

Advances and Challenges since Northridge Earthquake

Geotechnical Earthquake Engineering Accomplishments & Challenges

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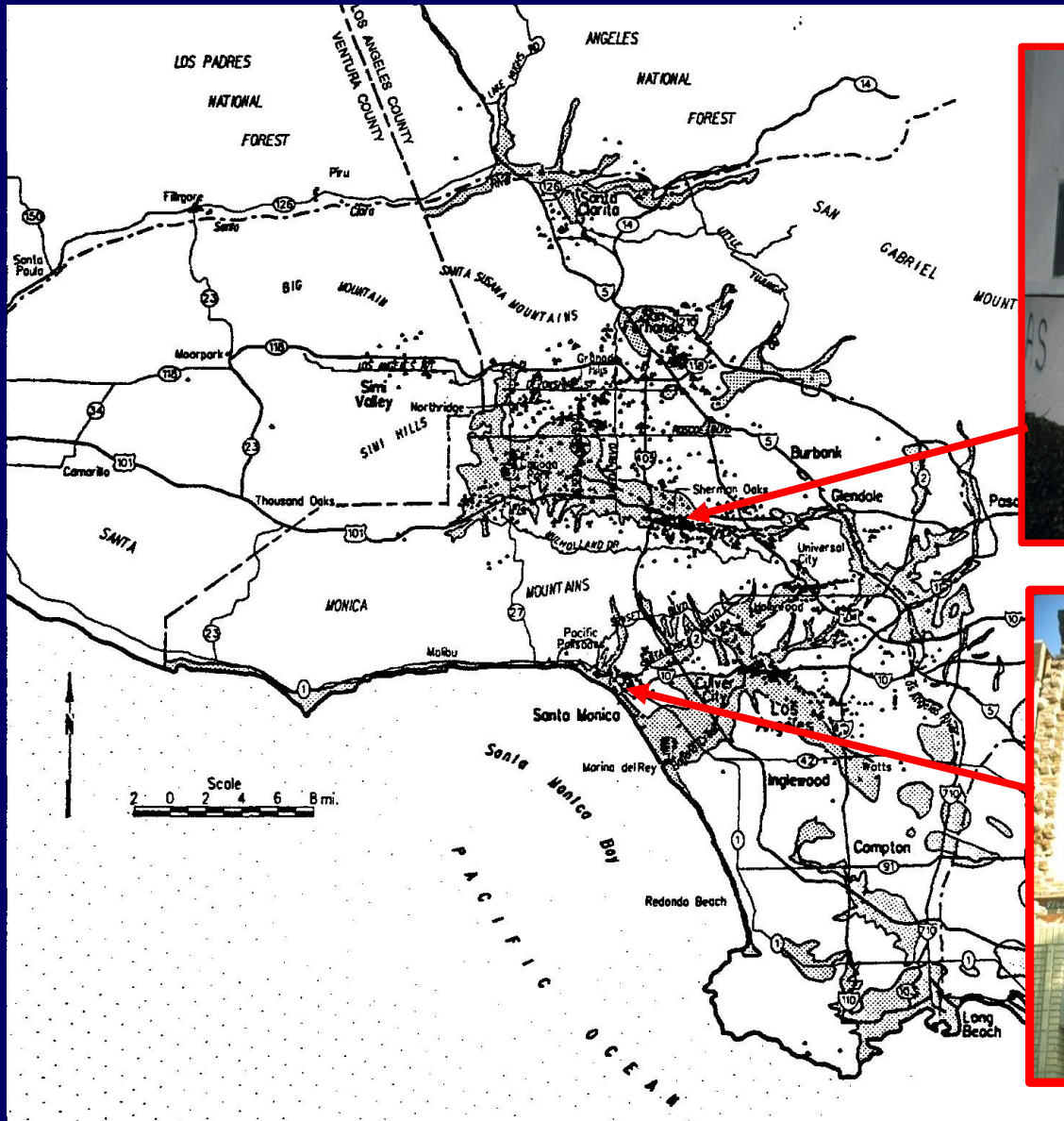
**Faculty Chair in Earthquake Engineering Excellence
University of California, Berkeley**



1994 Northridge EQ: 57 people killed



Seismic Site Effects



Santa Monica Freeway Damage at La Ciénaga



Liquefaction Led to Fires & Loss of Fire Suppression Capabilities



LA Times



Earth/Waste Structure & Slope Performance



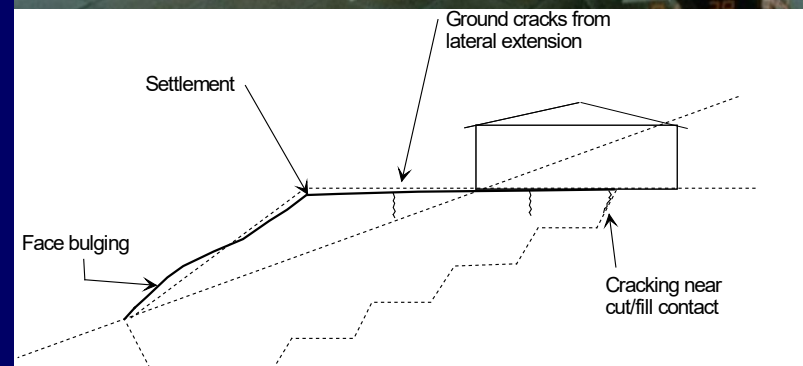
Tapo Canyon Liquefaction-Induced Tailings Dam Failure
(picture from Y. Moriwaki)



