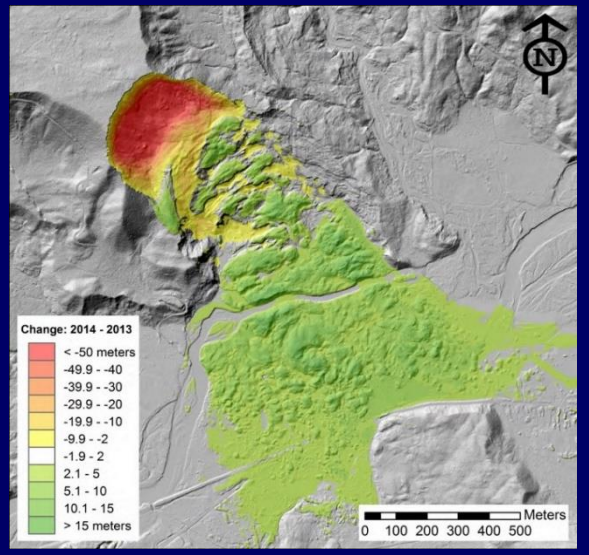
Document the geotechnical effects of extreme events to advance research and understanding



Adapazari, 1999 Turkey EQ
(Bray et al. 2004)



2008 Hurricane Gustave
(Wooten et al. 2009)



2014 Oso Landslide, Washington
(Wartman et al. 2014)

PRINCIPLES OF RECONNAISSANCE

- Safety
- Team & ethical approach
- Assess overall damage & identify key opportunities
- Will documentation of effects advance profession?
- 1 well-documented case history > many photos of damage
- Employ remote sensing, UAVs, Lidar, SfM, etc.
- Systematic, geocoded collection of perishable data
- “Just the facts” - there is time later to figure out “why”

Aerial Reconnaissance



1999 Kocaeli, Turkey EQ





1999 Chi-Chi, Taiwan EQ



‘Best Ride’ – 1999 Kocaeli EQ





US Marine CH-53E “Super Stallion” from USS *Kearsarge*

used to rescue CPT Scott O’Grady in Bosnia in 1995

‘Virtual Ride’ - UAV

Flyover of 2014 S Napa EQ Fault - Z-Q Chen & M Chen of UMKC

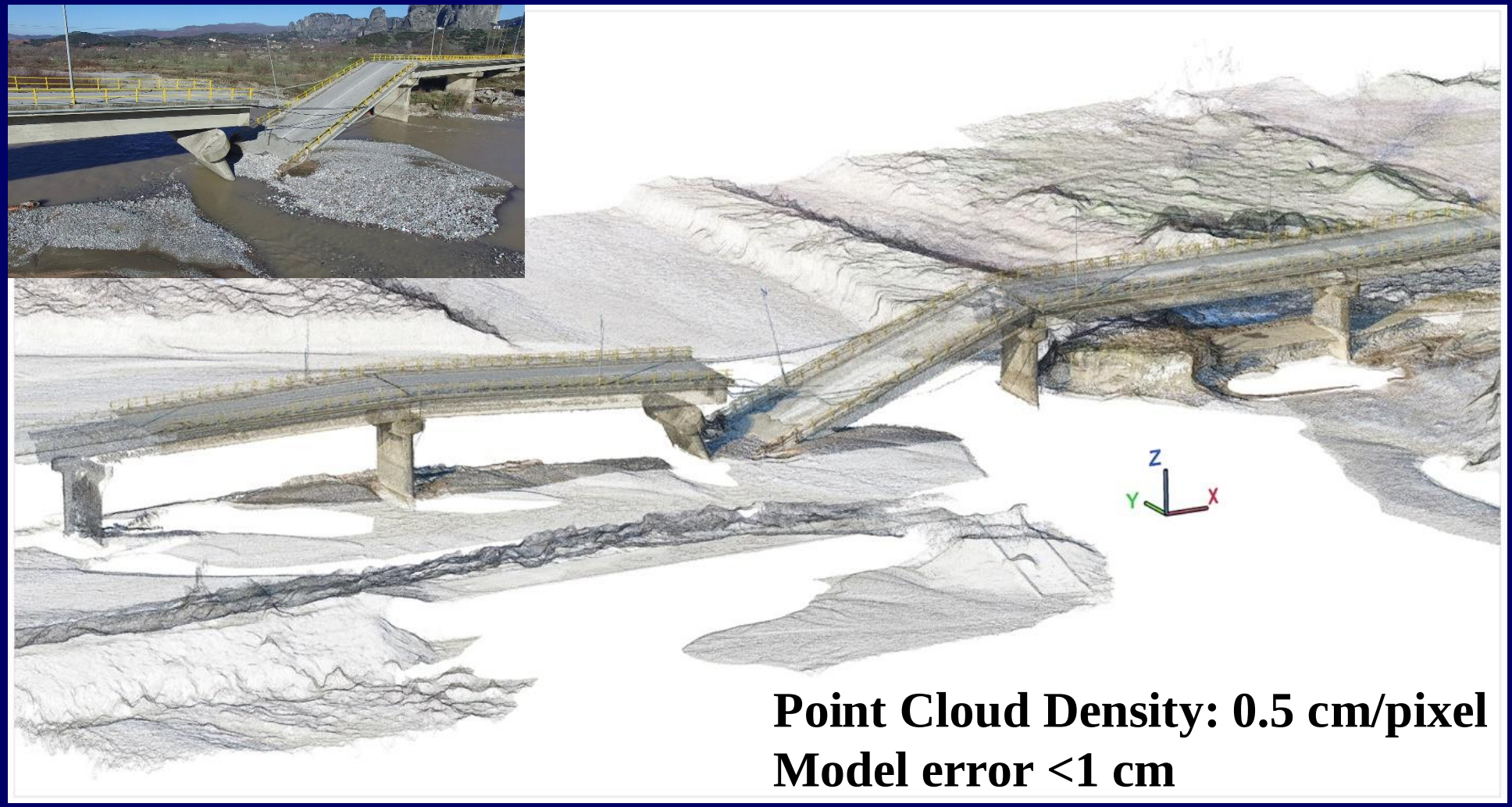




80 high-resolution 4000 x 3000 pixel images provide 2.4 cm/pixel detail

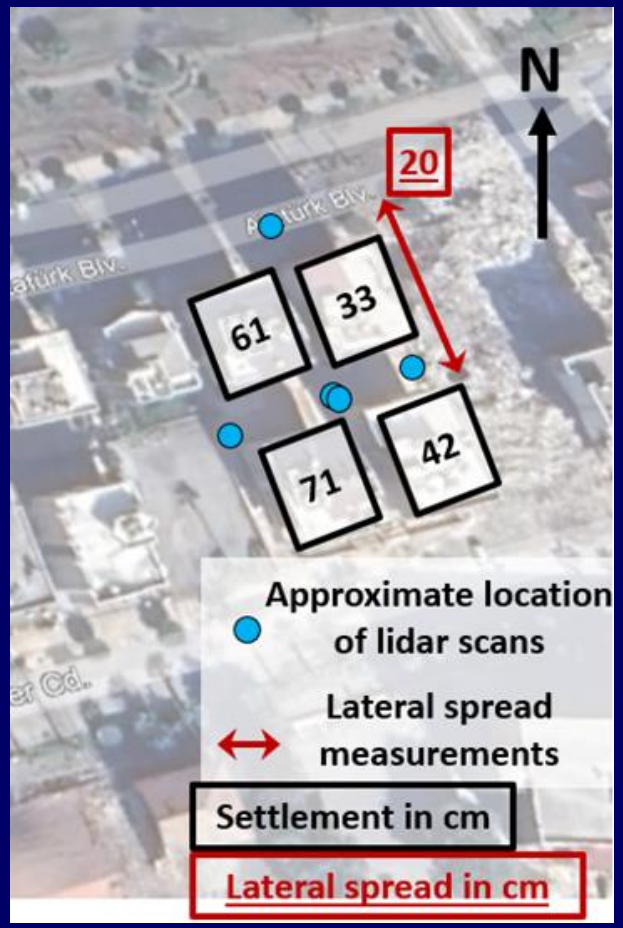
3D Point Cloud SfM Model of Scour-Induced Failure

- Failure location was physically inaccessible
- 3-hr UAV survey taking 649 photos at different points of view
- Reconstruct using Structure-from-Motion (SfM)



Zekkos et al. (2016)

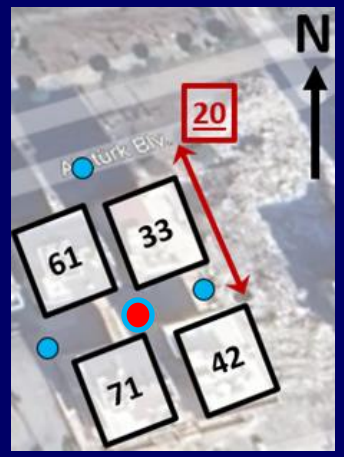
Lidar Survey of Liquefaction-Induced Building and Ground Settlement Iskenderun, 2023 Turkey EQ

