Linking Liquefaction Triggering to Damage Potential

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Acknowledgements

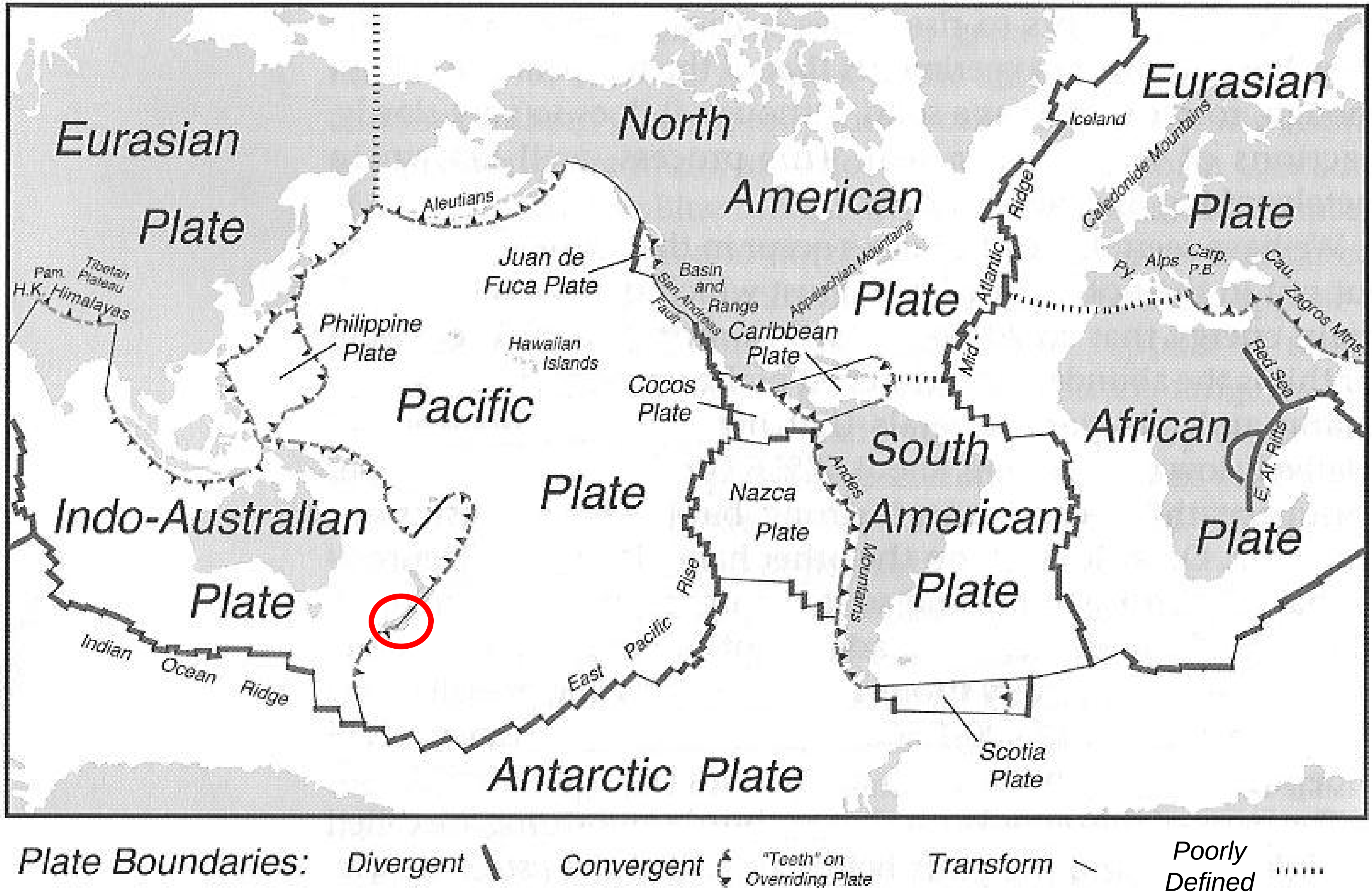
- **Brett Maurer** (Virginia Tech):
- Misko Cubrinovski, Brendon Bradley (University of Canterbury, Christchurch, NZ)
- Liam Wotherspoon (University of Auckland, Auckland, NZ)
- Sjoerd van Ballegooy (Tonkin and Taylor, Christchurch, NZ)
- Brady Cox (University Texas), Clinton Wood (University of Arkansas), Jonathan Bray (UC Berkeley), and Thomas O'Rourke (Cornell Univ.)
- Funding: NSF, GEER, New Zealand Earthquake Commission (EQC), US Army Engineer Research and Development Center

Outline

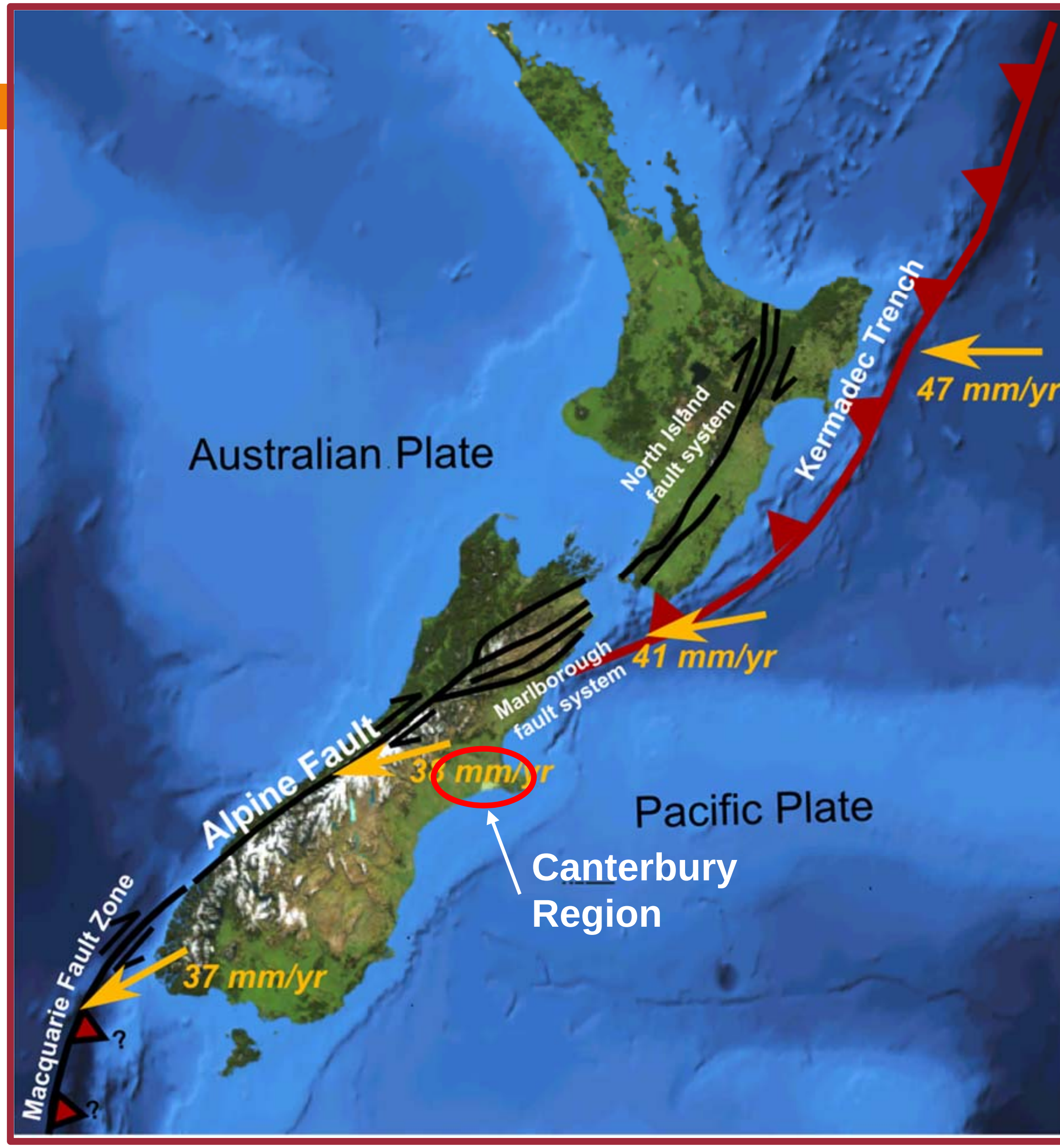
- 2010-2011 Canterbury Earthquake Sequence
- Soils of Christchurch
- Evaluation of CPT-Based Liquefaction Evaluation Procedures
- Liquefaction Damage Indices
  - Liquefaction Potential Index (LPI)
  - Ishihara's H_1-H_2 Chart
  - LPI_{ISH}
- Aging Effects
- Summary of Conclusions
- Work in Progress/Future Directions