Pacific Palisades Slope Failure



Oil Waste Fill Performance



Seismic Compression of Earth Fills

Geotechnical Earthquake Engineering

**Accomplishments
& Challenges**

Geotechnical Earthquake Engineering

**Post-Earthquake
Reconnaissance**



Google Earth™



Central Business District, Christchurch, New Zealand

UAVs Survey Damage Effectively

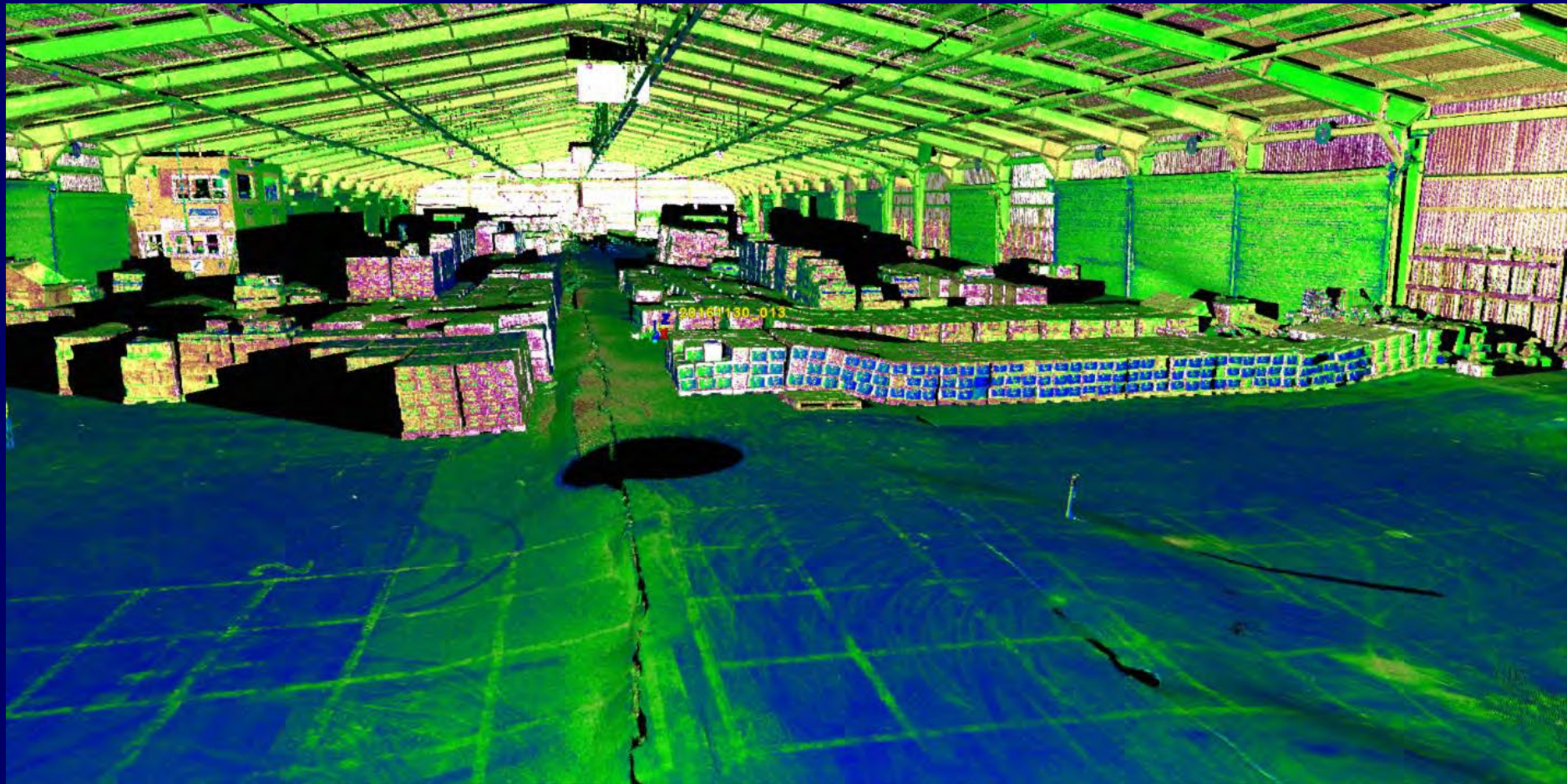
Flyover of 2014 S Napa EQ Fault - Z-Q Chen & M Chen of UMKC



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



Ground-Based LIDAR



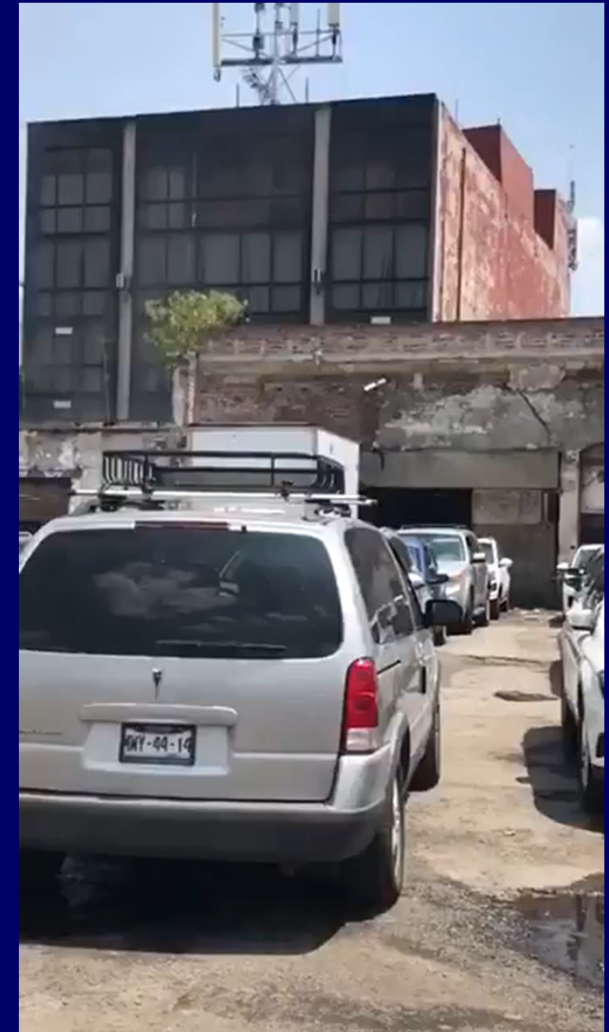
LIDAR scan inside Building S37 in CentrePort Wellington showing deformation around buried seawall from 2016 Kaikoura EQ (LIDAR survey by M. Olsen in Cubrinovski and Bray 2017)