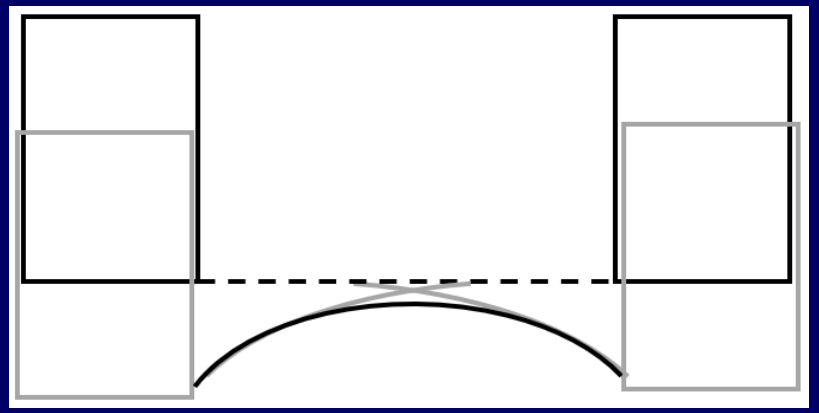


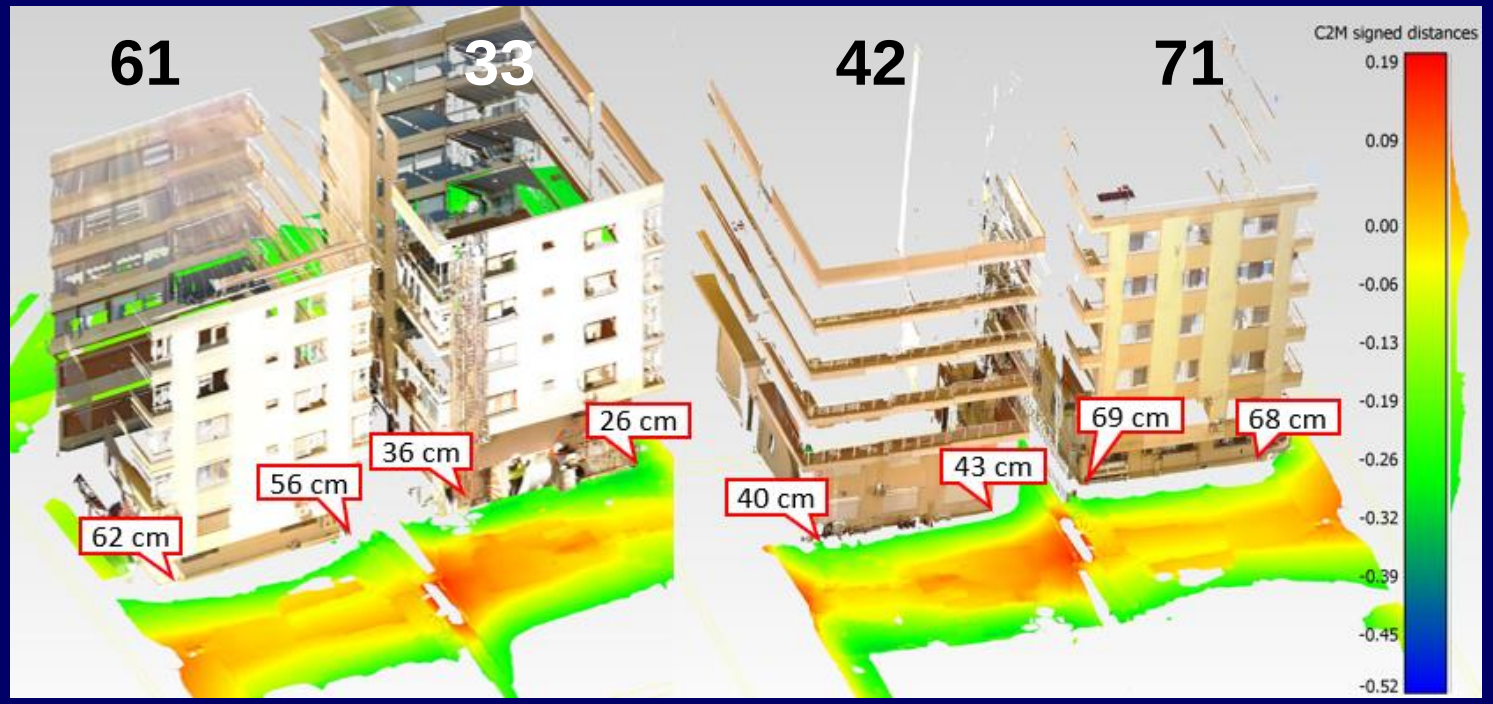


Moug, Bassal, Bray et al. (2023) GEER

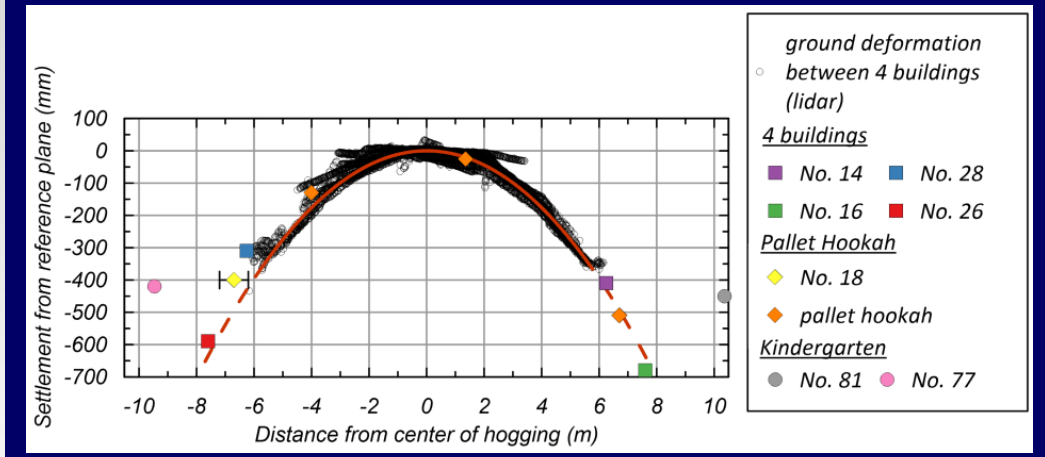
Lidar Survey of Liquefaction-Induced Building and Ground Settlement Iskenderun, 2023Turkey EQ







Lidar scan data facing north & south buildings



Moug, Bray et al. (2024)

REMOTE SENSING





Pre- and post-satellite images of tailings dam failure

(2010 Maule, Chile EQ; Bray & Frost et al. 2010)

Google Earth™



Central Business District, Christchurch, New Zealand

Google Earth™









Central Business District, Christchurch, New Zealand

19 SEP 2017 M7.1 Mexico EQ

Mexico City Building Responses from Social Media







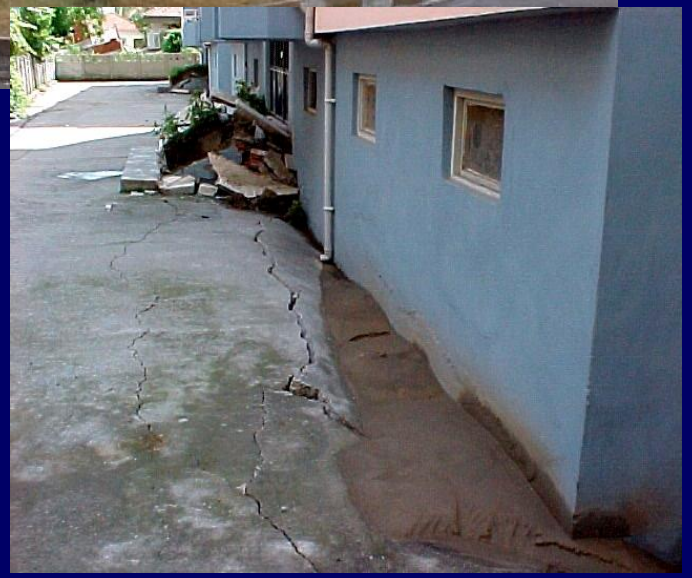
369 people killed

E. Rathje, UT, *DesignSafe*





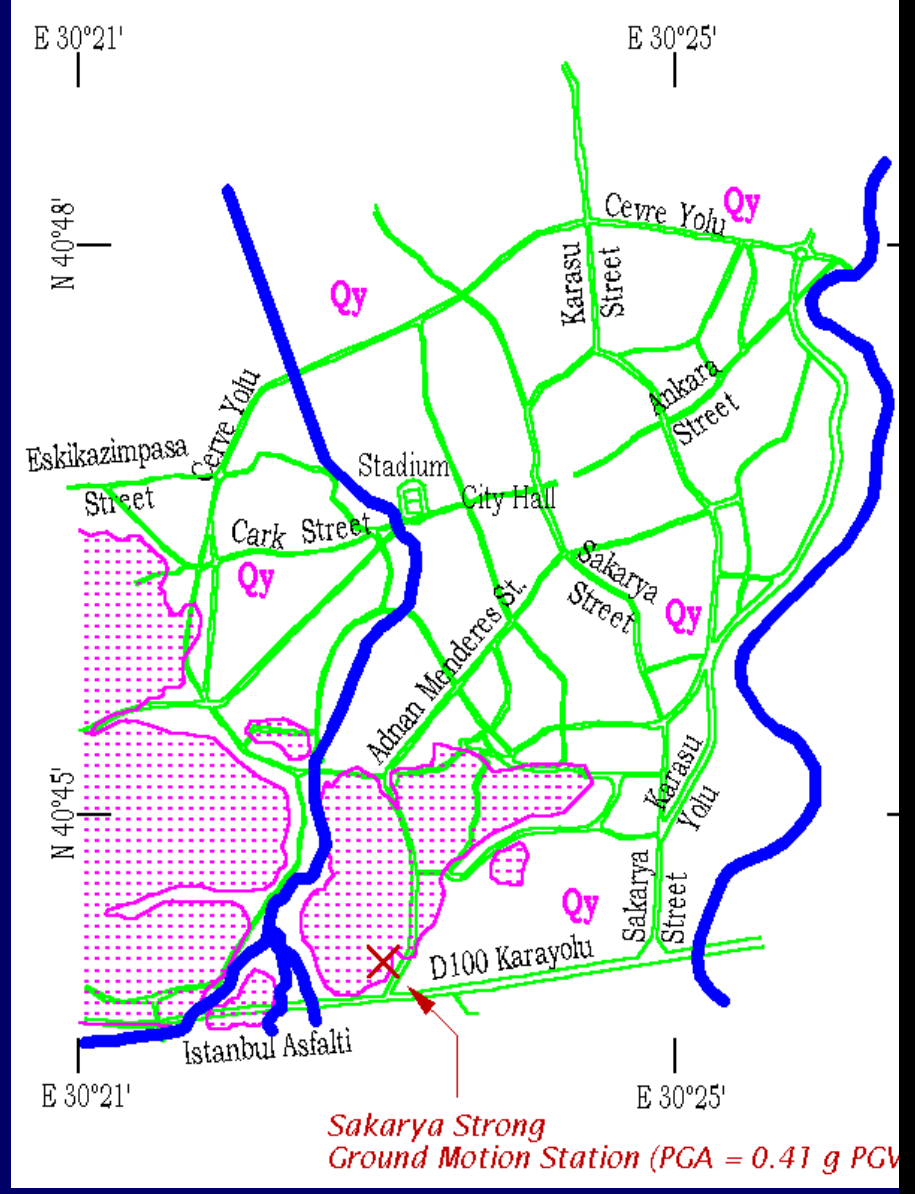




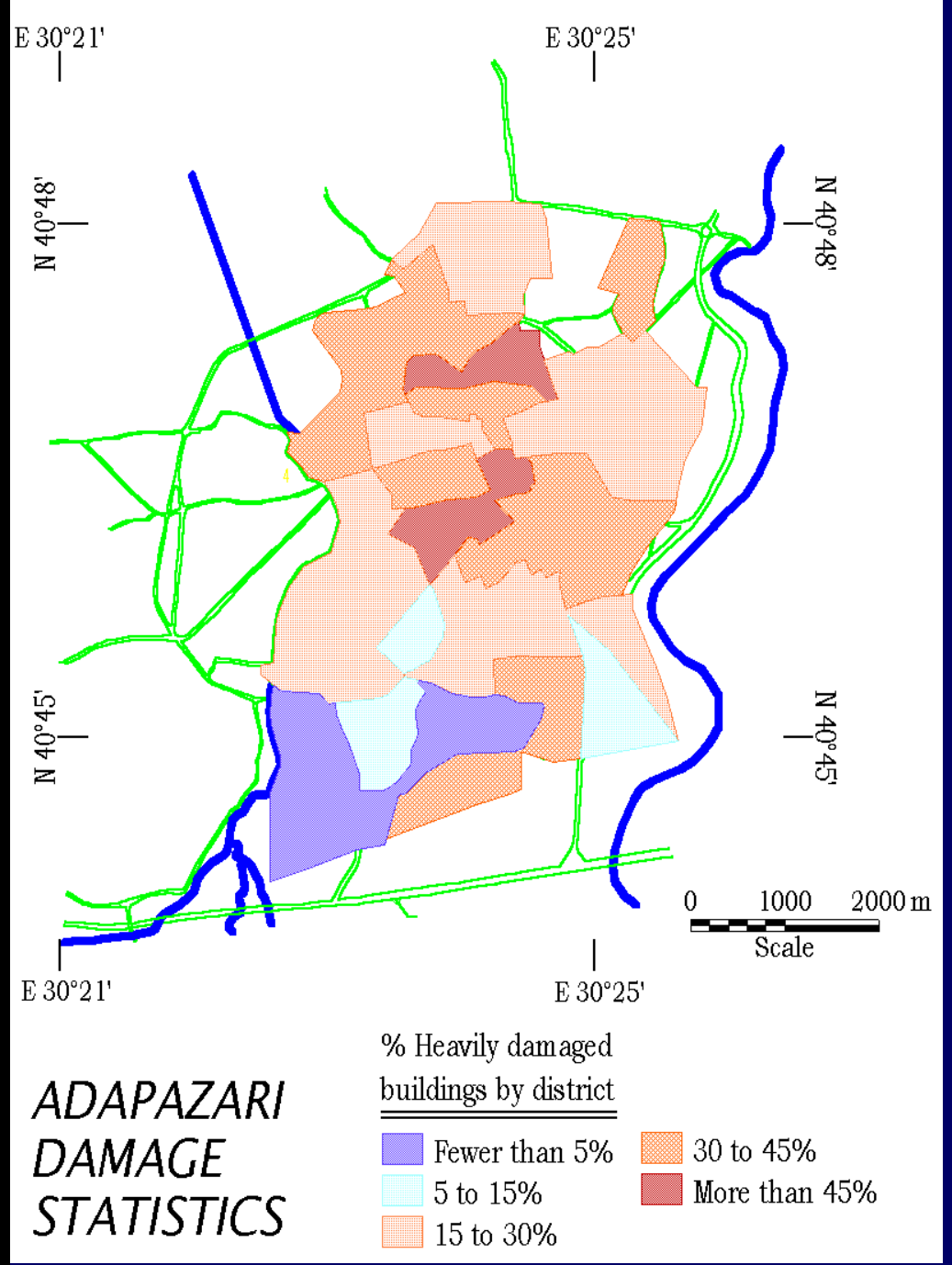
Adapazari, Turkey

1999 Kocaeli Earthquake: A. Ansal, N. Abrahamson, J. Bachuber, J. P. Bardet, A. Barka, M. Baturay, M. Berilgen, R. Boulanger, J. Bray, O. Cetin, L. Cluff, T. Durgunoglu, D. Erten, M. Erdik, D. Frost, I. M. Idriss, T. Karadayilar, A. Kaya, W. Lettis, J. Martin, J. Mitchell, G. Olgun, A. Onalp, T. O'Rourke, W. Paige, E. Rathje, C. Roblee, R. Sancio, W. Savage, R. Seed, P. Somerville, J. Stewart, B. Sunman, B. Swan, C. Synolakis, S. Toprak, D. Ural, R. Witter, M. Yashinski, T. Yilmaz, L. Youd