2010-2011 Canterbury Earthquake Sequence

Tectonics

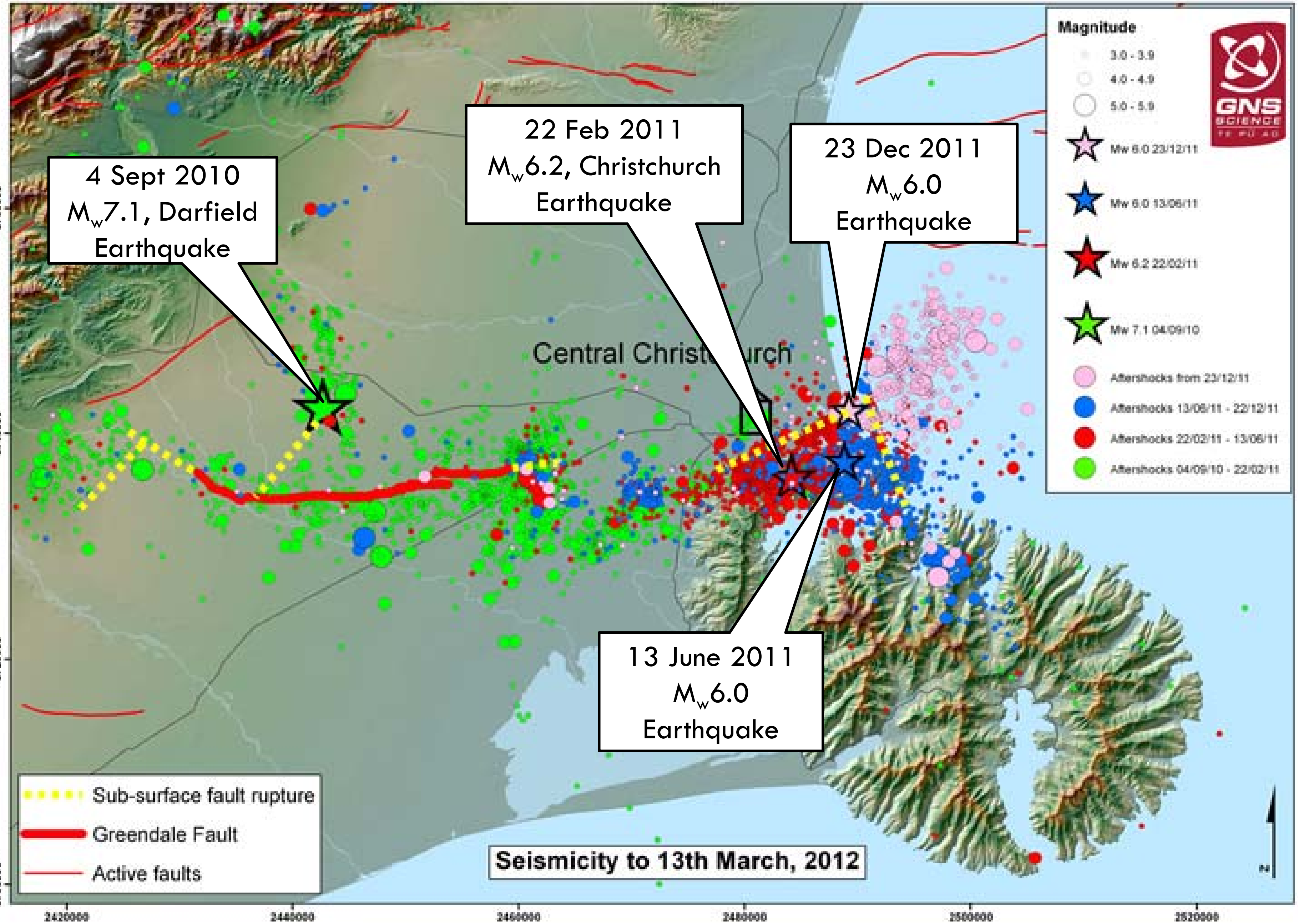

Eurasian
Plate
North
American
Plate
Eurasian
Plate
Iceland
Caledonide Mountains
Aleutians
Juan de
Fuca Plate
Basin
and
Range
Appalachian Mountains
San Andreas
Fault
Mid-Atlantic Ridge
Pam.
Tibetan
Plateau
H.K.
Himalayas
Philippine
Plate
Hawaiian
Islands
Caribbean
Plate
Py.
Alps
Carp.
P.B.
Cau.
Zagros Mts.
Red Sea
Cocos
Plate
Pacific
Plate
South
American
Plate
African
Plate
E. Af. Rifts
Andes
Nazca
Plate
Mountains
Indo-Australian
Plate
Rise
Pacific
East
Indian
Ocean
Ridge
Antarctic Plate
Scotia
Plate
Plate Boundaries:
Divergent
Convergent
"Teeth" on
Overriding Plate
Transform
Poorly
Defined

Tectonics



Australian Plate
North Island fault system
Kermadec Trench
47 mm/yr
41 mm/yr
Marlborough fault system
Alpine Fault
mm/yr
Pacific Plate
Canterbury Region
Macquarie Fault Zone
37 mm/yr
?
?

2010-2011 Canterbury Earthquake Sequence



Statistics

- Liquefaction Effects:
  - Residential Properties: 60,000 affected

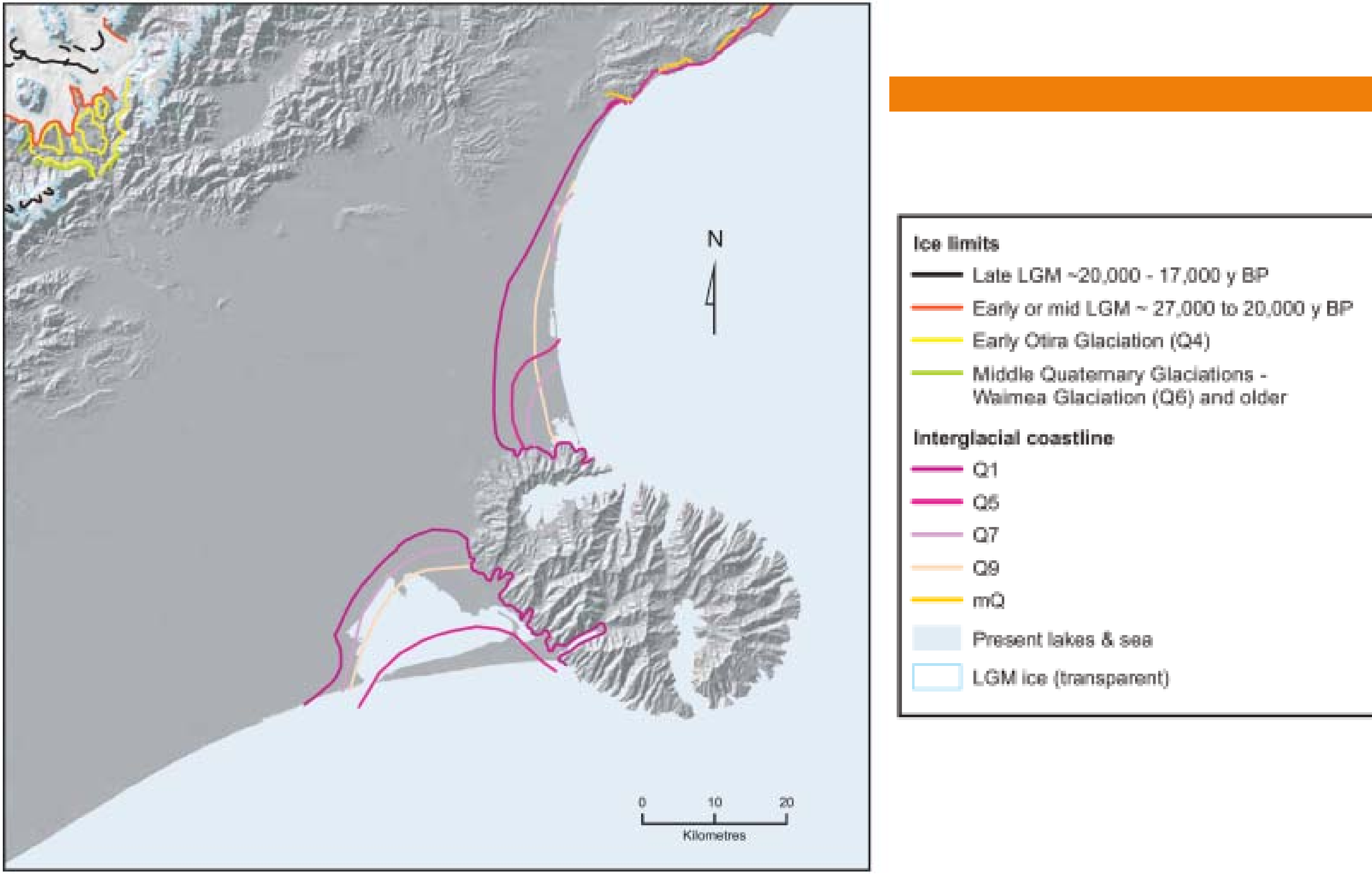
    20,000 severely affected

    8,000 abandoned
  - Pipe networks: ~700 km WW pipes (loss/limited service)