19 SEP 2017 M7.1 Mexico EQ



Videos of Mexico City Building Responses



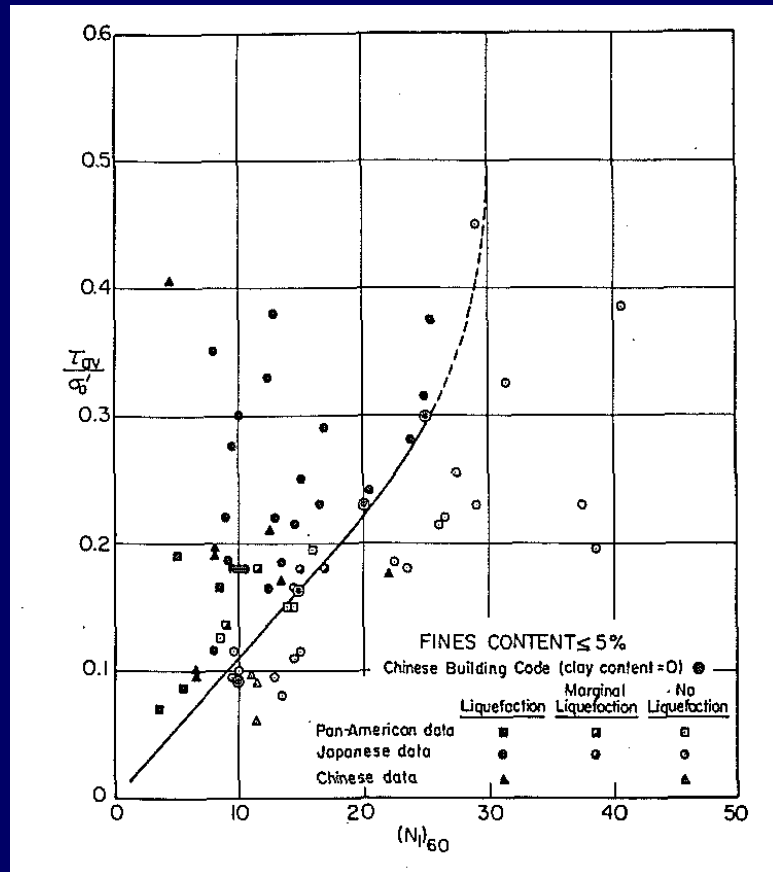
From E. Rathje, UT, *Design-Safe*

Geotechnical Earthquake Engineering

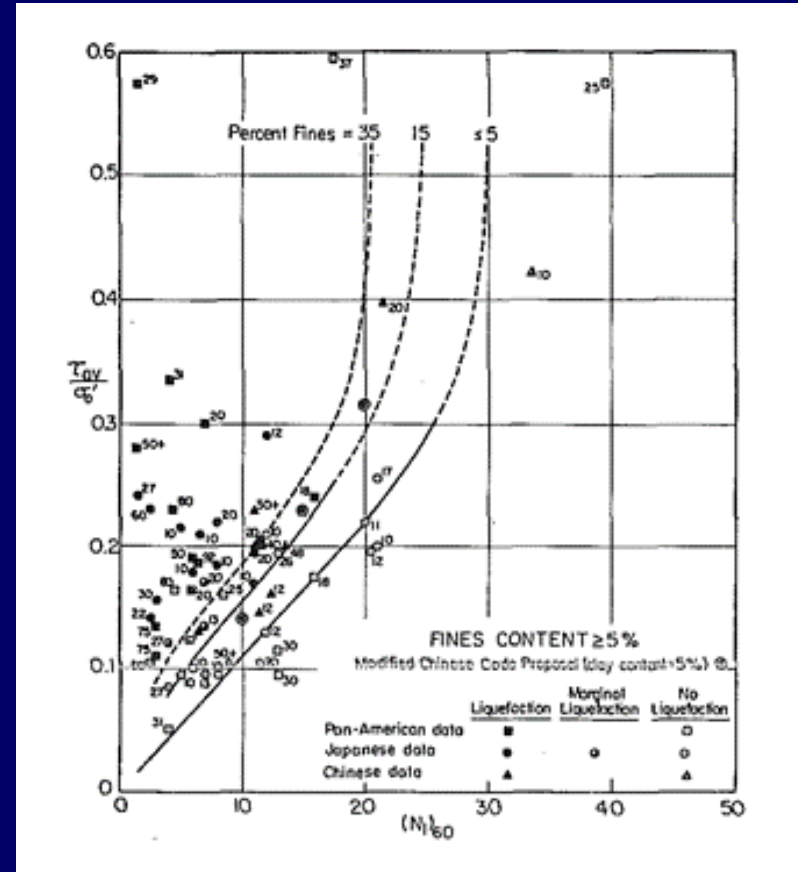
Liquefaction

Liquefaction Triggering

Seed et al. 1985



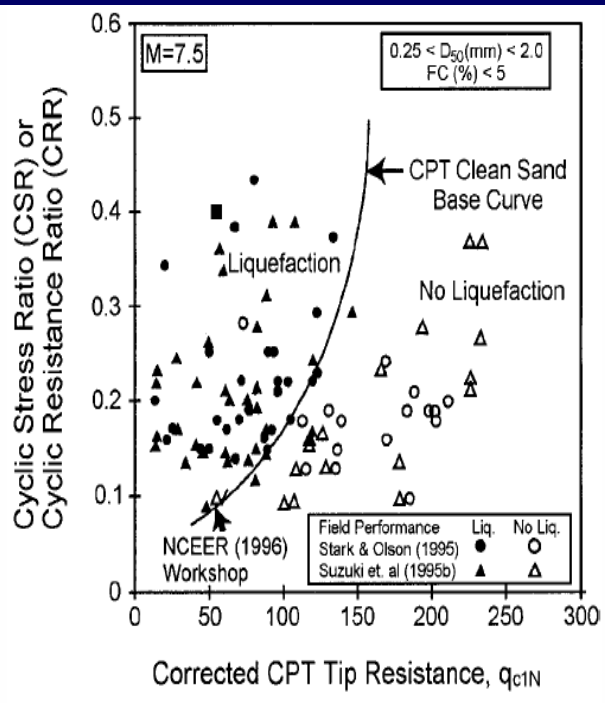
Clean Sand



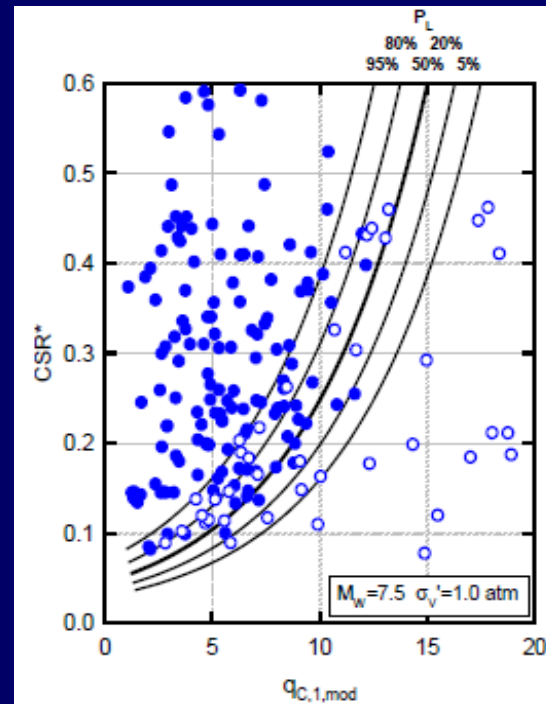
Silty Sand

SPT used primarily

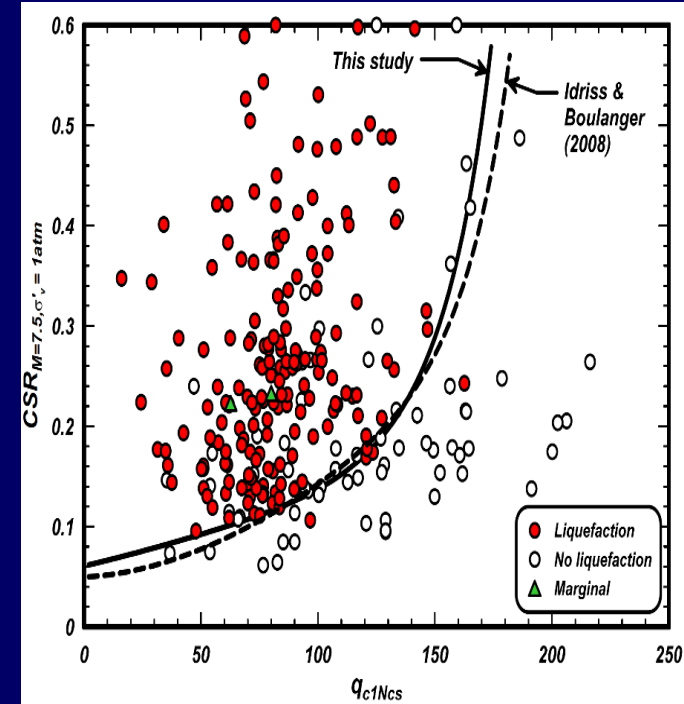
New Case History Data Led to New Relationships



Robertson & Wride (1998)



Moss et al. (2006)



Boulanger & Idriss (2014)

CPT used primarily

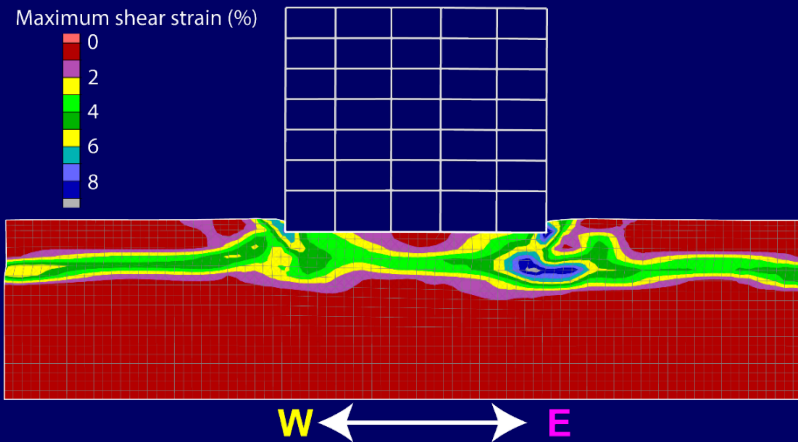
Renewed Focus on *Effects* of Liquefaction

Liquefaction-Induced Building Movements