17000+ people killed


E 30°21'
E 30°25'
N 40°48'
N 40°45'
Cevre Yolu
Qy
Karasu Street
Ankara Street
Eskikazimpasa Street
Cevre Yolu
Stadium
City Hall
Cark Street
Qy
Adnan Menderes St.
Sakarya Street
Qy
Karasu Yolu
Sakarya Street
Qy
D100 Karayolu
Istanbul Asfalti
Sakarya Strong
Ground Motion Station (PGA = 0.41 g PGV

Adapazari


E 30°21'
E 30°25'
N 40°48'
N 40°45'
0 1000 2000 m
Scale
ADAPAZARI
DAMAGE
STATISTICS
% Heavily damaged
buildings by district
Fewer than 5%
5 to 15%
15 to 30%
30 to 45%
More than 45%

Coburn & Spence 1992

Damage Distribution along Line 1

(60 Structures)

Collapse

Partial Collapse

Significant SE Damage

Minor SE Damage

Architectural Damage

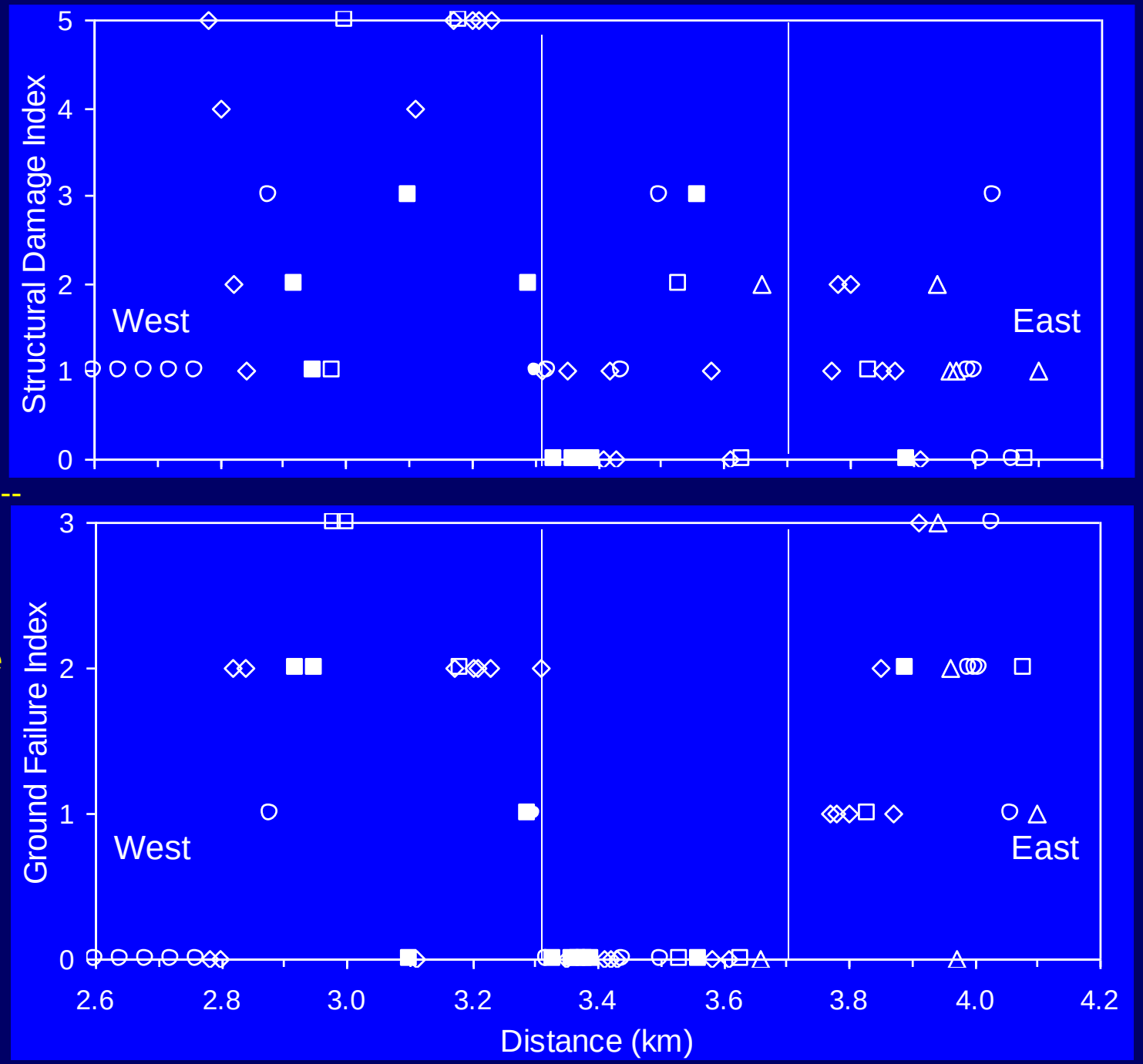
No Damage

Severe Ground Failure
(Δ > 25 cm)

Moderate Ground Failure
(10 < Δ < 25 cm)

Minor Ground Failure
(Δ < 10 cm)

No Ground Failure



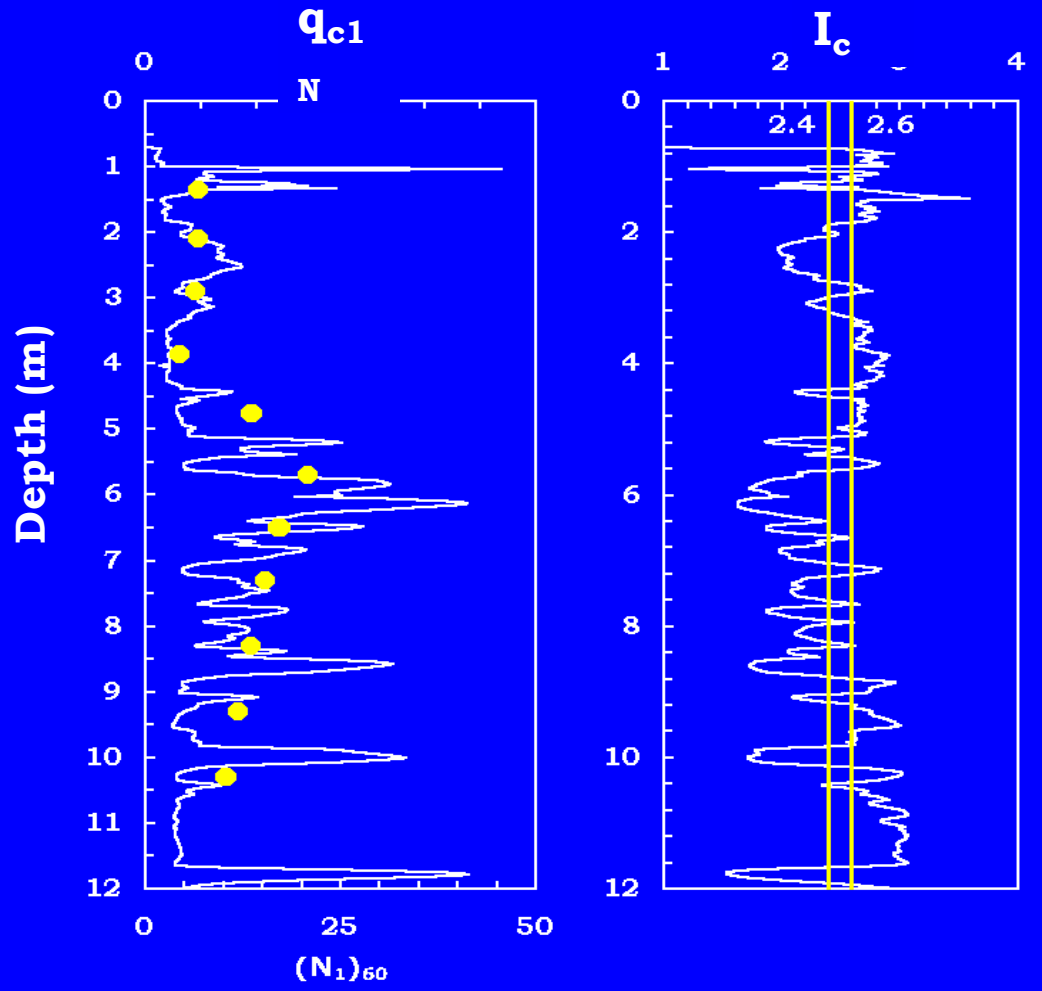
- 1 Story
- 2 Stories
- 3 Stories
- 4 Stories
- 5 Stories
- 6 Stories

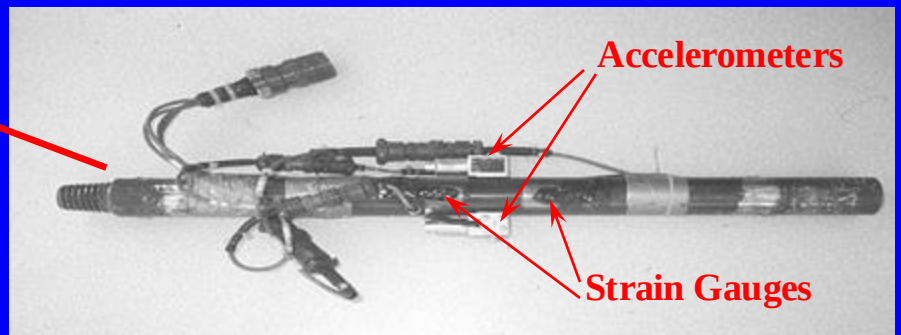
Bray & Stewart 2000

Subsurface Investigations (Sancio et al. 2002)









Collapse

Partial Collapse

Significant SE Damage

Minor SE Damage

Architectural Damage

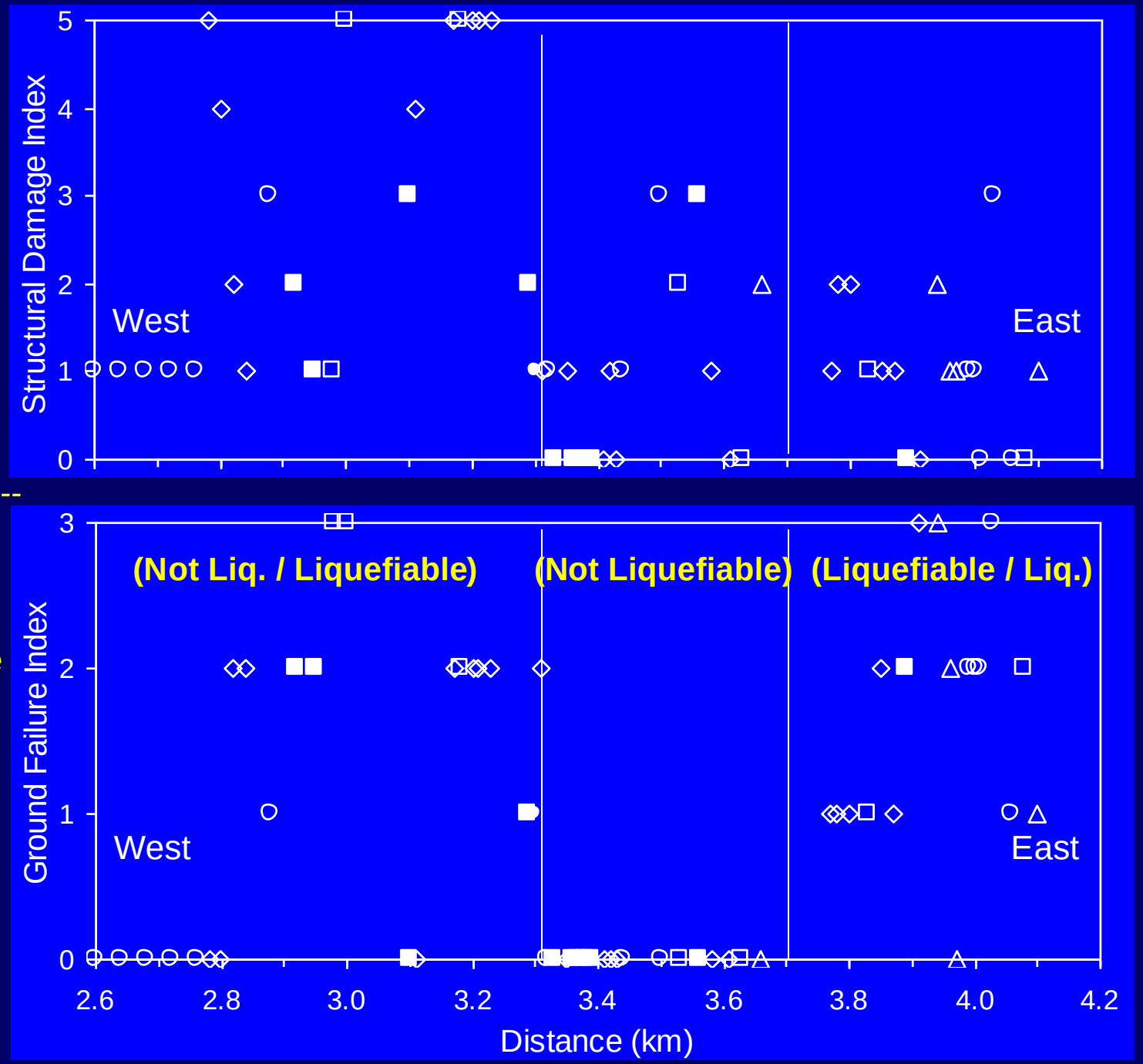
No Damage

Severe Ground Failure
(Δ > 25 cm)