    ~one break per km PW pipes (4000 km)
  - Many CBD buildings, bridges, …

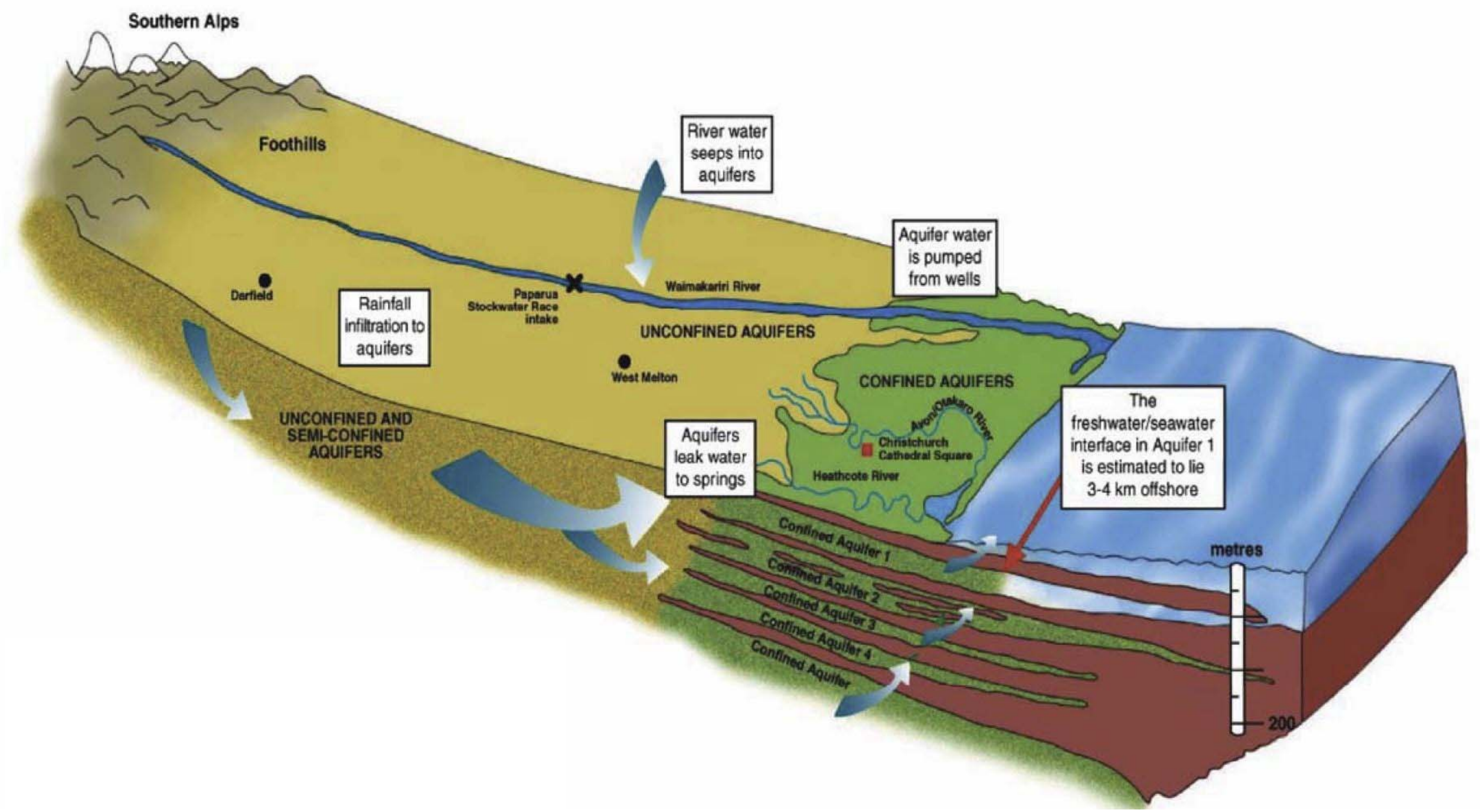
Soils of Christchurch

Ancient Coastlines

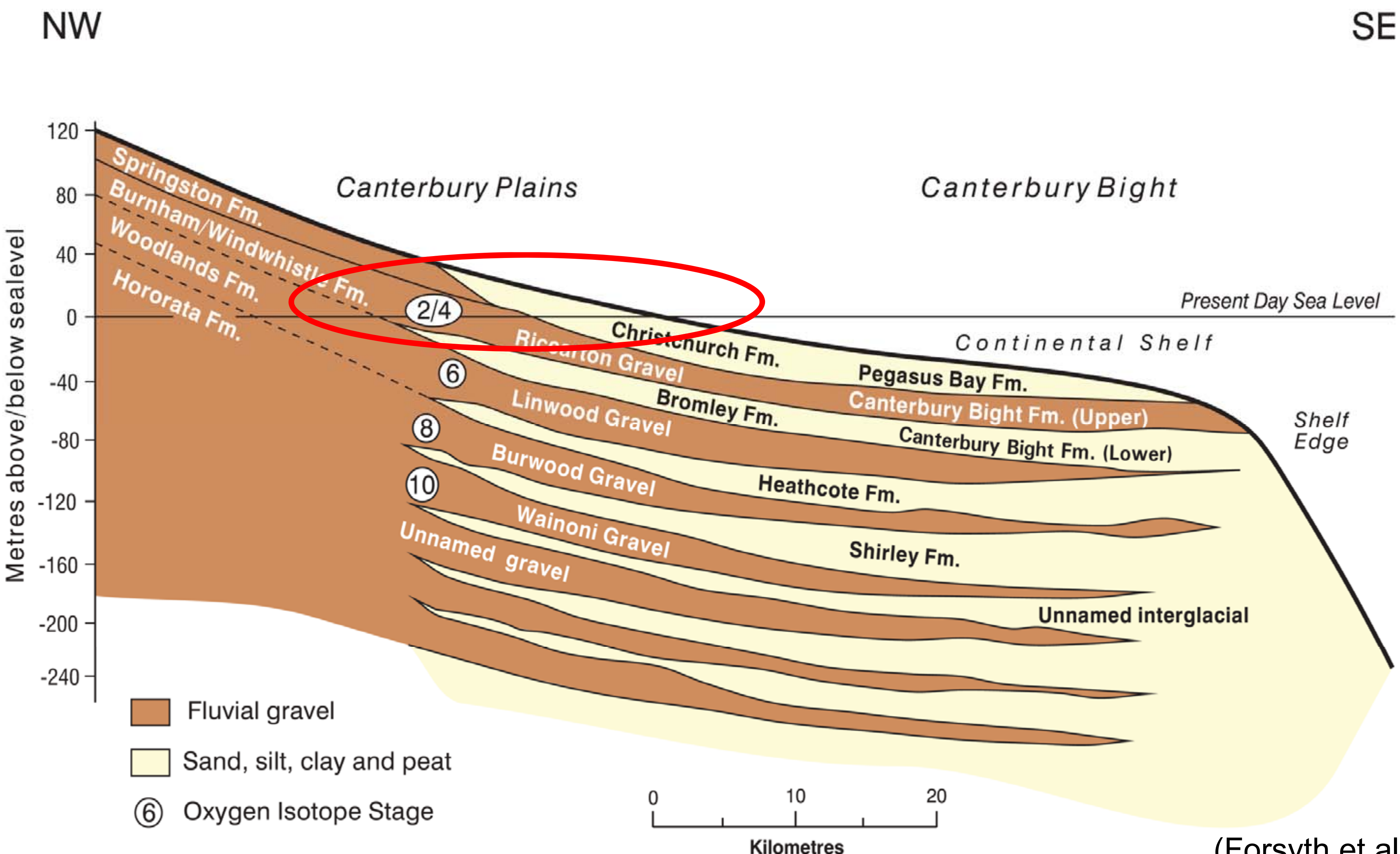


(Forsyth et al. 2008)