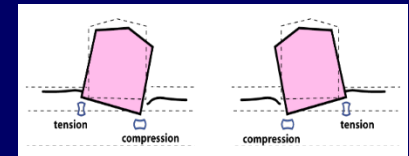
2011 Tohoku, Japan EQ ($M_w = 9.1$) Tokimatsu et al. (Ashford et al. 2011)



FTG7 Building – Deformation Mechanisms & Estimates 2011 Christchurch EQ



- SSI Ratcheting (& Ejecta)
- Shear strain & settlement accumulation at edges of building

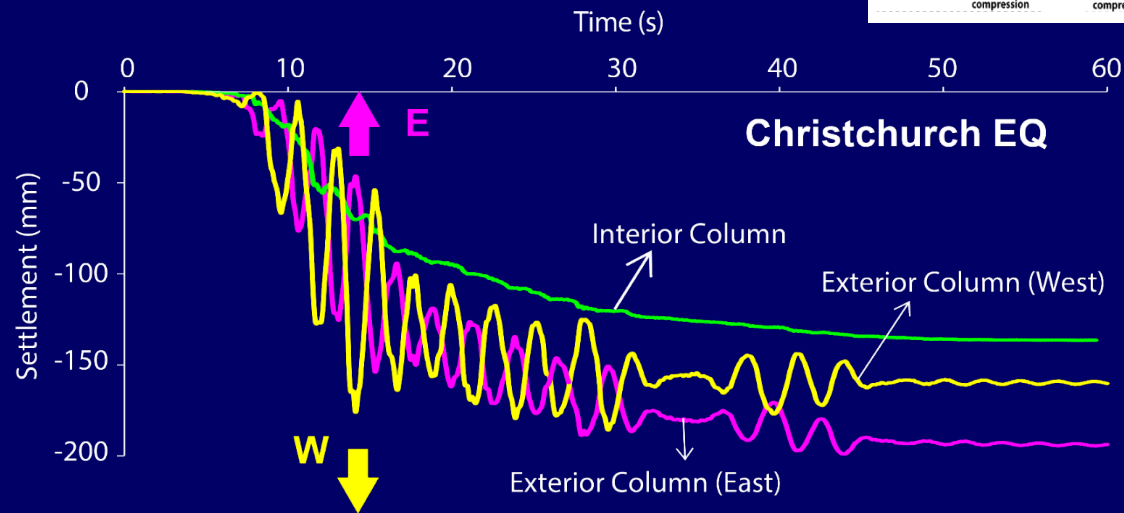


Differential Settlements

Event	Calculated (mm)	Measured (mm)
Darfield	5 – 10	-
Christchurch	20 – 50	10 – 30
13 June 2011	10 – 20	0 – 25

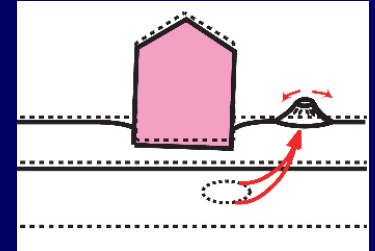
Luque & Bray (2017)

using *FLAC* with *PM4Sand* model
(Boulangier & Ziotopoulou 2015)



Nonlinear Effective Stress Analyses used to Develop Simplified Procedure for Estimating Shear-Induced Settlement (Bray & Macedo 2017)