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(Δ < 10 cm)

No Ground Failure



Coburn & Spence 1992

Damage Distribution along Line 1

(60 Structures)

NSF GEER EERI

- 1 Story
- 2 Stories
- 3 Stories
- 4 Stories
- 5 Stories
- 6 Stories

Bray & Stewart 2000

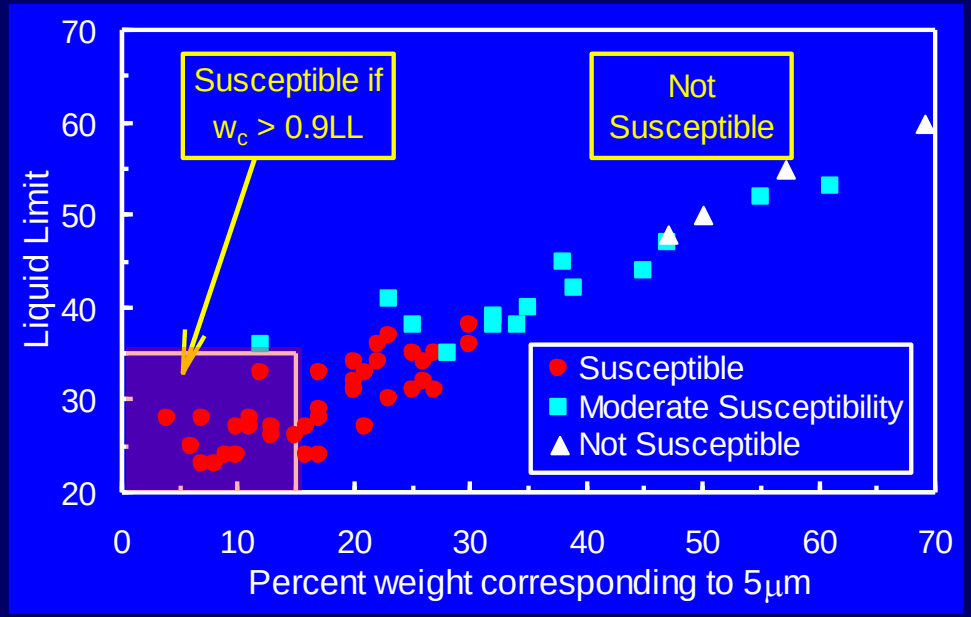
New Liquefaction Susceptibility Criteria

OLD

Chinese Criteria

(Seed and Idriss 1982

in Youd et al. 2001)



NEW

PI & w_c/LL Criteria

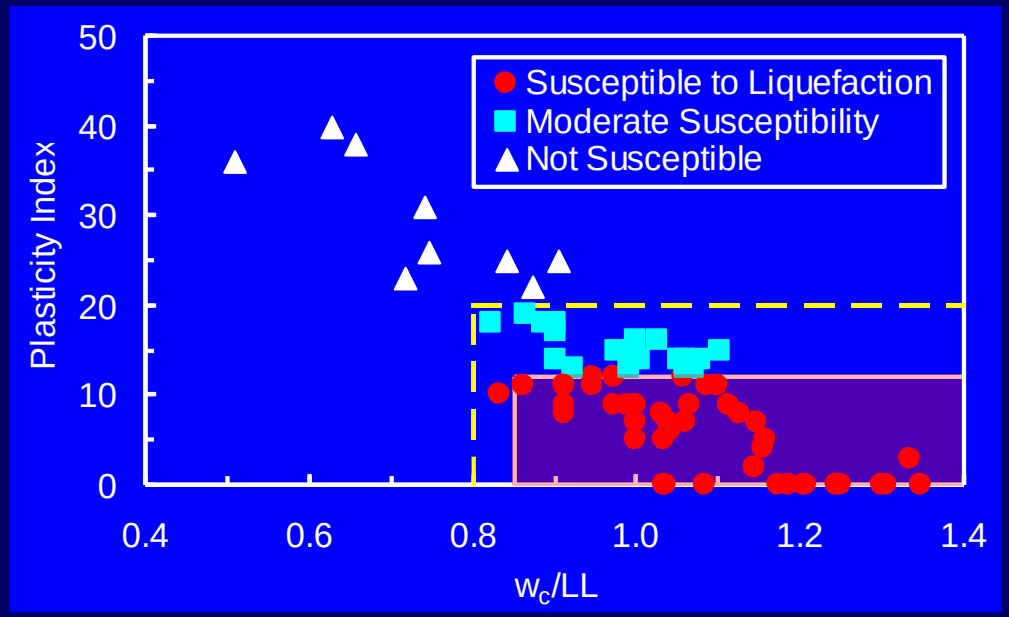
(Bray & Sancio 2006)

Susceptible:

PI ≤ 12 & w_c/LL ≥ 0.85

Moderate Susceptibility:

w_c/LL > 0.8 & 12 < PI ≤ 20



Geotechnical Effects of the 2010 Chile Earthquake

Jonathan Bray, UC Berkeley; David Frost, Georgia Tech; Ramon Verdugo, Universidad de Chile; Christian Ledezma, Pontificia Universidad Catolica de Chile; Terry Eldridge, Golder Assoc.

Pedro Arduino, Univ. of Washington; Scott Ashford, Oregon State Univ.; Dominic Assimaki, Georgia Tech; David Baska, Terracon; Jim Bay, Utah State Univ.; R. Boroschek, Universidad de Chile; Gabriel Candia, UC Berkeley; Leonardo Dorador, Univ. de Chile; Aldo Faúndez, Servicio de Salud Arauco; Gabriel Ferrer, Pontificia Univ. Catolica de Chile; Lenart Gonzalez, Golder Assoc.; Youssef Hashash, Univ. of Illinois; Tara Hutchinson, UC San Diego; Laurie Johnson, Laurie Johnson Consulting; Katherine Jones, UC Berkeley; Keith Kelson, Fugro William Lettis & Assoc.; Rob Kayen, US Geological Survey; Gonzalo Montalva, Universidad de Concepcion; Robb Moss, Calif. Polytechnic Univ. SLO; Sebastian Maureira, Universidad de Chile; George Mylonakis, Univ. of Patras; Scott Olson, Univ. of Illinois; Kyle Rollins, Brigham Young Univ.; Nicholas Sitar, UC Berkeley; Jonathan Stewart, UC Los Angeles; Mesut Turel, Georgia Tech; Alfredo Urzúa, Prototype Engineering; Claudia Welker, Golder Assoc.; Rob Witter, DOGAMI; & Chilean Air Force

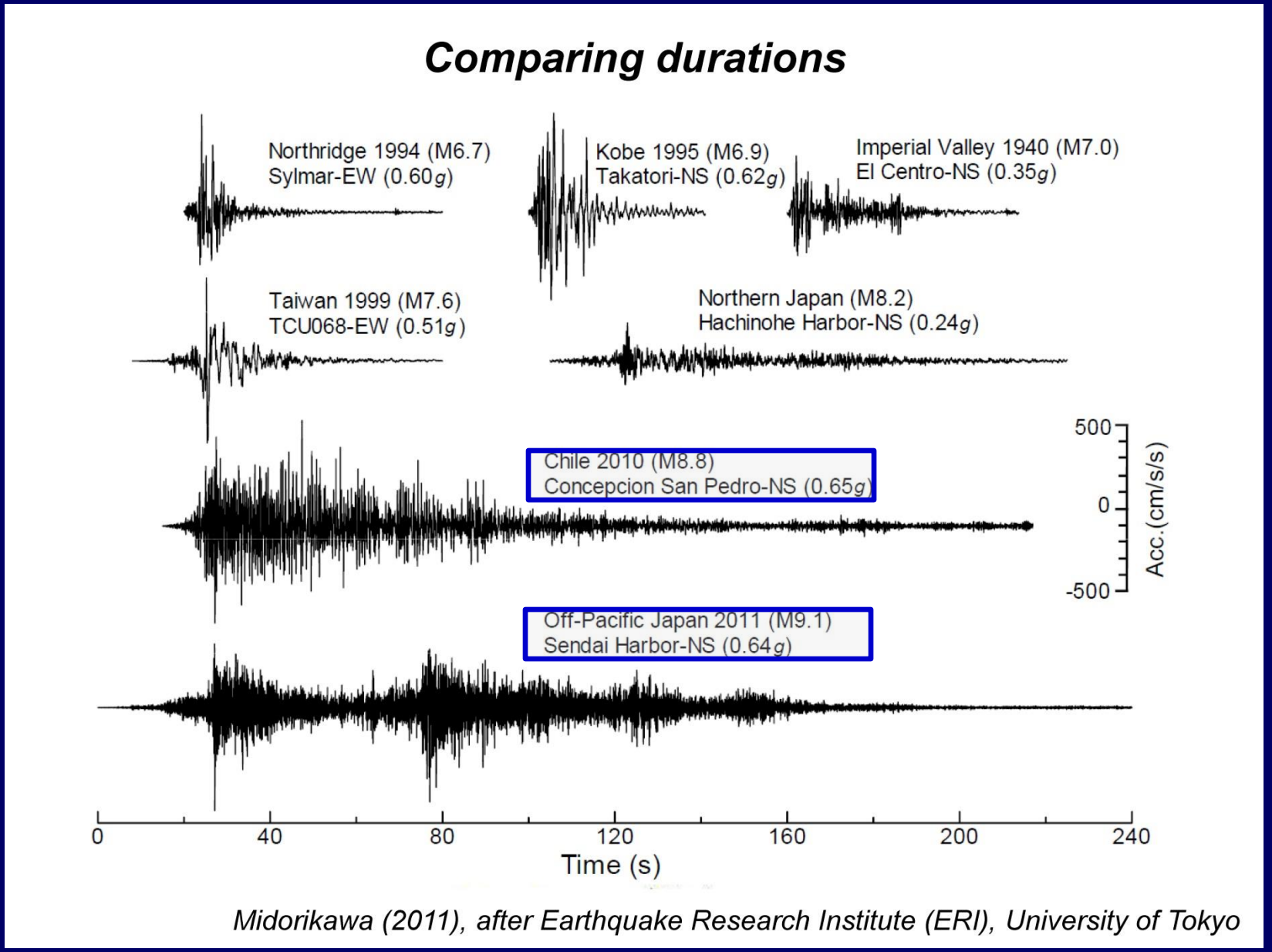
550 people killed

Geotechnical Extreme Events Reconnaissance

Turning Disaster into Knowledge

www.geerassociation.org

Seismic Demand of Subduction Zone EQs



Midorikawa (2011), after Earthquake Research Institute (ERI), University of Tokyo