Regional Soil Stratigraphy

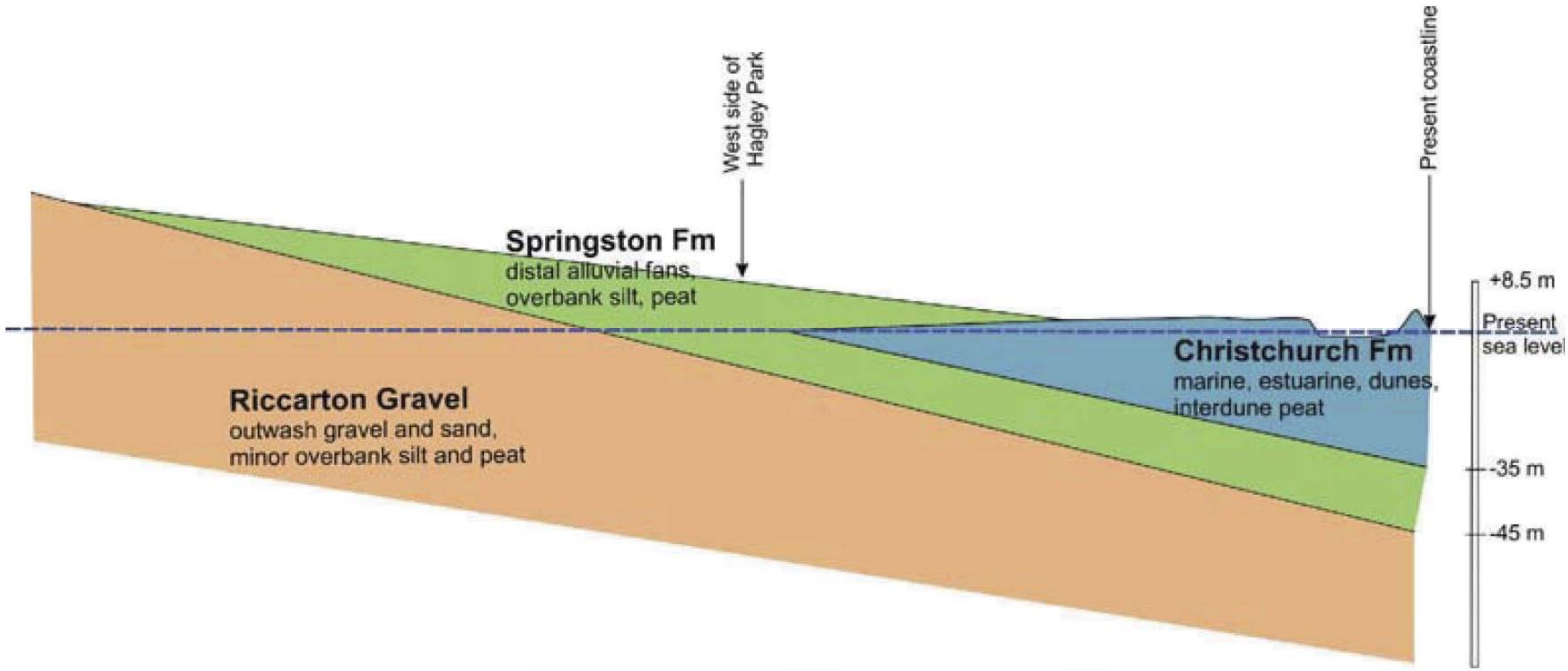


Regional Soil Stratigraphy

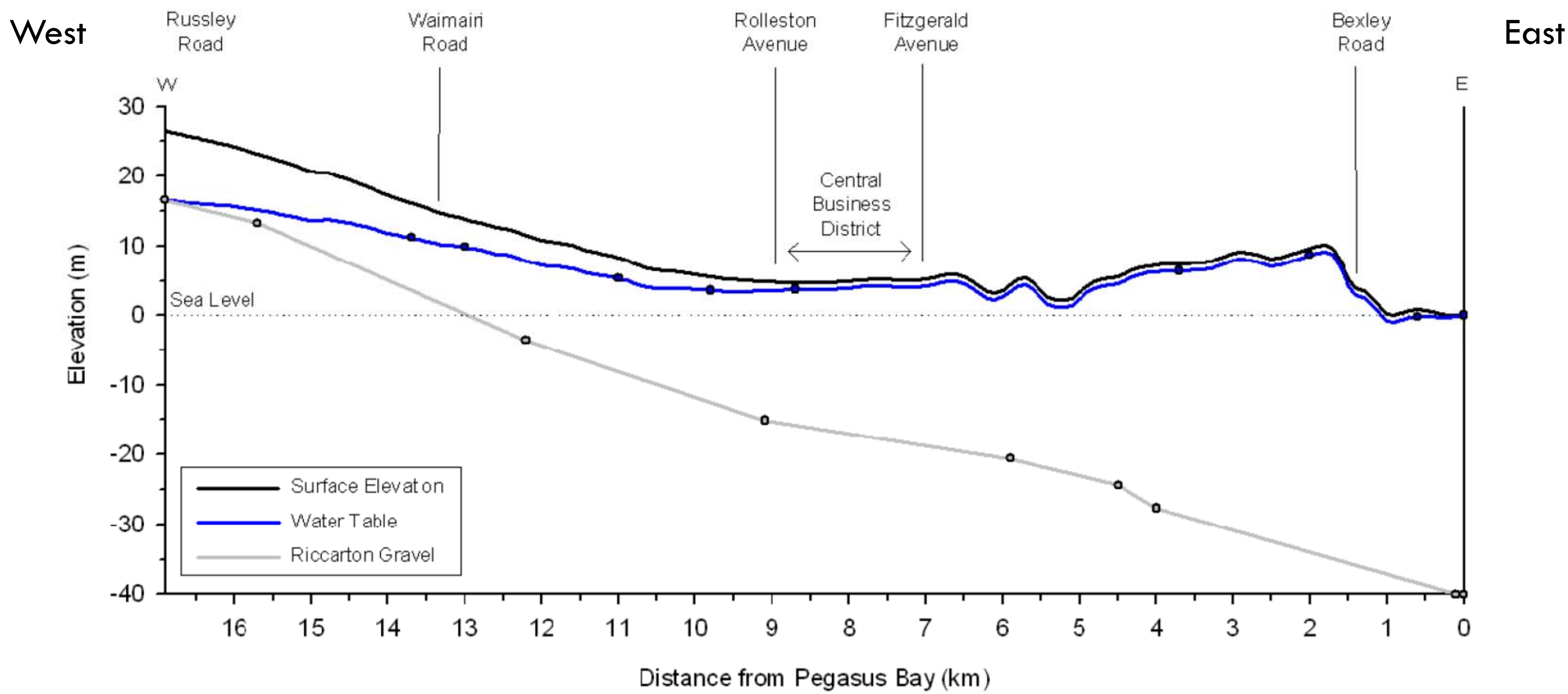


(Forsyth et al. 2008)

Regional Soil Stratigraphy

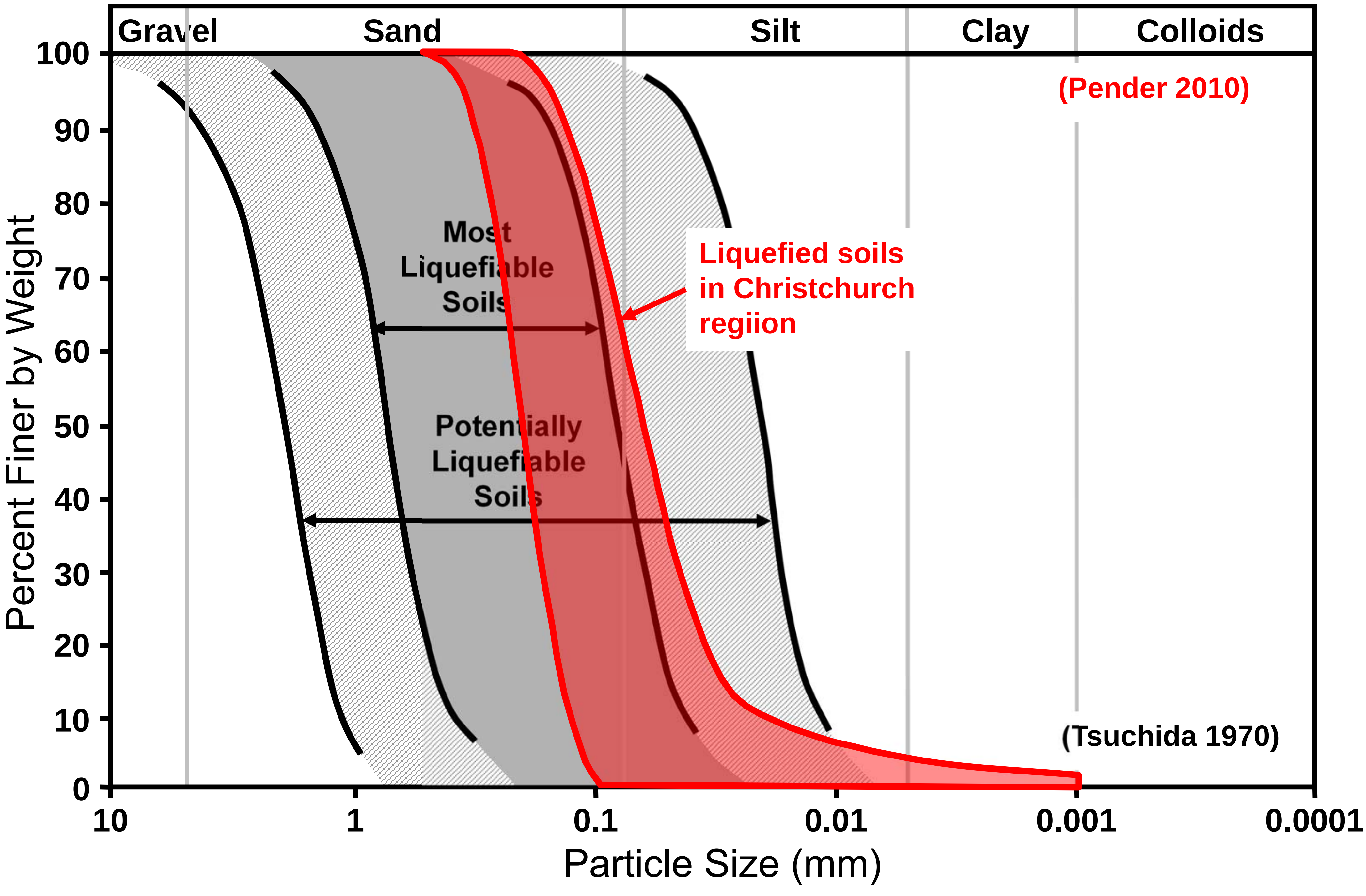


Ground Water Table: E-W, along Bealey Ave (north border of CBD)

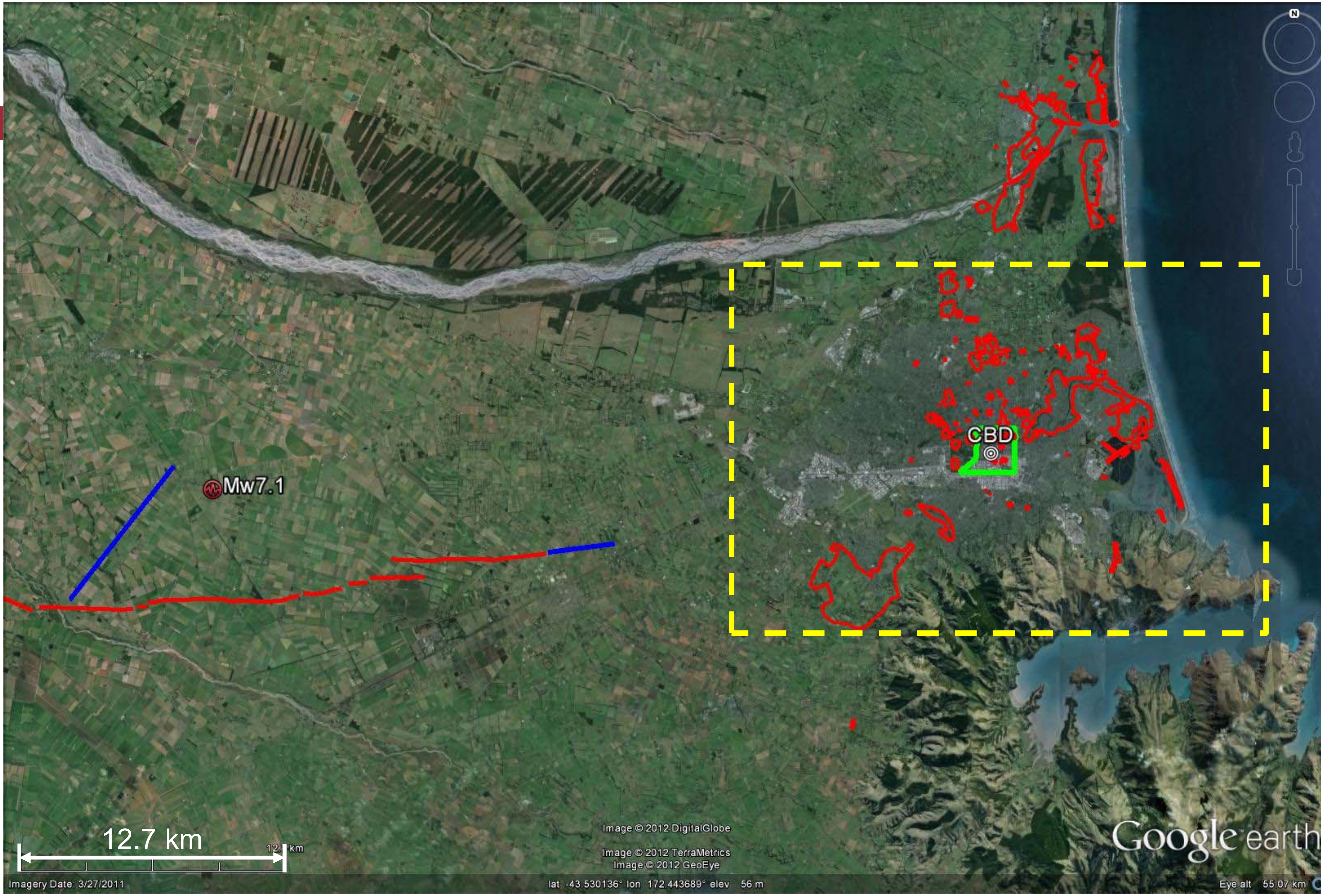


(Cubrinovski et al. 2011)