Challenge in Estimating Ejecta-Induced Settlement

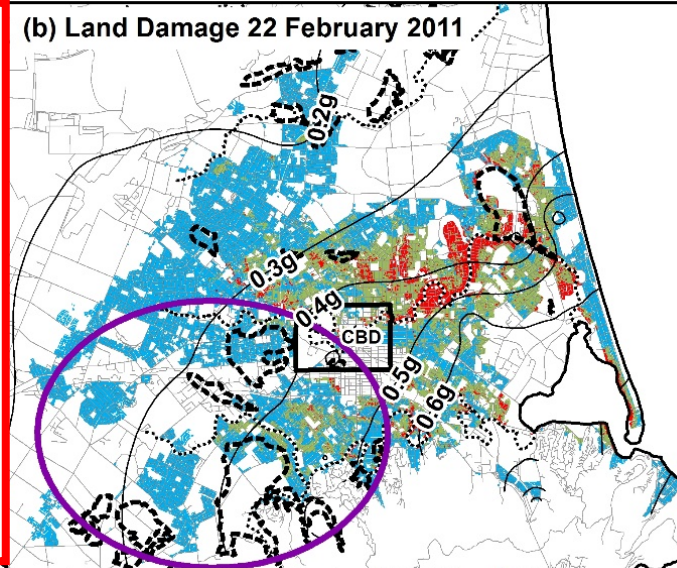


Sediment Ejecta

Observed vs. Estimated Liquefaction Damage

**Observed
Land
Damage**

(b) Land Damage 22 February 2011

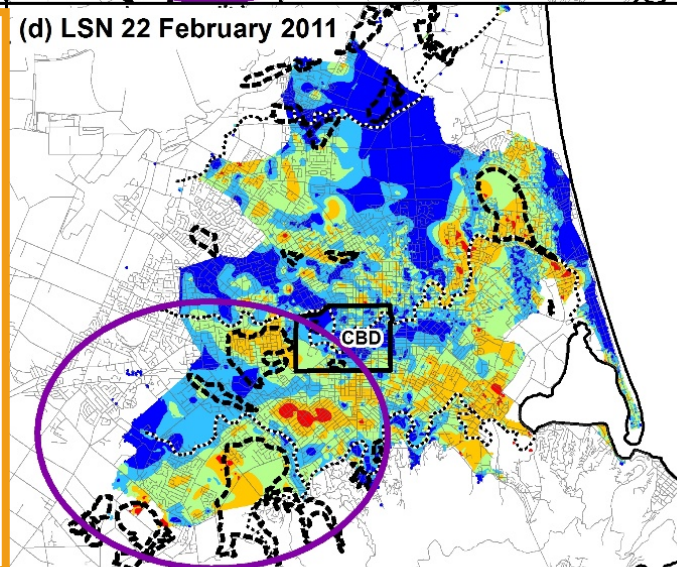


**LSN
Estimates**

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

(van Ballegooy et al. 2014)

(d) LSN 22 February 2011



LEGEND

- Swamp Areas
- Rivers
- PGA (0.1g) Contours

LSN

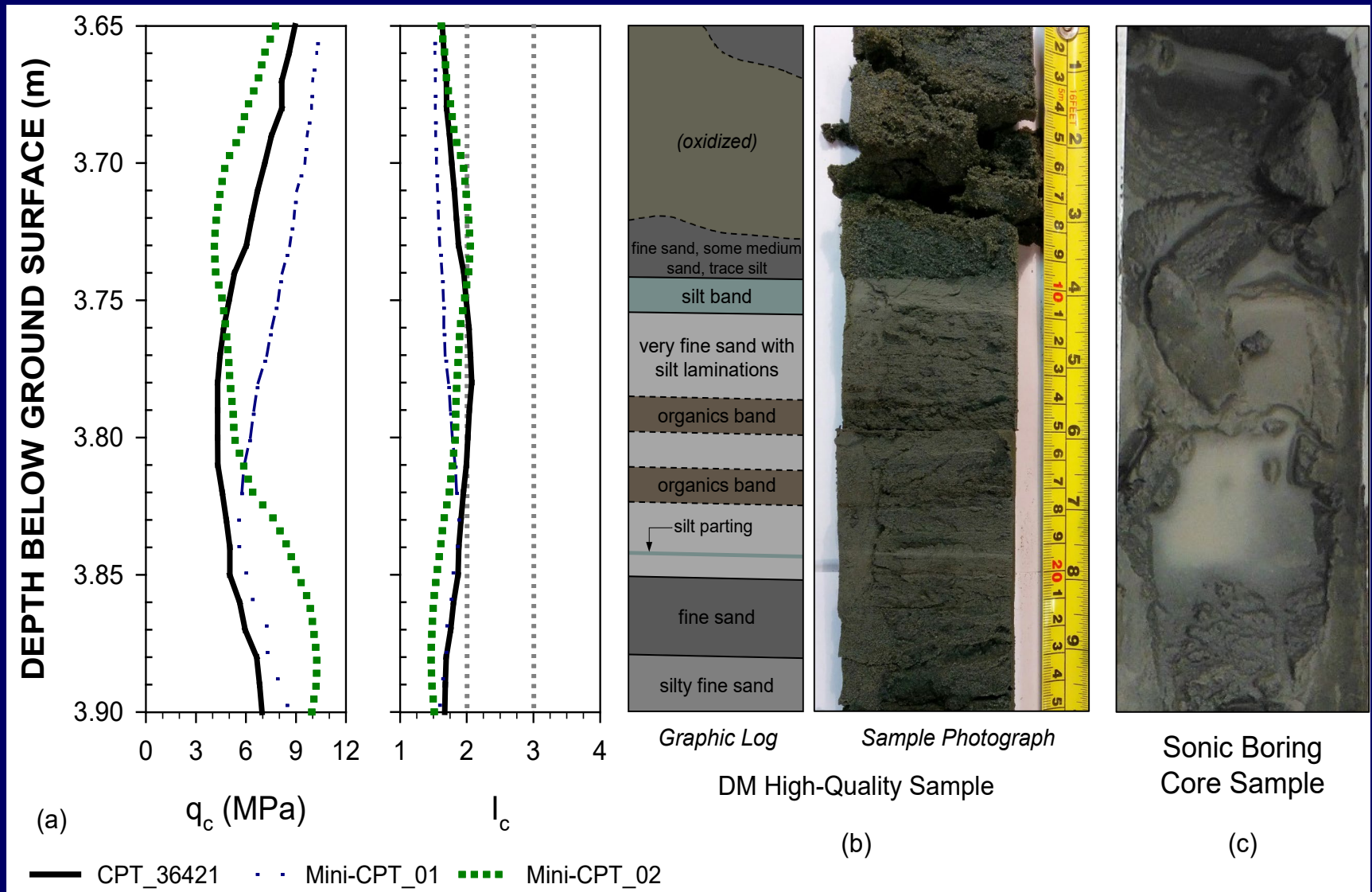
- 0 - 8
- 8 - 16
- 16 - 25
- 25 - 40
- 40 +