NSF-Sponsored GEER Reconnaissance



Chile-US Partners ★



Aerial Recon



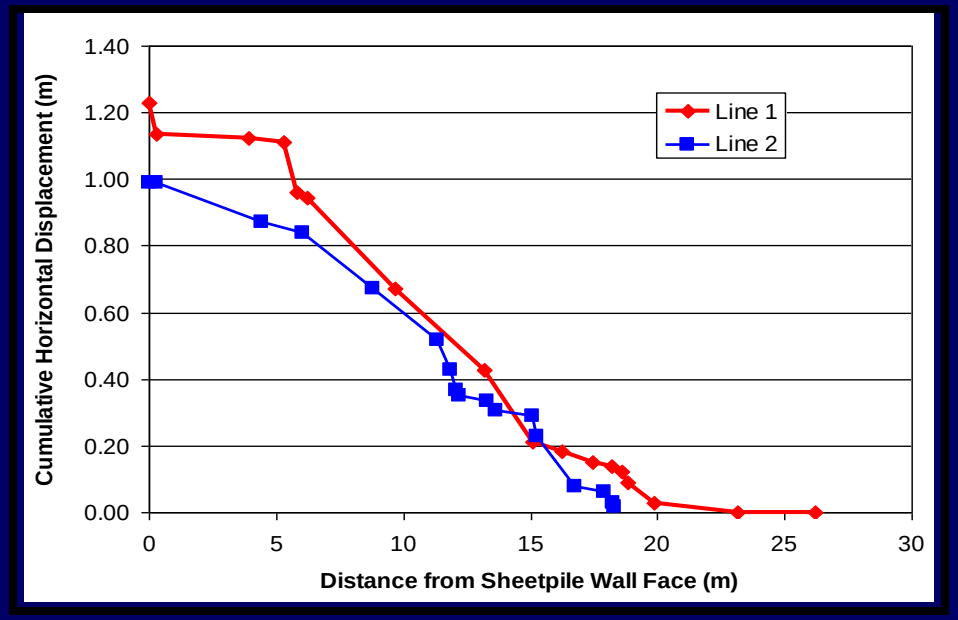
Ground Recon



Damage to Ports: Coronel







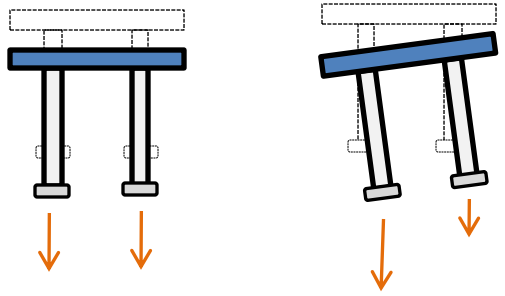
Seismic Performance of Infrastructure

Juan Pablo II Bridge: Liquefaction-induced pier settlements along bridge span





Modes of deformation

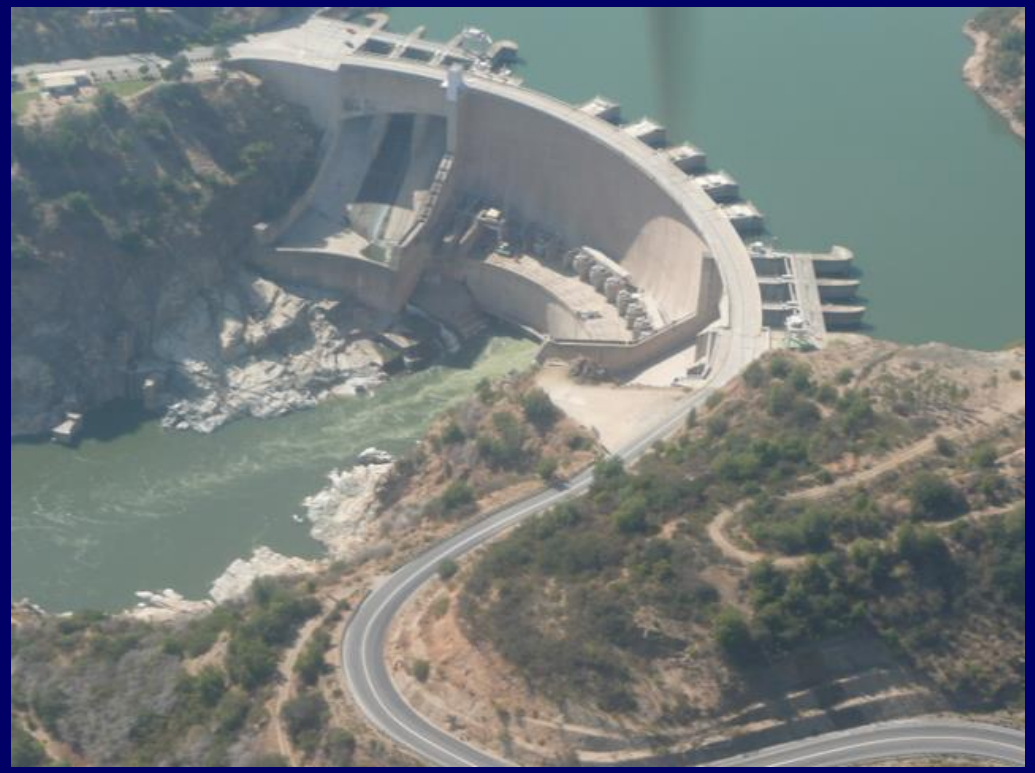




Seismic Performance of Dams - 2010 Chile EQ

(Verdugo et al. 2012 – *Earthquake Spectra*)

Most dams performed well



Rapel Concrete Dam
(112-m high concrete arch dam)



Los Cristales Dam
(27-m high earth dam with 60-cm thick asphalt concrete core)

Coihueco Earth Dam (H_{max} = 31 m)

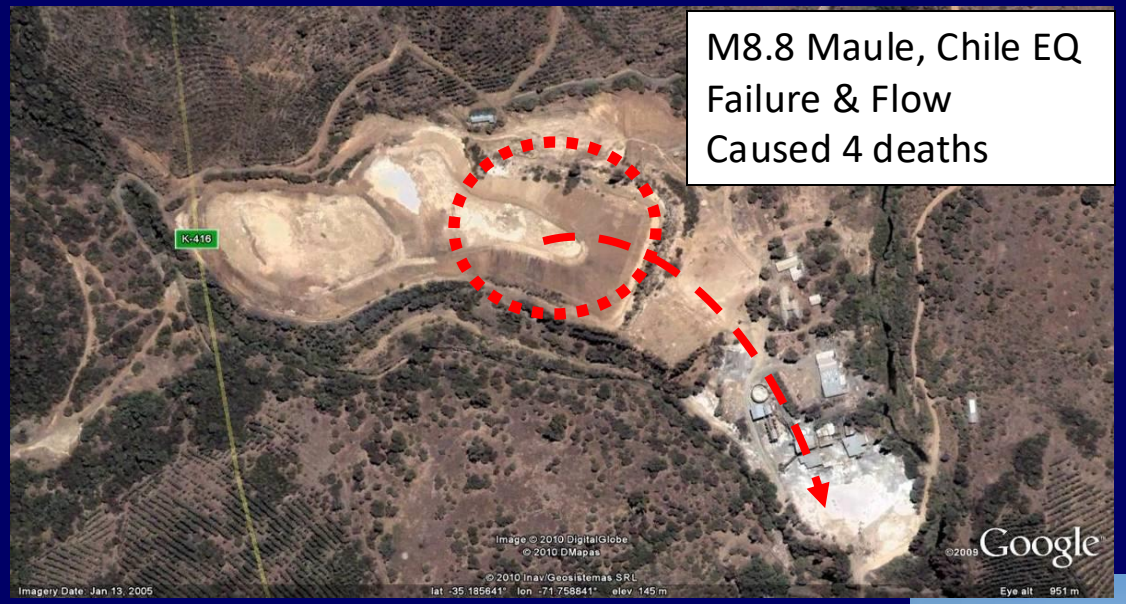




$D_{obs} \approx 350$ cm

Bray & Frost 2010

Las Palmas Gold Mine Tailings Dam Failure



Upstream construction



Bray & Frost 2010

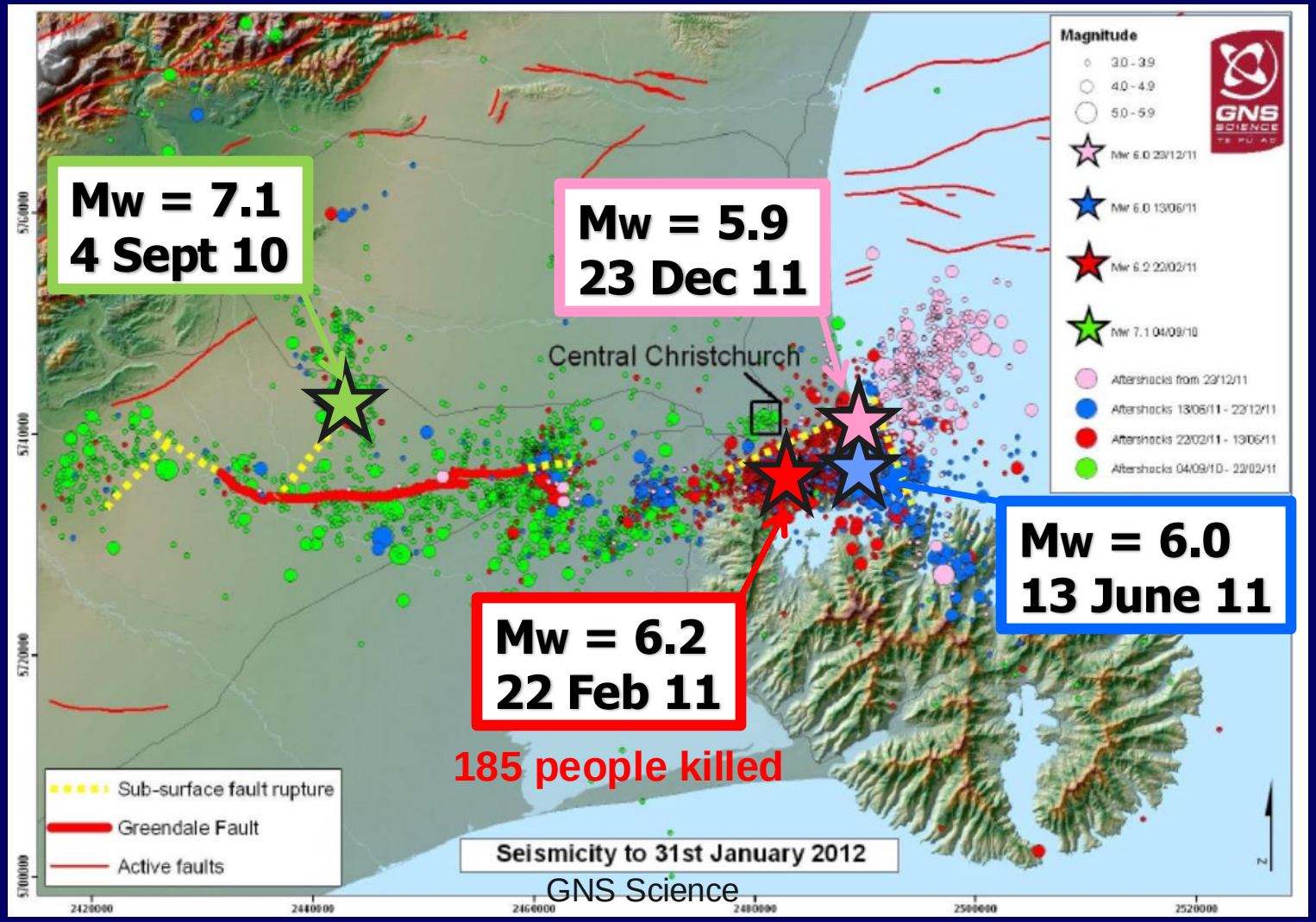


Sand ejecta near toe of flow debris



View from scarp looking downstream

2010-2011 Canterbury Earthquake Sequence



Cubrinovski, Bradley, Green, Bray, Wotherspoon, O'Rourke, van Ballegooy, Wood, Pender, Jacka, Wentz, Taylor, Allen, Bradshaw, Riz, Robinson, Henderson, Giorgini, Ma, Winkley, Zupan, DePascale, Wells,, Quigley, et al.