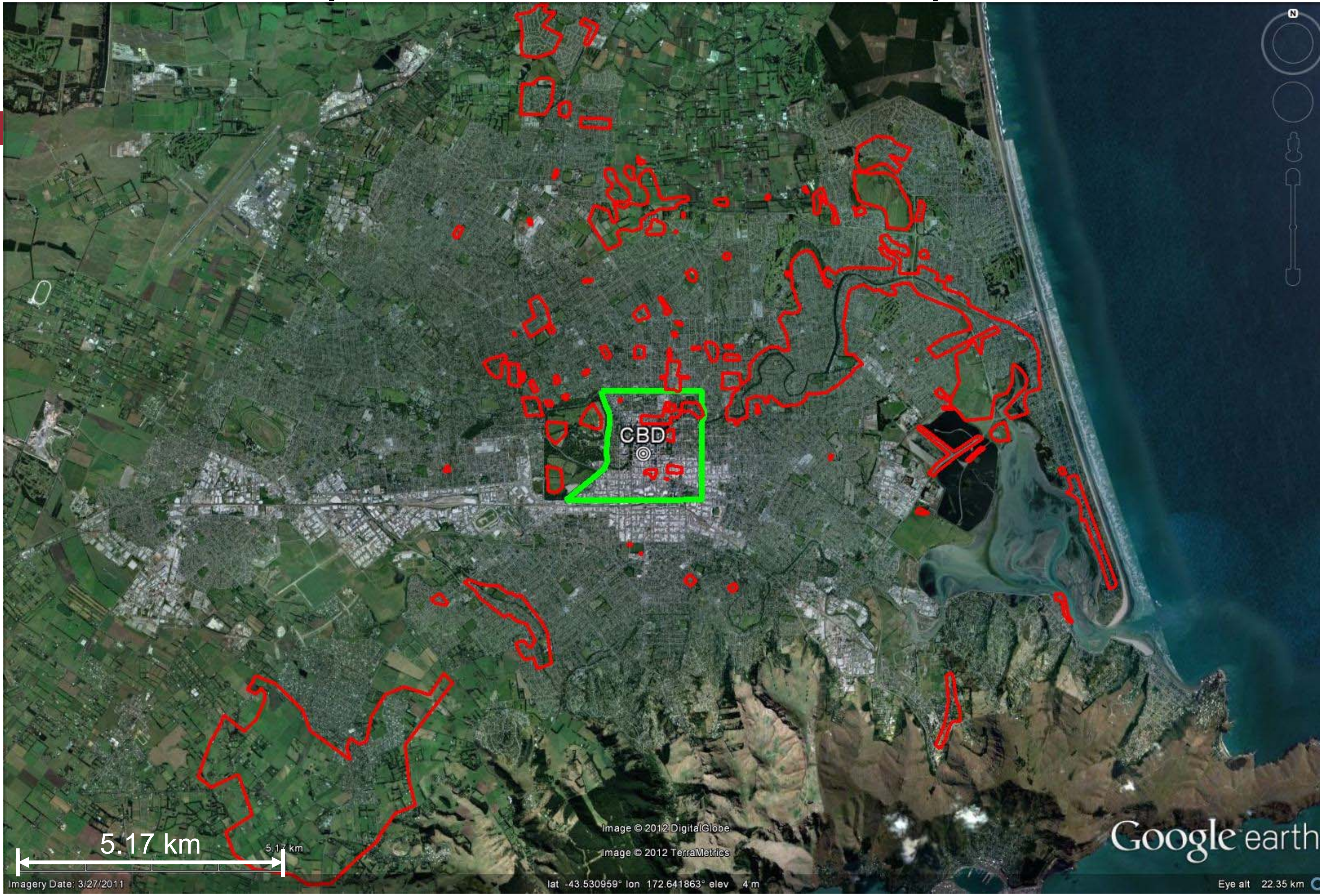
Liquefaction: Grain-size Distributions



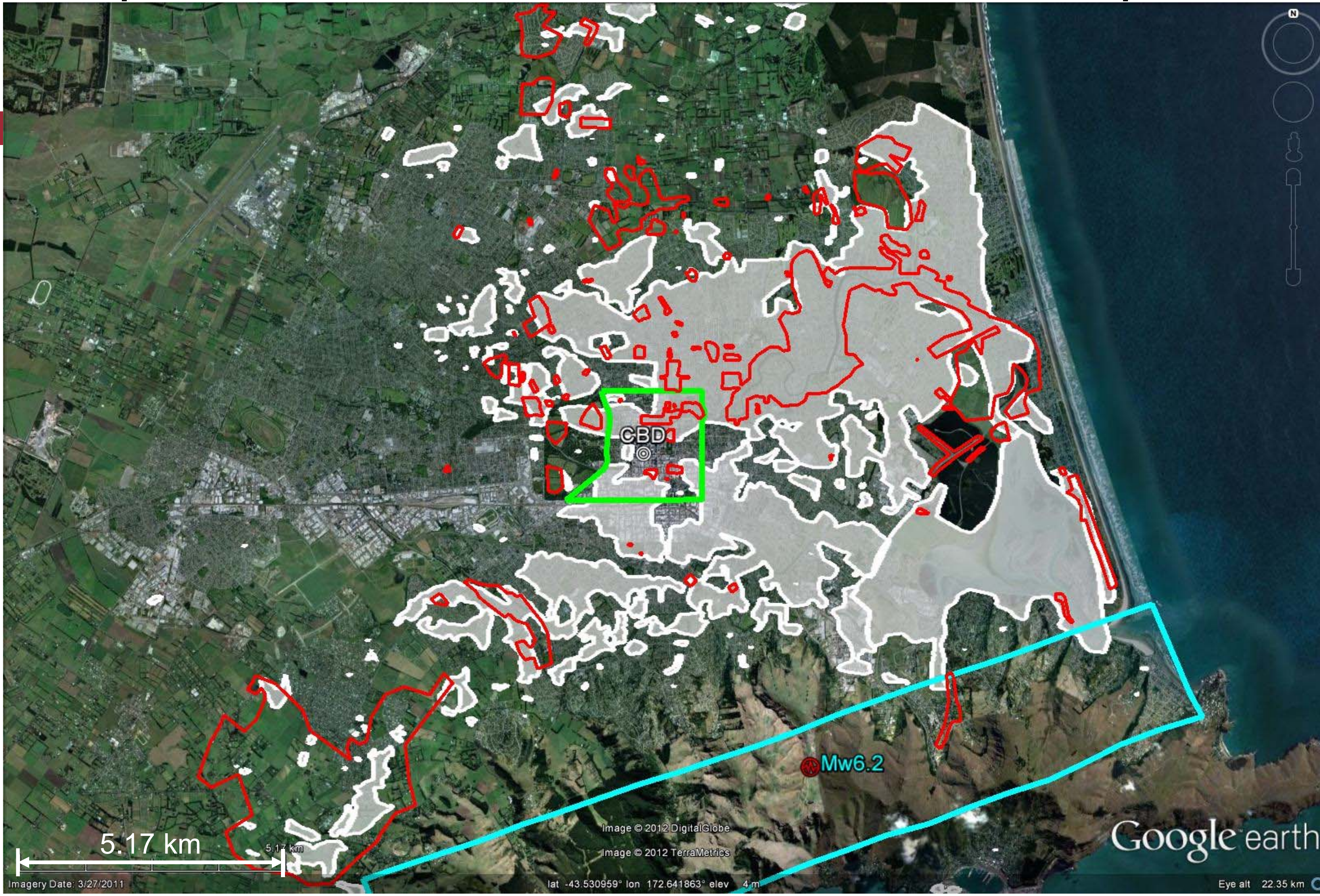
Liquefaction: Darfield Earthquake



Liquefaction: Darfield Earthquake



Liquefaction: Darfield and Christchurch Earthquakes



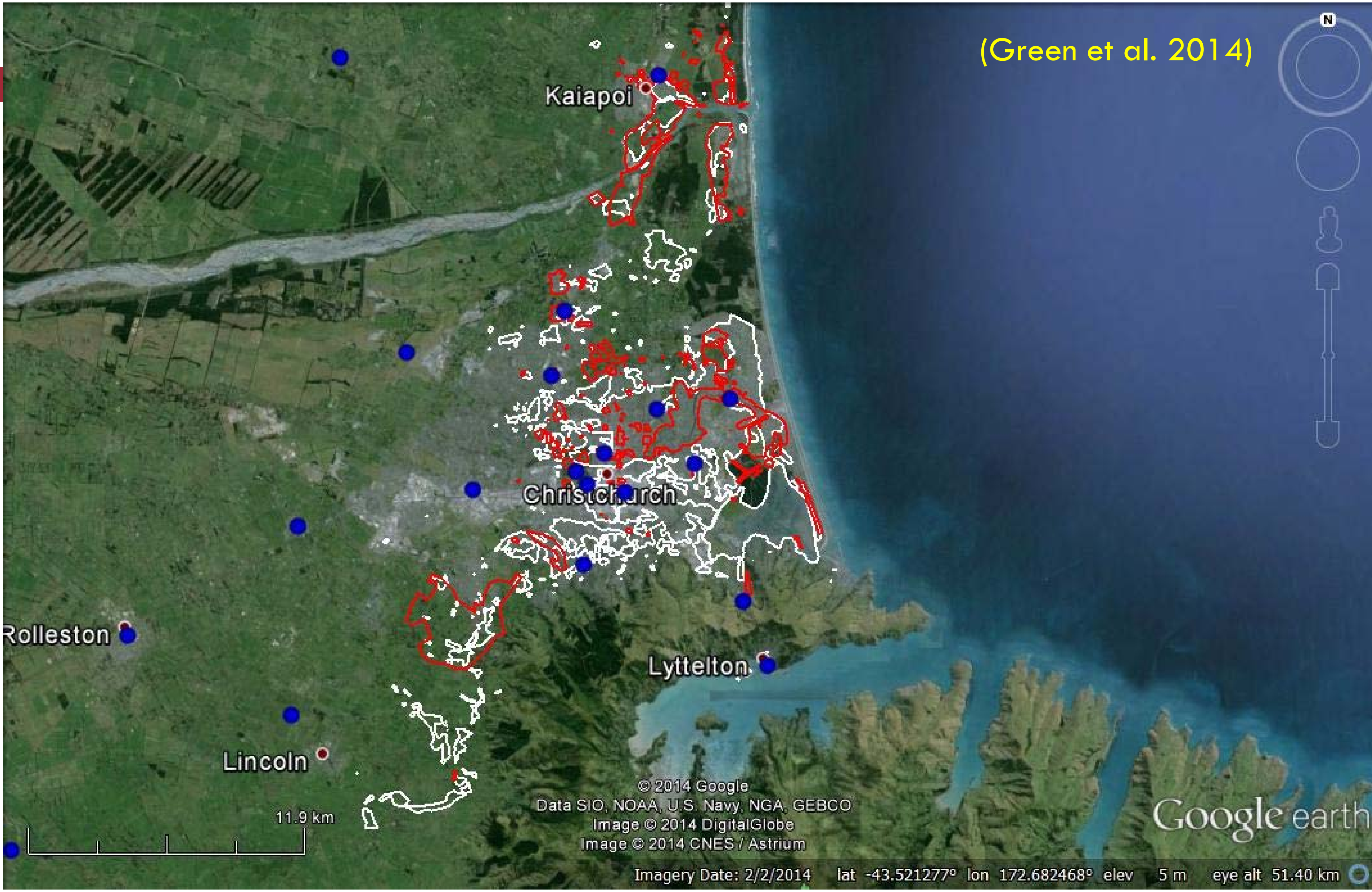
Severe Liquefaction in Eastern Suburbs

(Mark Quigley: Avonside)