Observed Liquefaction Related Land Damage

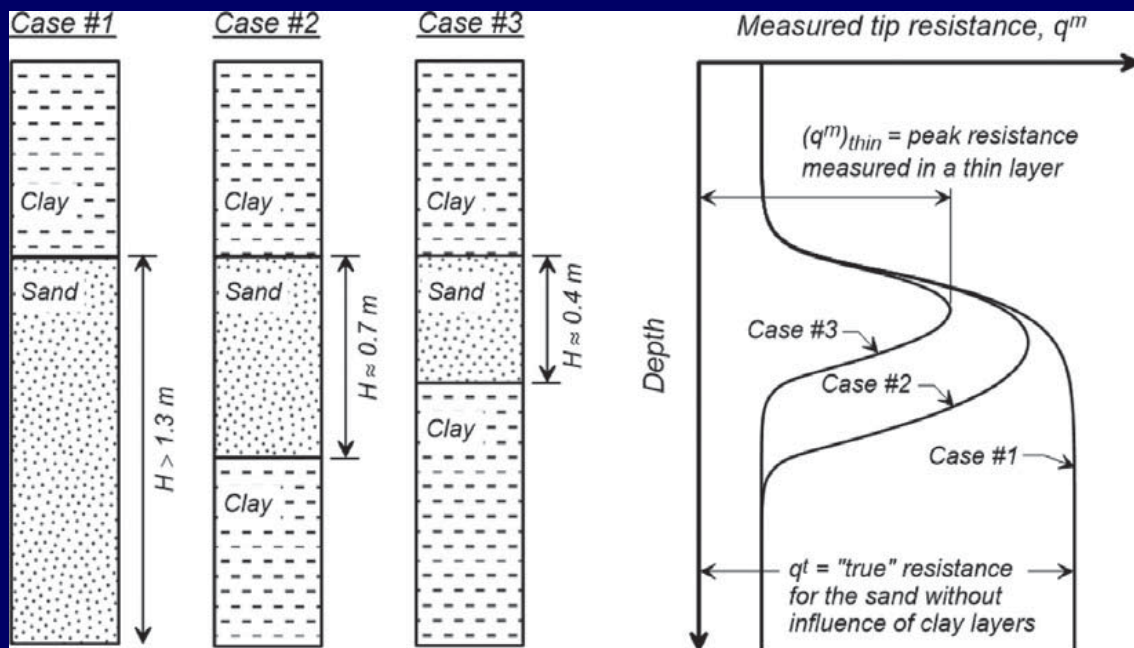
- None-to-Minor
- Minor-to-Moderate
- Moderate-to-Severe



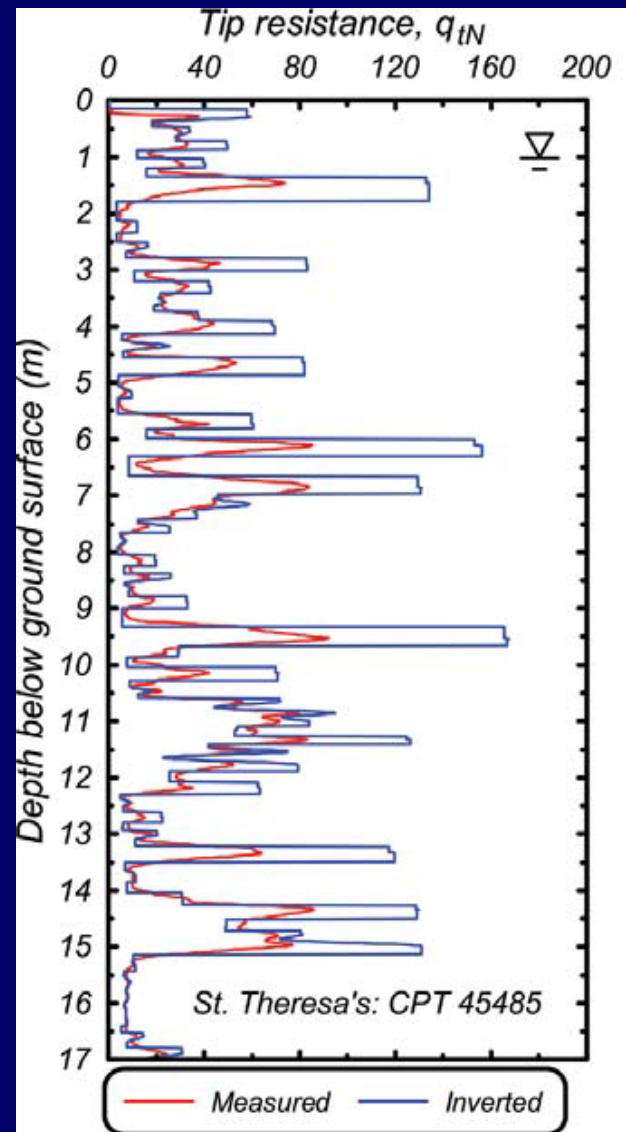
Site Characterization Tools in Challenging Soil Deposits



Enhanced CPT Characterization



**Cone Tip Can Underestimate True Resistance
in Thin Layers (Robertson & Fear 1995)**



**Use Inverse Filtering Procedure
(Boulangier & DeJong 2018)**

Liquefaction-Induced Ground Movements Effects

NSF sponsored US-NZ-Japan Workshop

PEER Report 2017/02

Cross-Cutting Research Priorities:

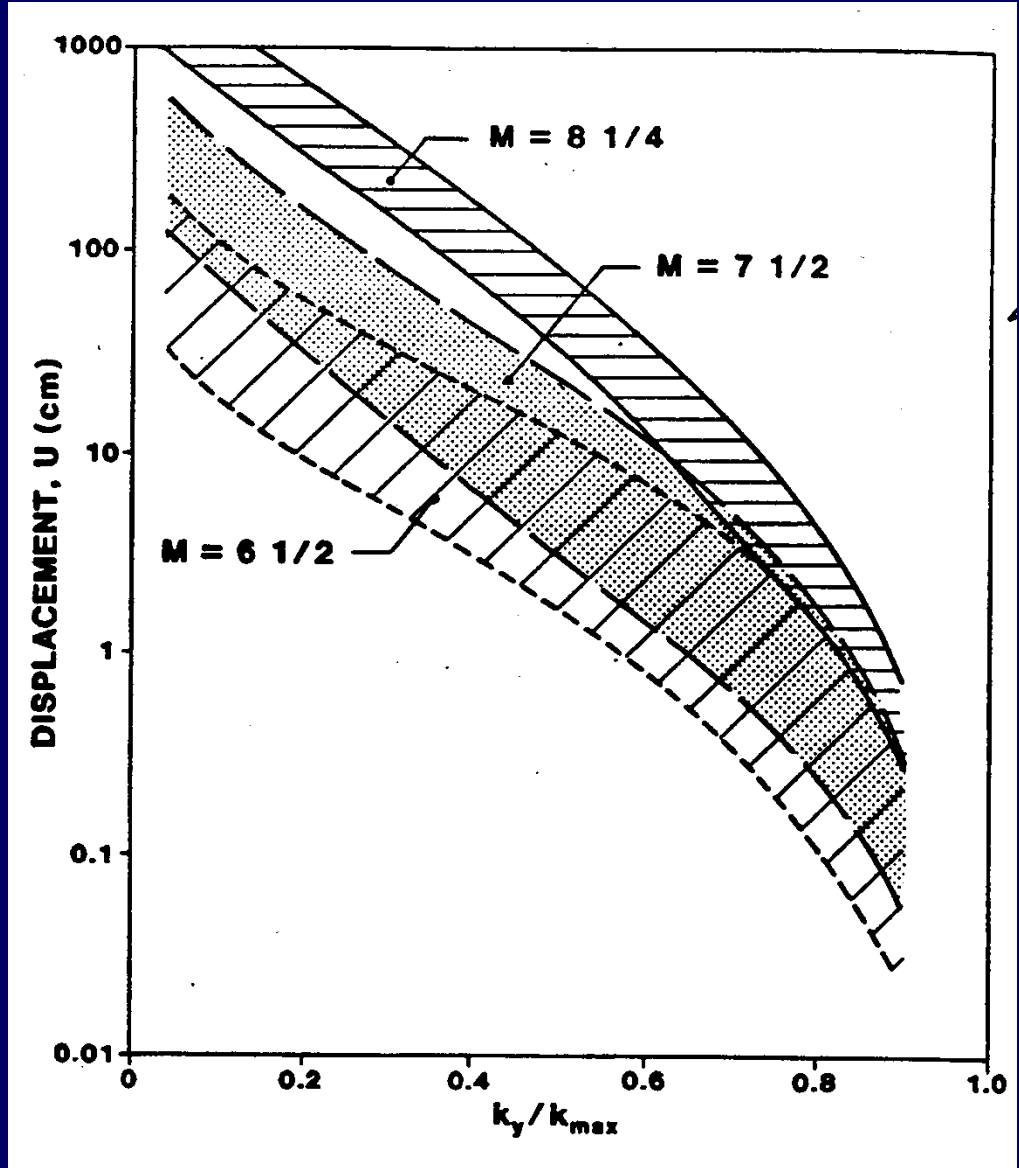
1. Case History Data
2. Integrated Site Characterization
3. Numerical Analysis
4. Challenging Soils
5. Effects and Mitigation of Liquefaction in the Built Environment and Communities



Geotechnical Earthquake Engineering

**Seismic Slope
Stability**

Simplified Estimates of Seismic Slope Displacement (Makdisi & Seed 1978)



*Few Motions Available in 1977:
Performed Limited Number of Analyses*

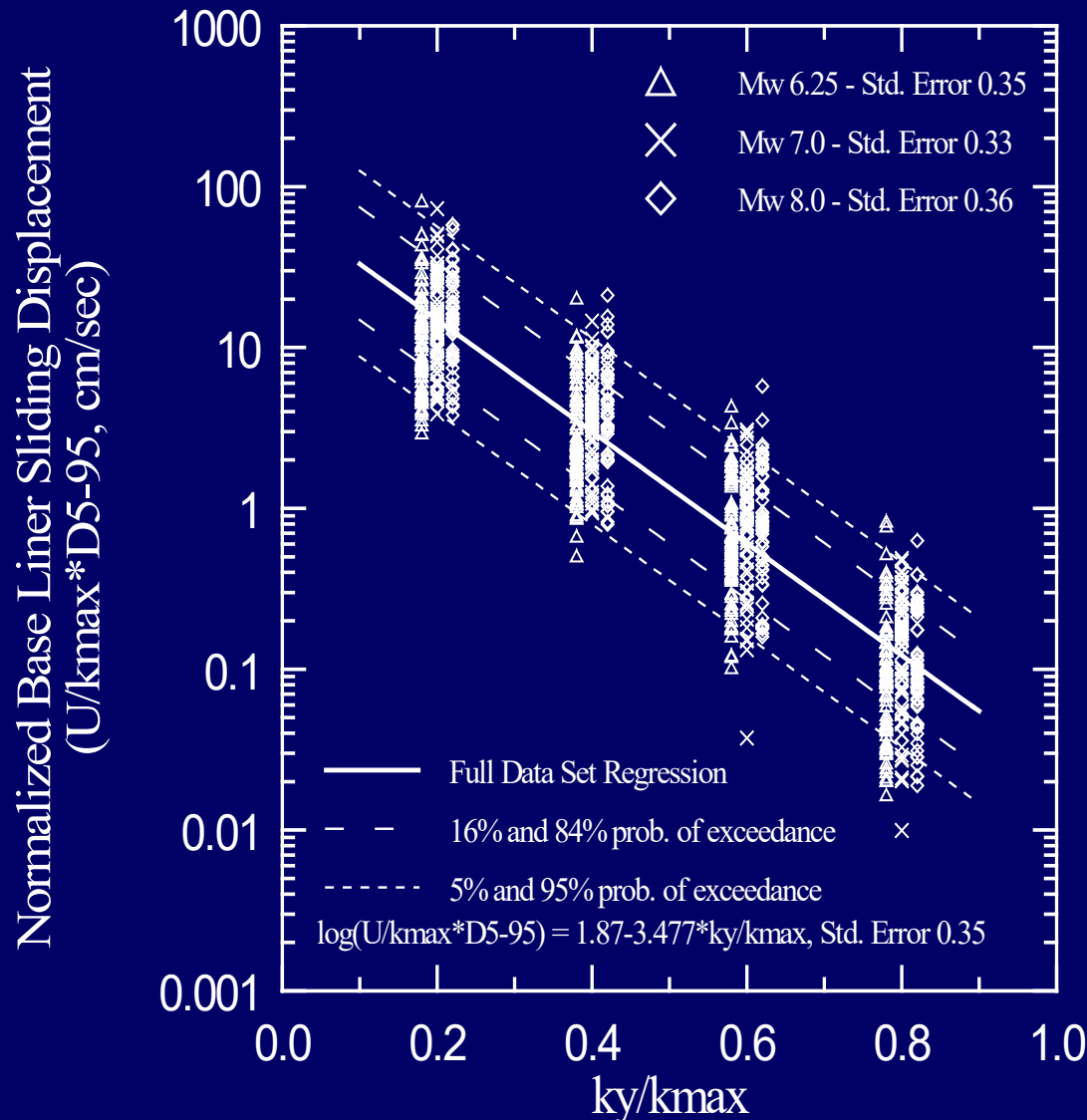
&

Decoupled 'Shear-Slice' Model

Not True Upper & Lower Bounds

No Estimate of Uncertainty

Simplified Estimates of Seismic Slope Displacement (Bray & Rathje 1998)