Canterbury EQs: Widespread Liquefaction









Cubrinovski et al. 2011

Repeated Liquefaction Events

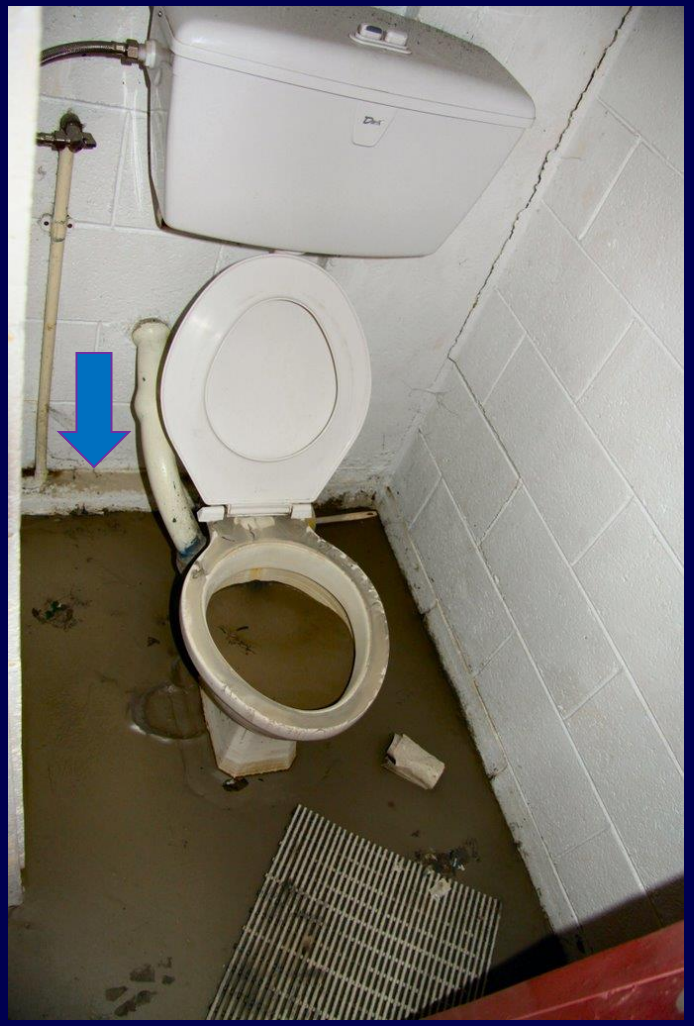


(Mark Quigley: Avonside)

Liquefaction Effects in Christchurch



From M. Cubrinovski



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

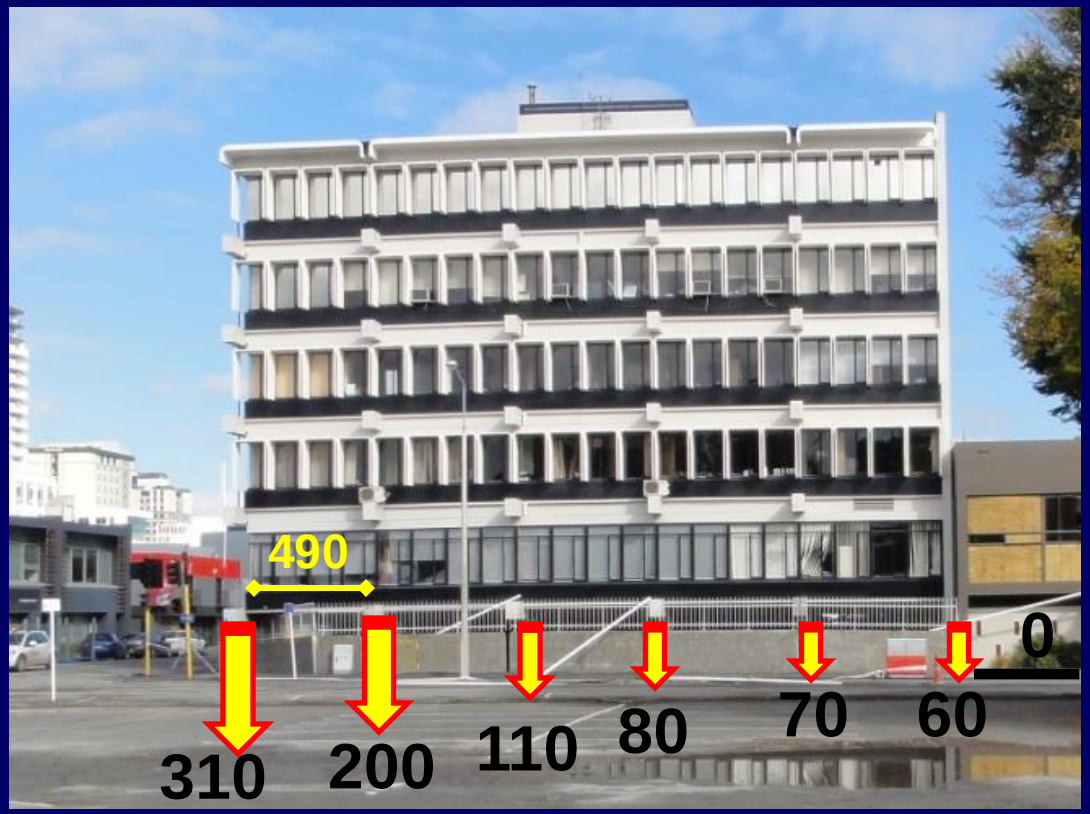


from Christchurch: Swamp to City
(photo from 1880, 30 years after Christchurch was founded)

from M. Cubrinovski

CTUC Building

Liquefaction-Induced Differential Settlement Induces Distress



Building Settlement (mm)