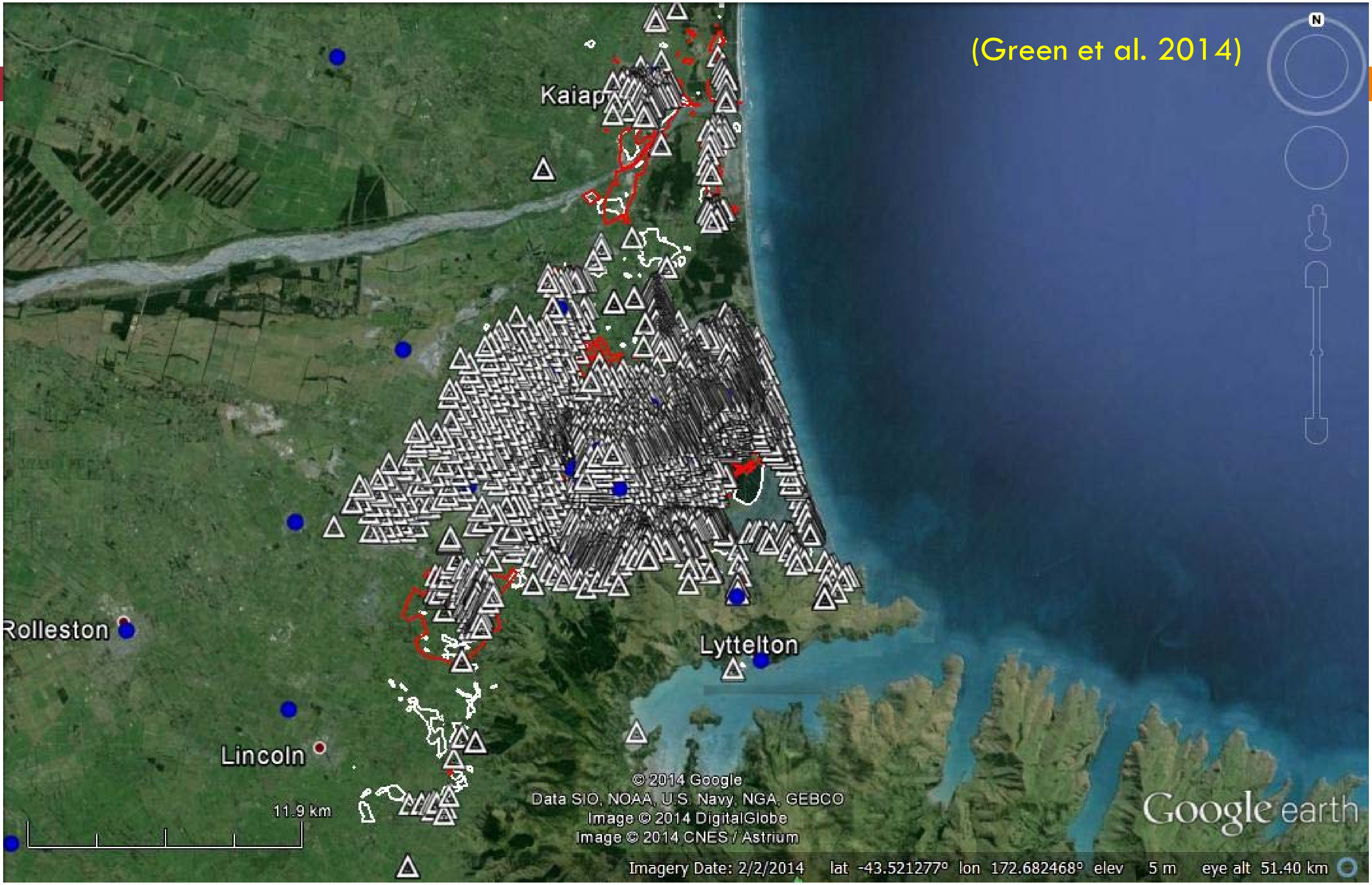
Piles of Liquefaction Ejecta

Evaluation of CPT-Based Liquefaction Triggering Evaluation Procedures

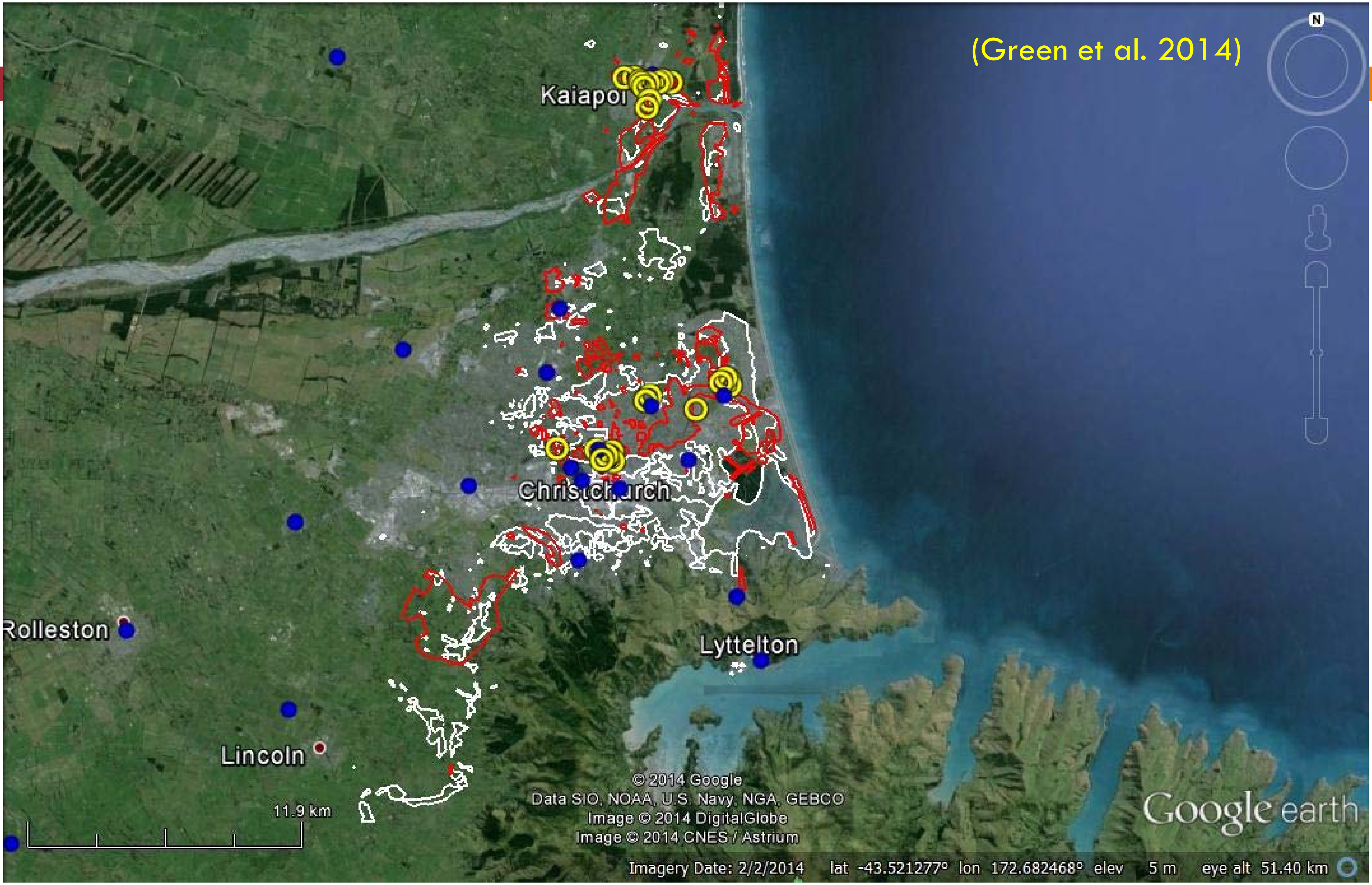
Strong Motion Stations



CPT Soundings

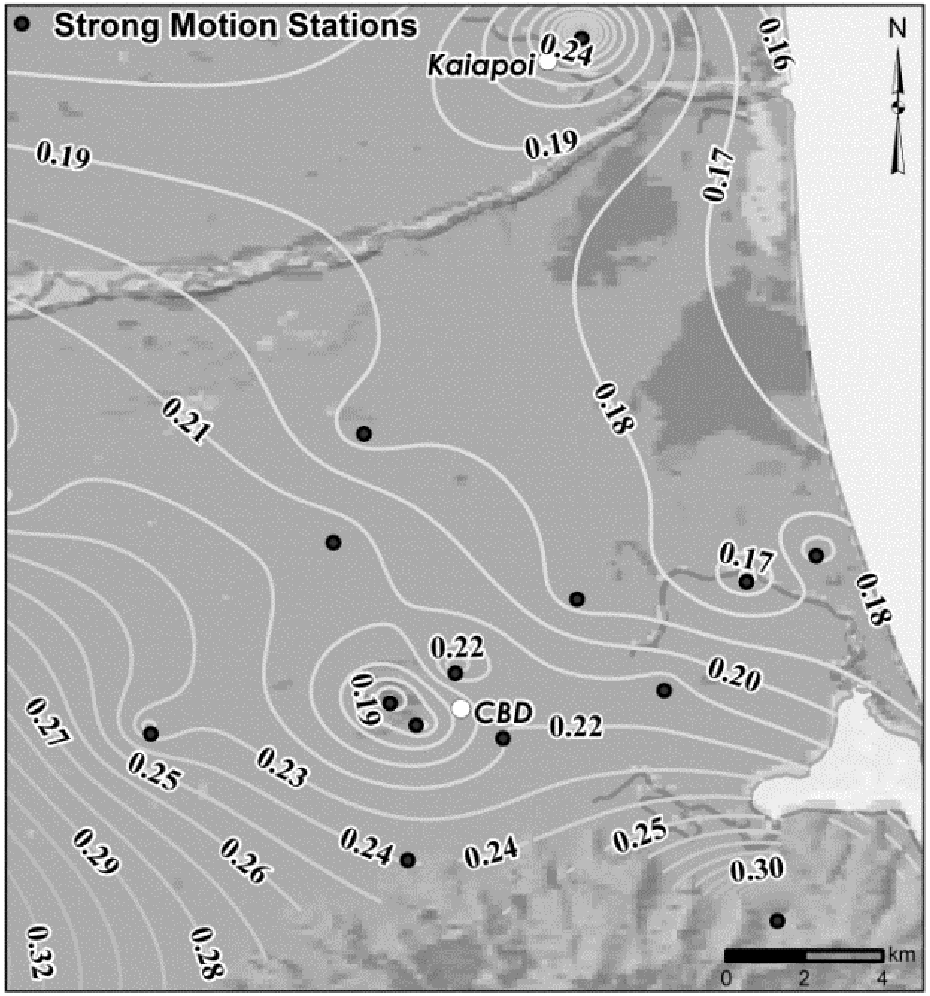