**More Motions
Available in 1997:
Hundreds of
Analyses Performed**

&

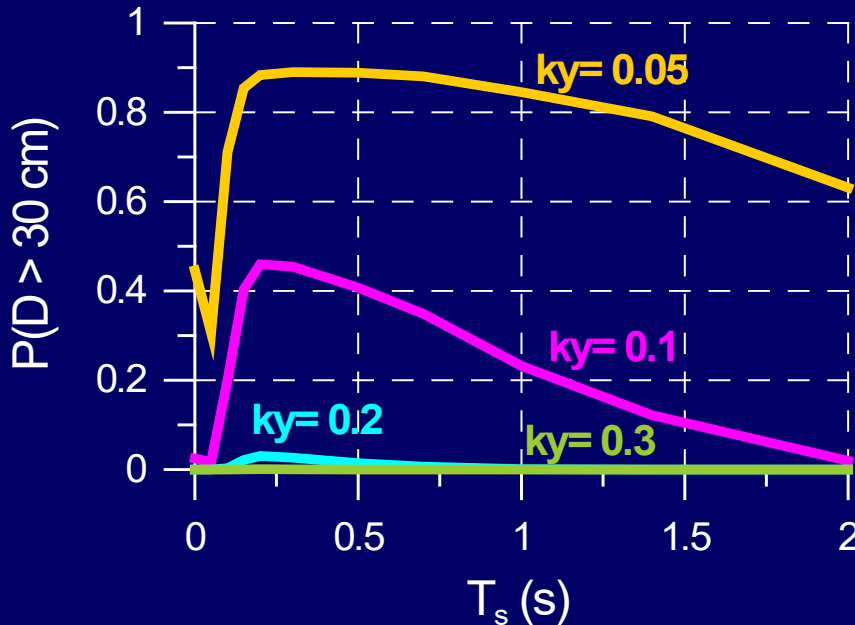
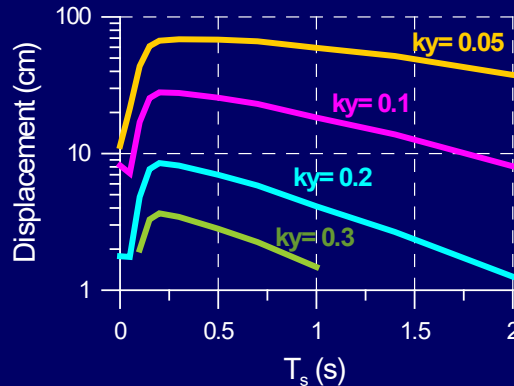
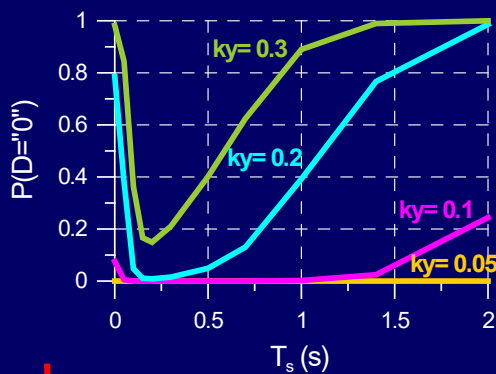
**Coupled Nonlinear
Model**

**Seismic Demand
(k_{max}) Estimated &
then Resulting Slope
Displacements**

**Ad Hoc Estimate of
Uncertainty**

Simplified Estimates of Seismic Slope Displacement (Bray & Travasarou 2007)

Scenario: M 7 at 10 km "Soil" – SS fault



688 NGA-West
Motions with 80 k_y &
 T_s Combinations:
Over 55,000
Analyses Performed

&

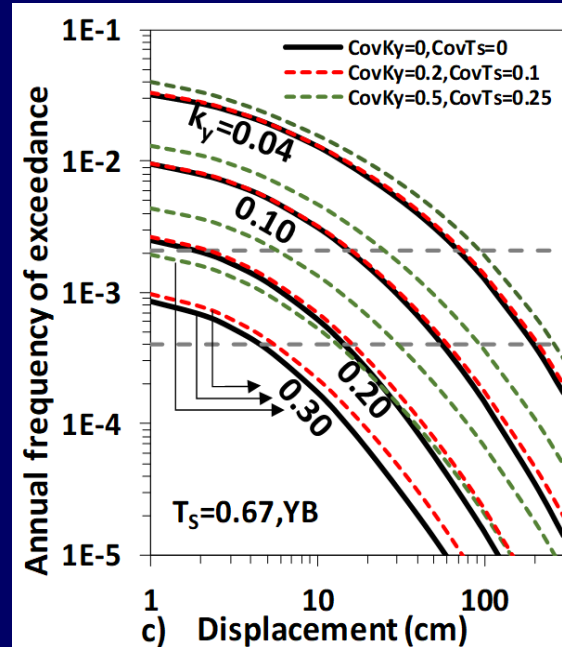
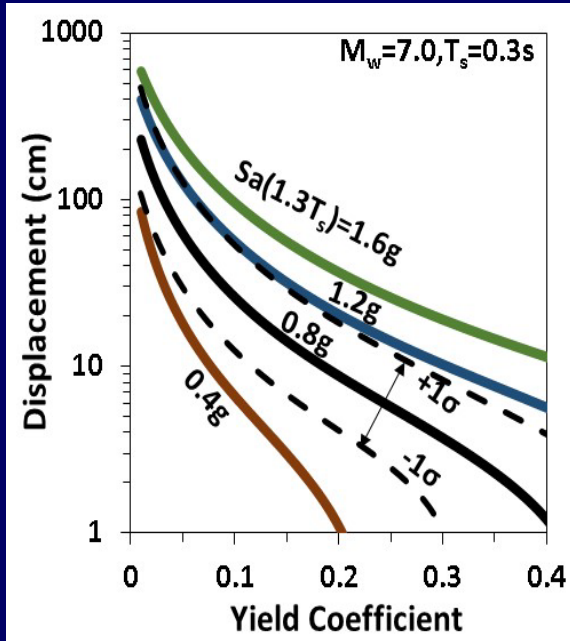
Fully Coupled
Nonlinear Model

Seismic Displacement
Estimated Using
 $S_a(1.5T_s)$, k_y , T_s & M_w

Captures Full
Uncertainty due to
Ground Shaking

Simplified Estimates of Seismic Slope Displacement (Bray & Macedo 2019 & Macedo et al. 2019)

Scenario & Full Probabilistic Procedures



6,711 NGA-West-2
Motions with 130 k_y &
 T_s Combinations:
Nearly 3,000,000
Analyses Performed

&

Fully Coupled
Nonlinear Model

Seismic Displacement
Estimated Using
 $S_a(1.3T_s), k_y, T_s$ & M_w

Performance-Based
Approach Captures
Uncertainty due to All
Key Factors

Geotechnical Earthquake Engineering

- 1994 Northridge EQ challenged our understanding of earthquake phenomena
- Advanced survey tools enable effective documentation of field case histories
- Capture liquefaction effects using enhanced characterization & numerical simulations
- Wealth of ground motion records is advancing many fields in EQ engineering including seismic slope stability