Maximum Angular Distortion ≈ 1 / 50

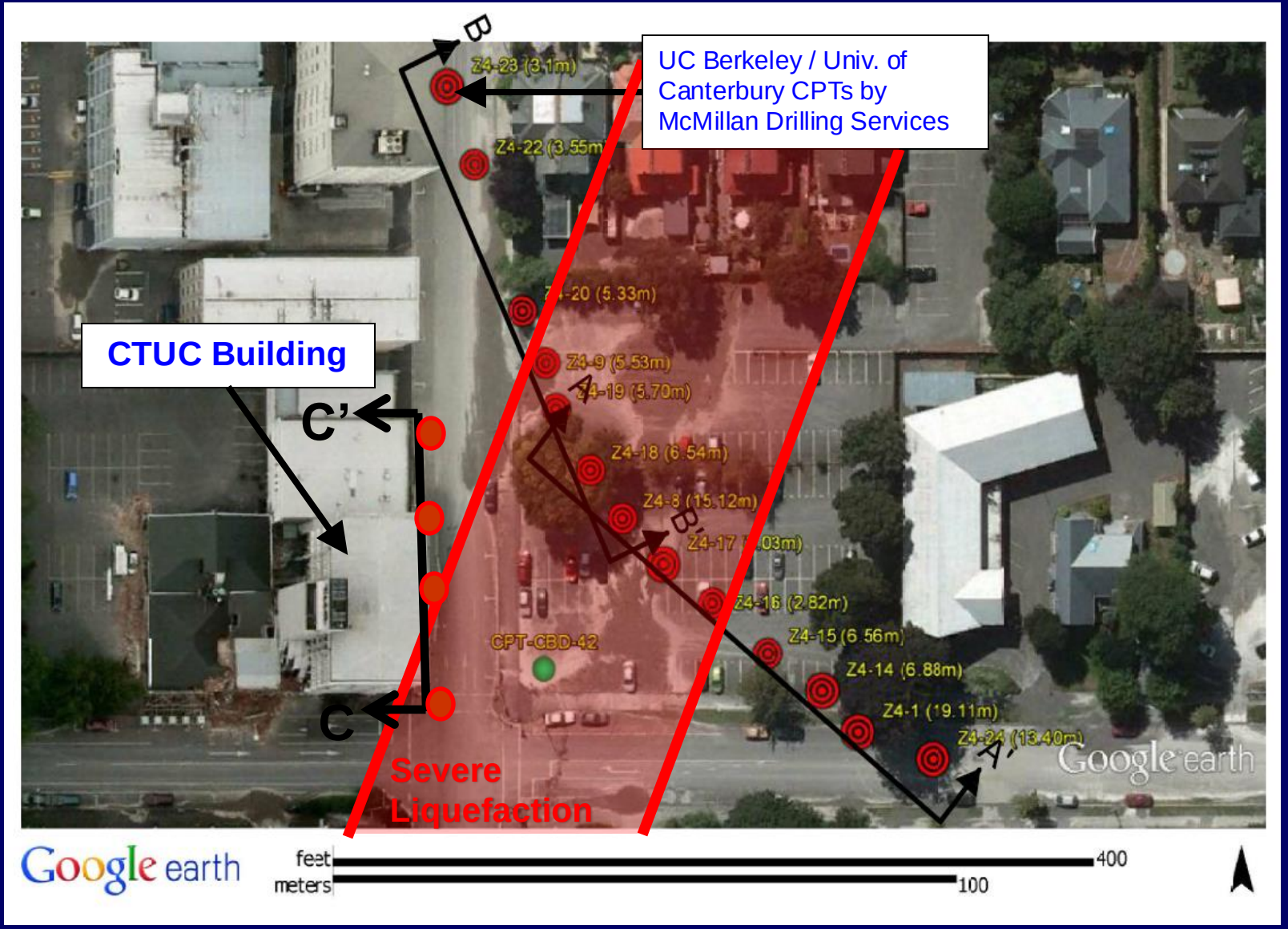




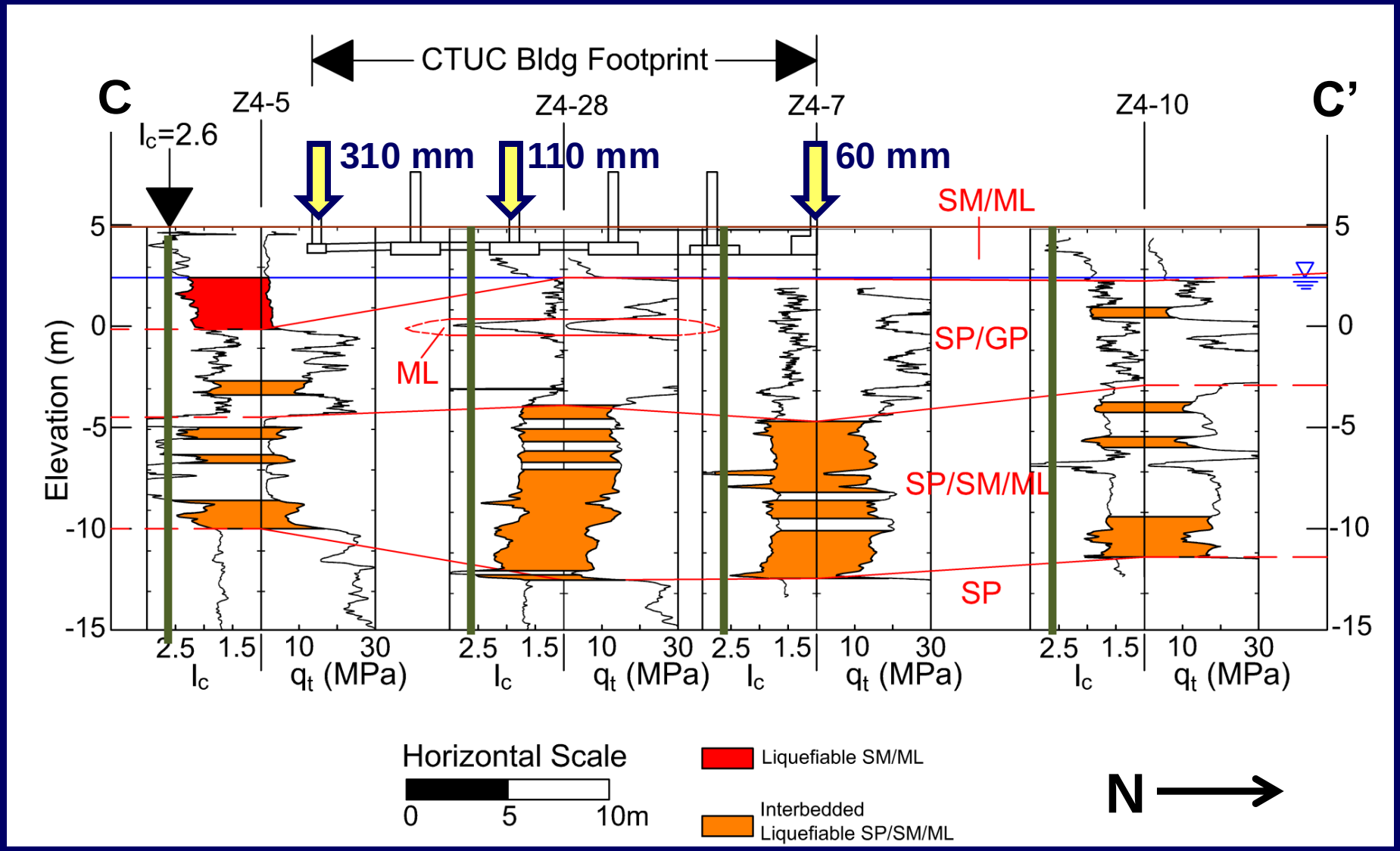
Bray et al. (2014) *EQ Spectra*

Liquefaction of Shallow Soil Deposits

Car Park & CTUC Building

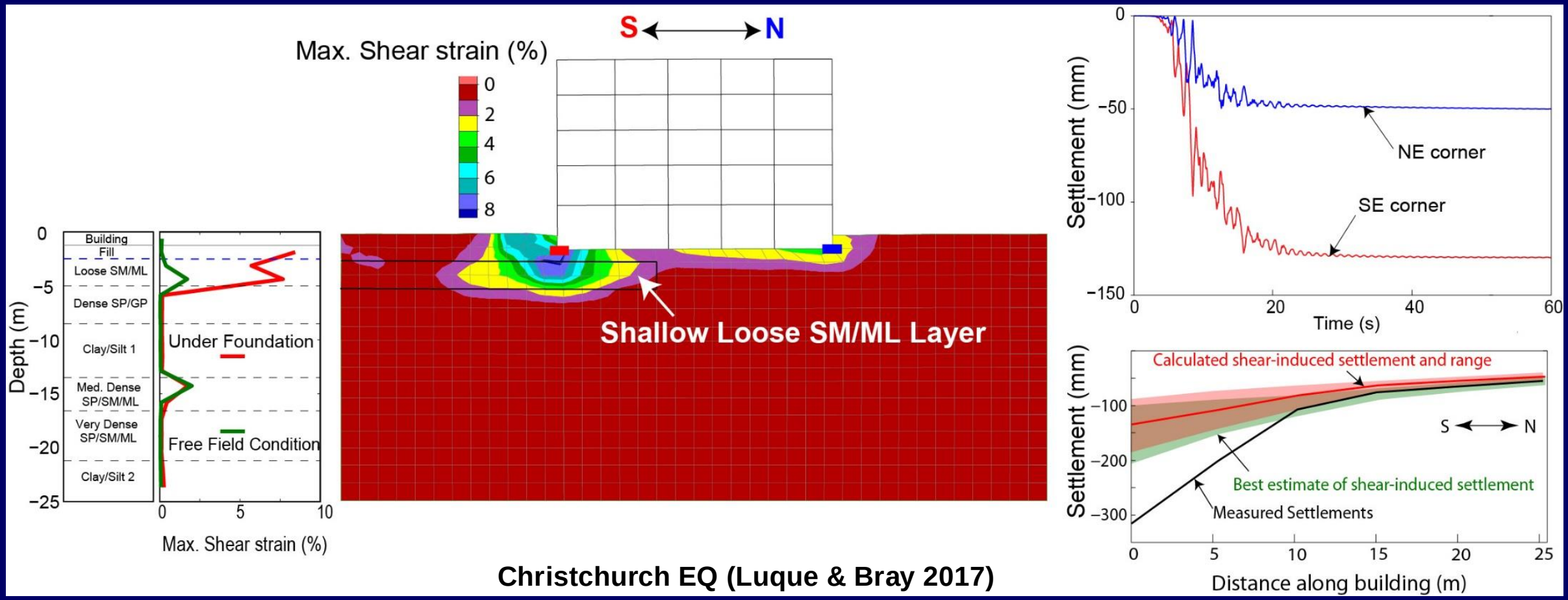


CTUC Building: Christchurch EQ



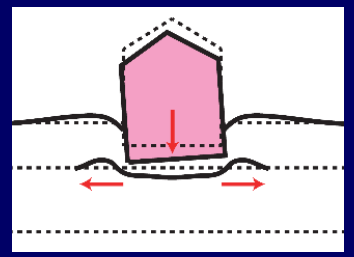
2011 Christchurch EQ: Robertson & Wride (1998)

Soil-Structure-Interaction Case History

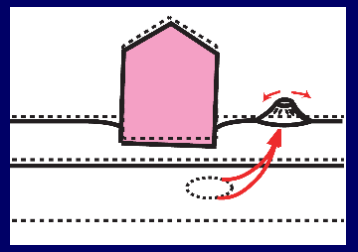


Christchurch EQ (Luque & Bray 2017)

Bearing Capacity



Ejecta



Liquefaction Shear-Induced Building Settlement Procedure

Bray & Macedo (2017)

Validation with 19 Field Case Histories

FTG7



CTUC



CTH



C2



F1



Case	Building	EQ[1]	Observed Ds (mm)	Estimated Ds from CPT(mm)
			Ds	D16 - D84
1	FTG7	C	150	100 - 270
4	FTG4	C	110-150	60 - 160
5	CTUC	C	100-200	110 - 290
8	CTH	C	50-210	70 - 180
9	CTH	D	0-20	30 - 70
10	CTH	J	10-30	20 - 60
17	C2	K	175	90 - 250
19	F1	K	450	220 - 600

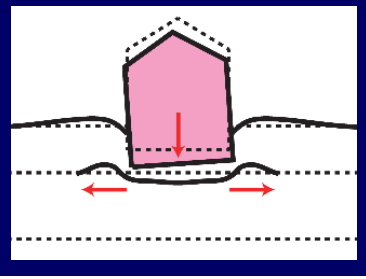
Notes:

1. C: Christchurch, D: Darfield, J: June, K: Kocaeli
2. D16: 16% estimate, and D84: 84% estimate

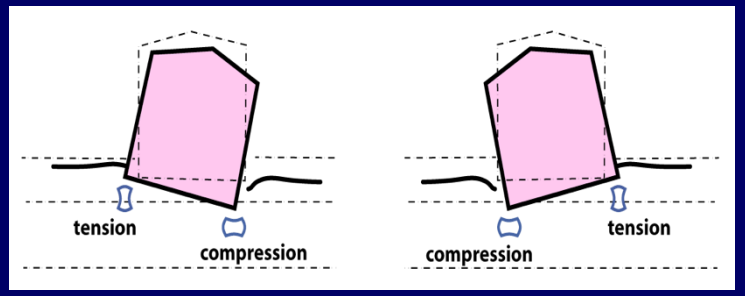
BUILDING & GROUND DISPLACEMENT MECHANISMS

1. Shear-Induced Building Settlement

Bearing Capacity ($\varepsilon_{q\text{-}BC}$)

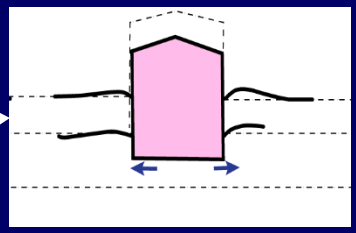


SSI Ratcheting ($\varepsilon_{q\text{-}SSI}$)



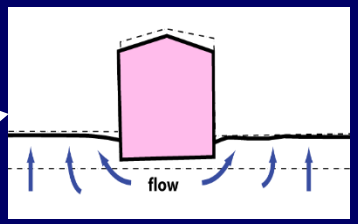
2. Volumetric Ground Settlement

Partial Drainage ($\varepsilon_{p\text{-}DR}$)

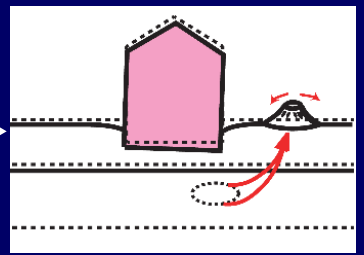


Sedimentation ($\varepsilon_{p\text{-}SED}$)

Consolidation ($\varepsilon_{p\text{-}CON}$)



3. Ejecta-Induced Settlement



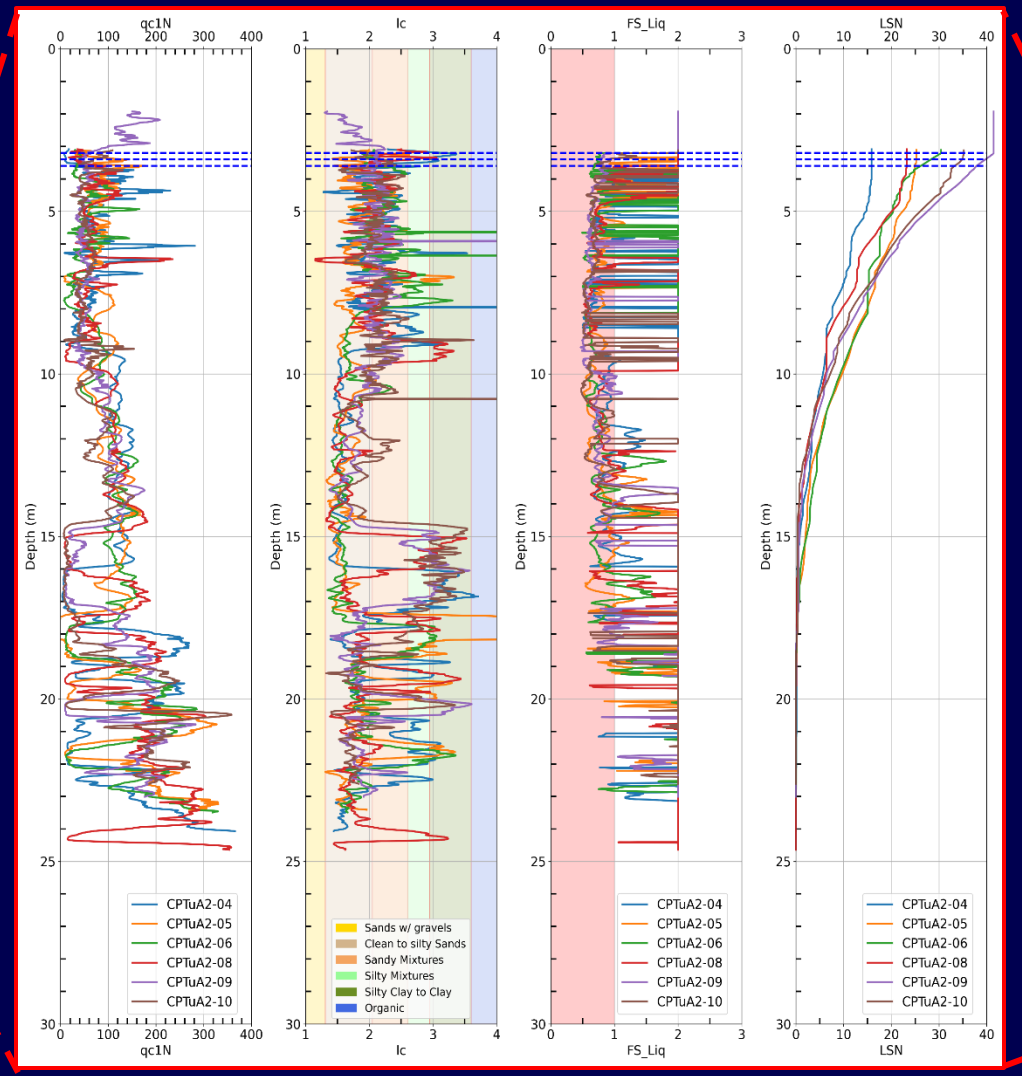
LIQUEFACTION GROUND SETTLEMENT FIELD CASE HISTORIES