Case History Sites

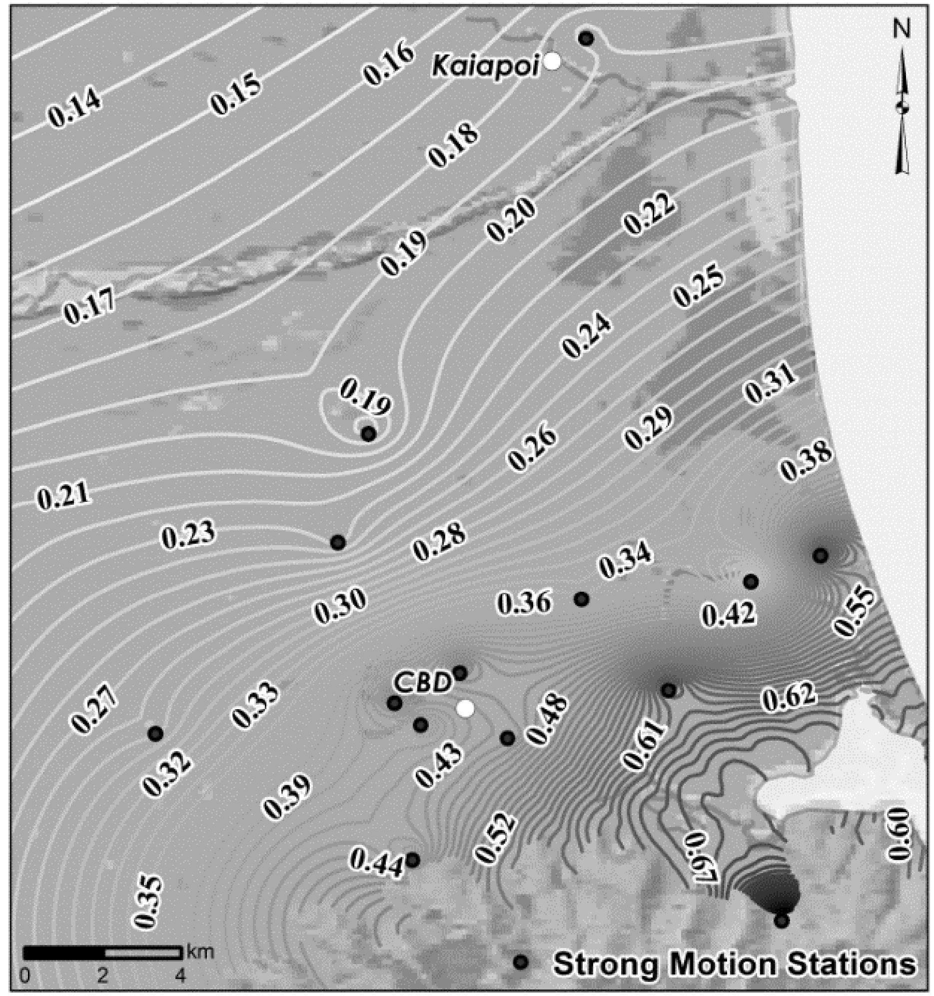


Estimated PGAs (Bradley, 2014)

M_w7.1 Darfield Earthquake

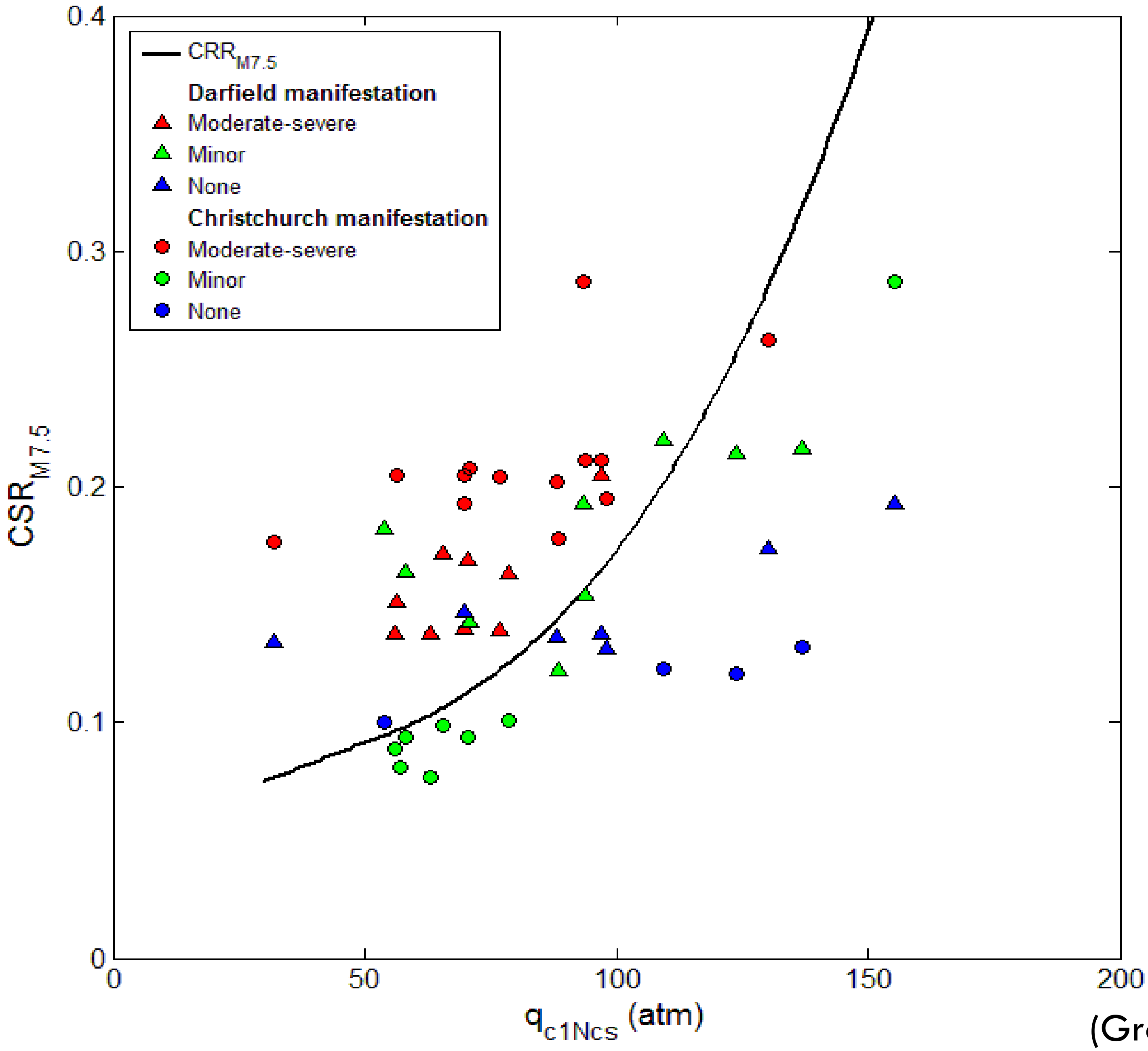


M_w6.2 Christchurch Earthquake



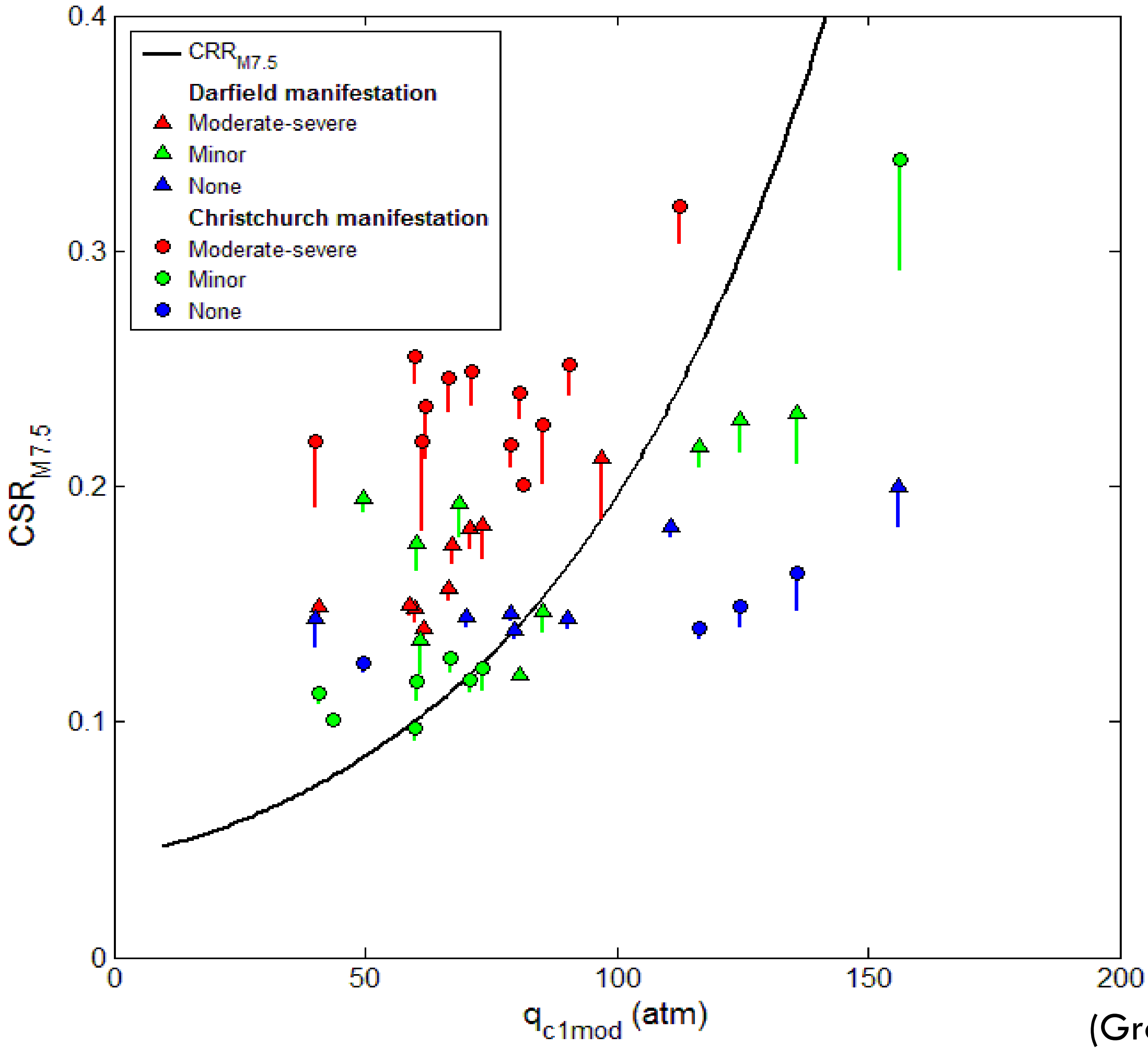
(Green et al. 2014)