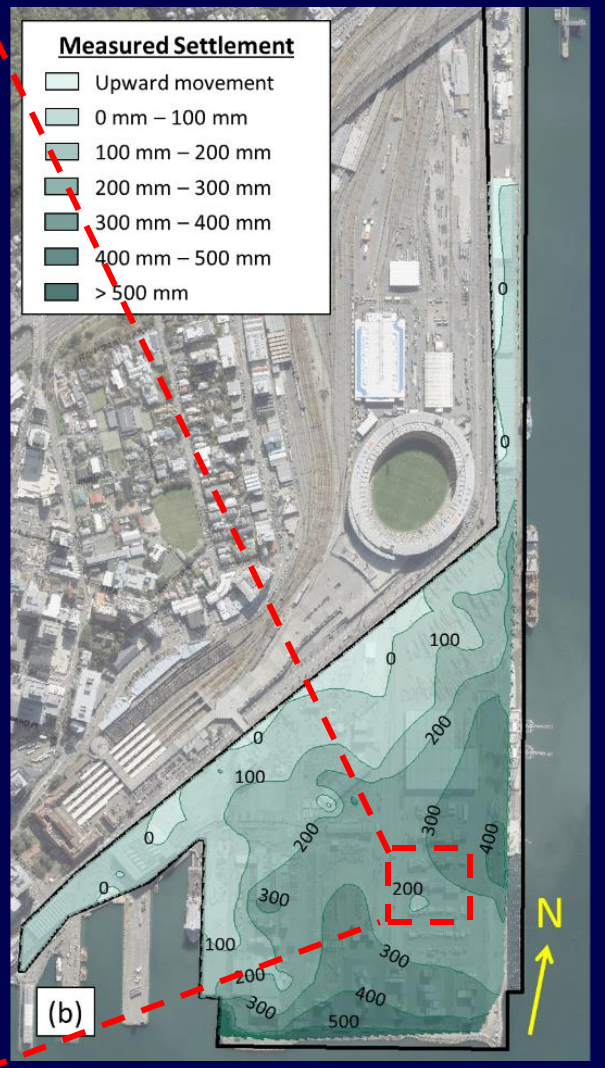
205 case histories of liquefaction-induced ground settlement: 163 natural sites & 42 hydraulic fills



69 CPTs - Dhakal et al. (2020)

Site 4 Olaya & Bray (2022)



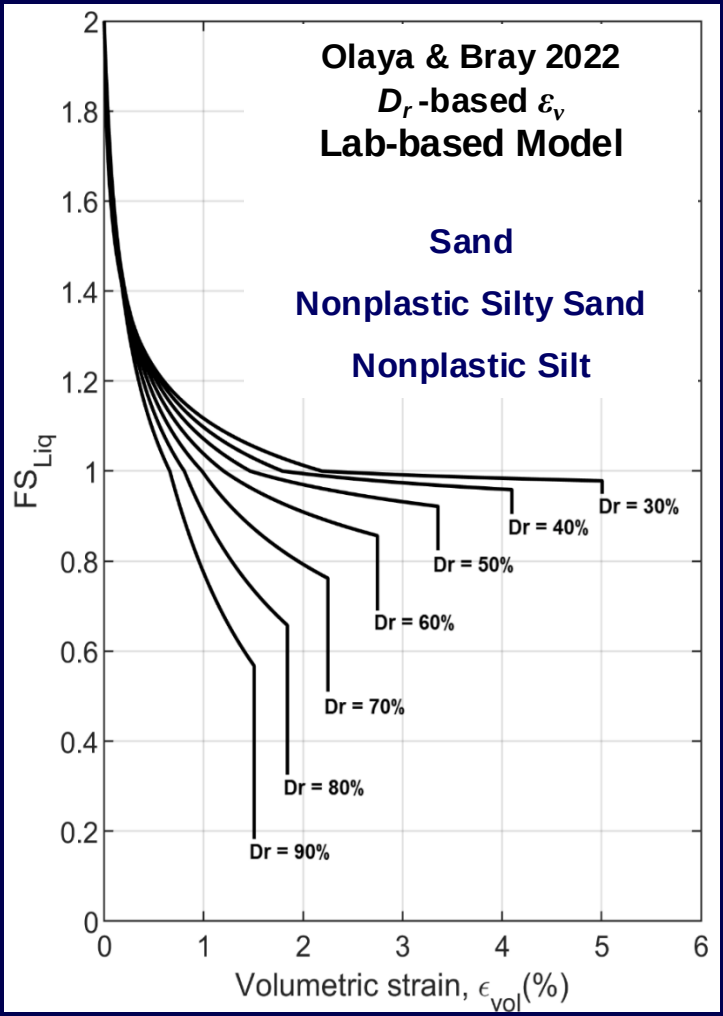


Post-EQ settlement Dhakal et al. (2020)

WELLINGTON, NZ – 2016 KAIKOURA EQ (M_w = 7.8)

Probabilistic CPT Liquefaction Ground Settlement Model (S_v)

Bray & Olaya (2023)



$$S_v = C \cdot SB \cdot MF \cdot \sum_i \left(\frac{\varepsilon_{vi}}{100\%} * \Delta z_i \right) \cdot e^{\varepsilon}$$

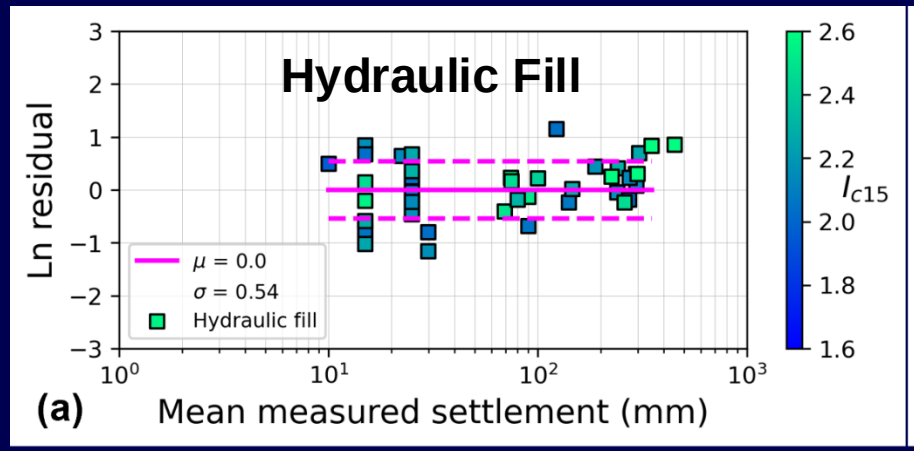
$$C = 1.05 \text{ if hydraulic fill, or } 1.50 \text{ if natural soil}$$

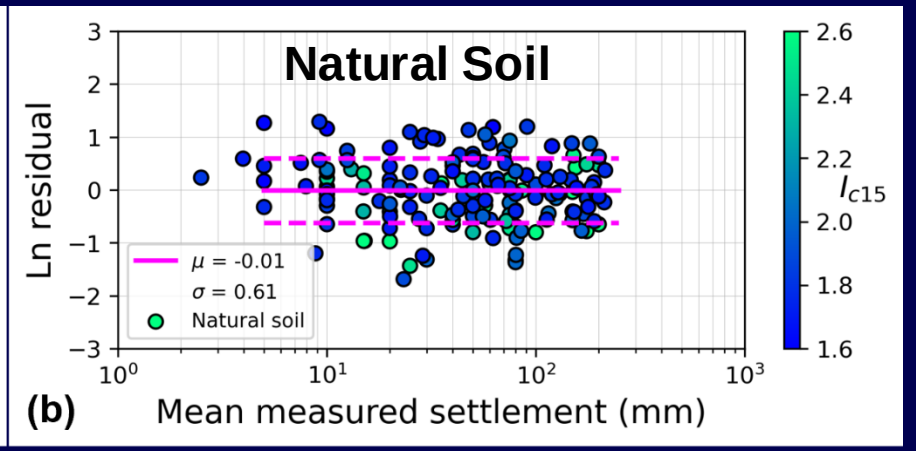
$$SB = exp(-0.675 \cdot \max(I_c, 1.8) + 1.215)$$

$$MF = exp(0.214 \cdot M_w - 1.498)$$

$$\sigma_{Dr} = \begin{cases} 0.54 - \text{hydraulic fill} \\ 0.61 - \text{natural soil} \end{cases}$$

$$\sigma_{\psi_o} = \begin{cases} 0.53 - \text{hydraulic fill} \\ 0.61 - \text{natural soil} \end{cases}$$



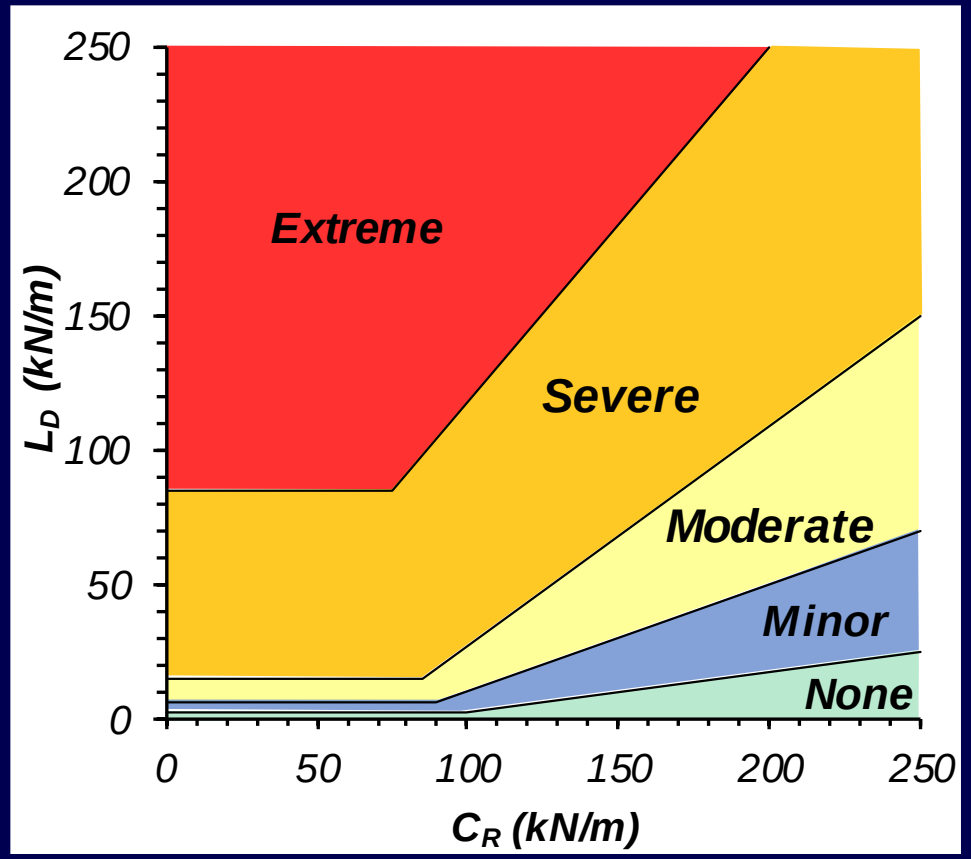


D_r-based Model Residuals

Liquefaction-Induced Ejecta



Ejecta-Induced Severity & Settlement Estimate



Hutabarat & Bray (2022)

Liquefaction Demand (L_D)

$$L_D\ (\mathrm{kN/m}) = \gamma_w \int_{z_A}^{z_B} \frac{k_v}{k_{cs}} (h_{exc} - h_A)\, dz$$

$$when\ h_{exc} \geq h_A,\ otherwise\ L_D = 0$$

Crust Resistance (C_R)

$$C_R\ (\mathrm{kN/m}) = \int_{0\ m}^{z_A} s_u\, dz$$

Clean Sand Sites

Severity	*LSN*	$L_D - C_R$
None (n = 47)	49%	66%
Severe (n = 19)	21%	74%

Stratified Silty Soil Sites

Severity	*LSN*	$L_D - C_R$
None (n = 74)	18%	88%

True Positive Rate (n = # cases > 5)

Hutabarat & Bray (2022)

Ejecta severity category	Localized free-field ejecta-induced settlement (mm)
None	0
Minor - Moderate	≤ 50
Severe - Extreme	50 - 200

Bray & Olaya 2023 (based on Mijic et al. 2022 data)

LESSONS LEARNED FROM DISASTERS

- Well-documented case histories advance our knowledge
- Grass-roots approach with key standards
- Google Earth™ enables us to see the world
- Remote sensing, LiDAR, & SfM capture post-event conditions
- Geo-coded digital observations enable documentation, sharing & archiving
- Reconnaissance leads to new design methods