Robertson and Wride (1998): RW98



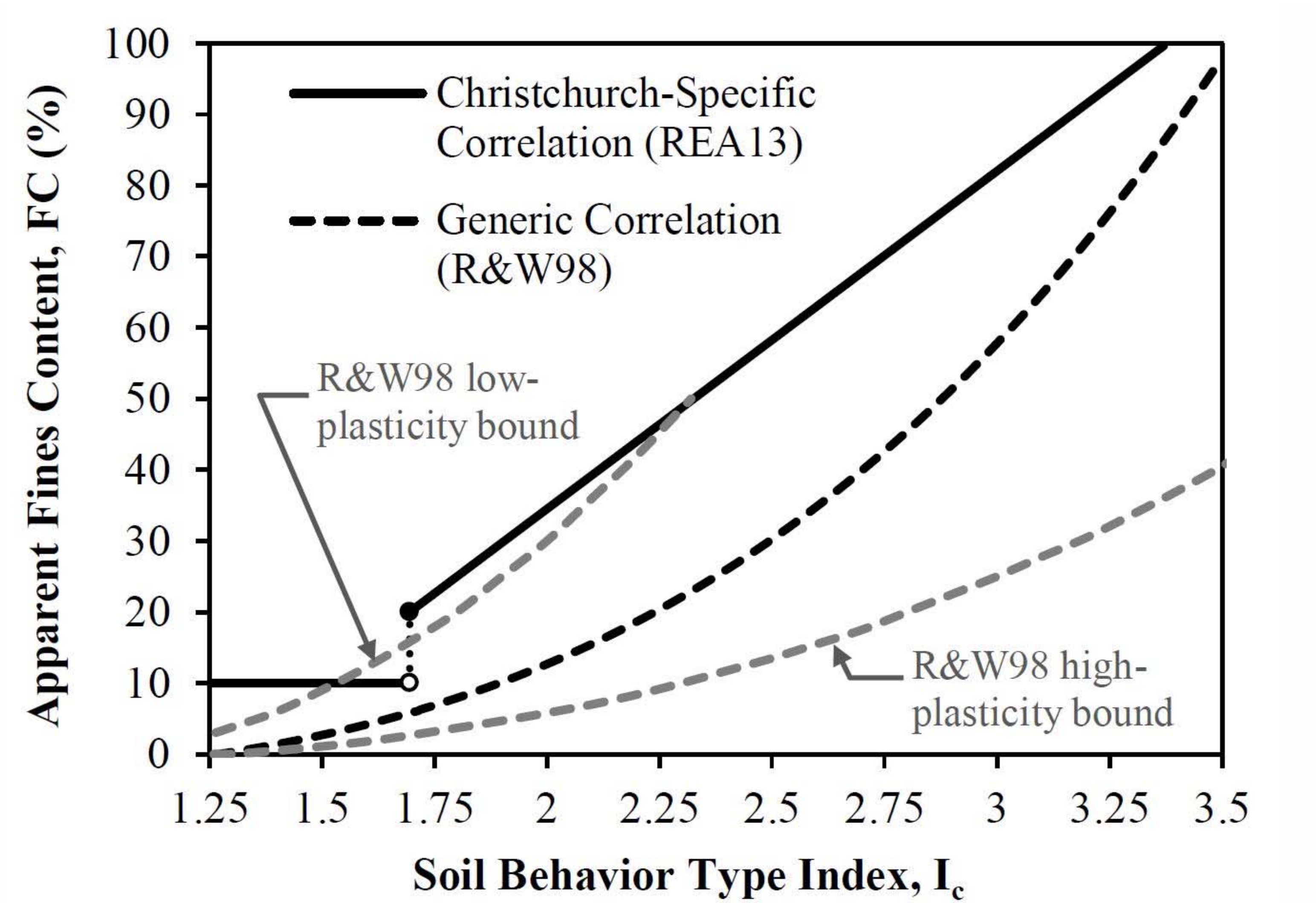
(Green et al. 2014)

Moss et al. (2006): MEA06



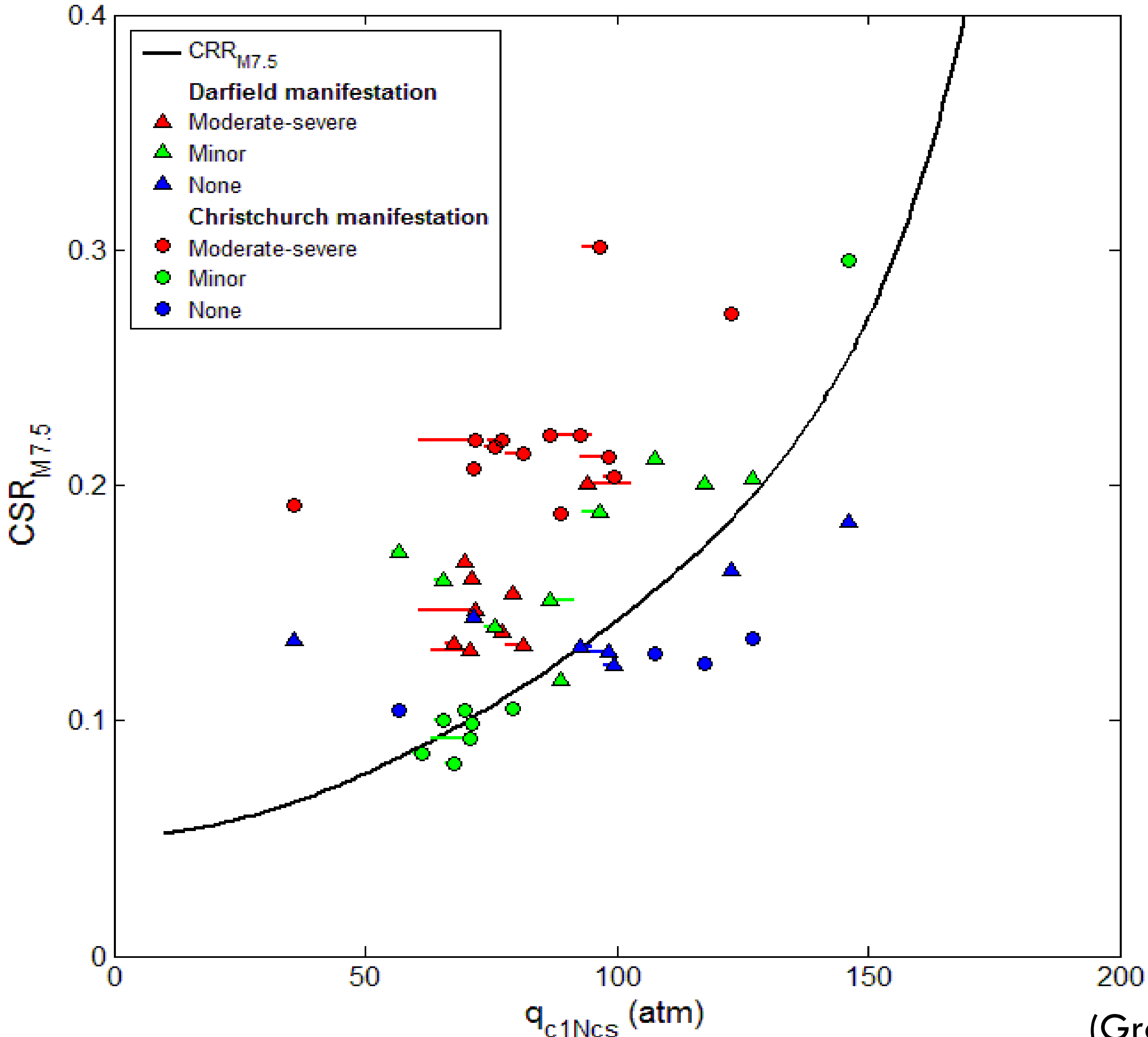
(Green et al. 2014)

Ic – FC Correlation (latest version)



(Maurer et al. 2015a)

Idriss and Boulanger (2008): IB08



(Green et al. 2014)

Conclusion 1

- Based on *select* case history data from the Canterbury Earthquake Sequence:
  - All of the CPT-base procedures do a reasonable job predicting field observations.
  - Idriss and Boulanger (2008) performed better than the other procedures.

(Green et al. 2014)

Is FS Okay???

Some "rules of thumb" that have been used in the past:

FS > 1.4: Okay, small strains

FS > 1.25: Probably okay if consequences are not bad

FS < 0.9: Problem, go directly to remediation

0.9 ≤ FS ≤ 1.25: Marginal, more field testing

What about thickness and depth of the liquefied layer; are these important considerations???

Is FS Okay???

You really need to look at the potential consequences:

- Lateral Spreading
- Flow liquefaction
- Bearing capacity failure
- Post-liquefaction consolidation settlement
- Slope failure
- Buoyant uplift of buried tanks/pipelines

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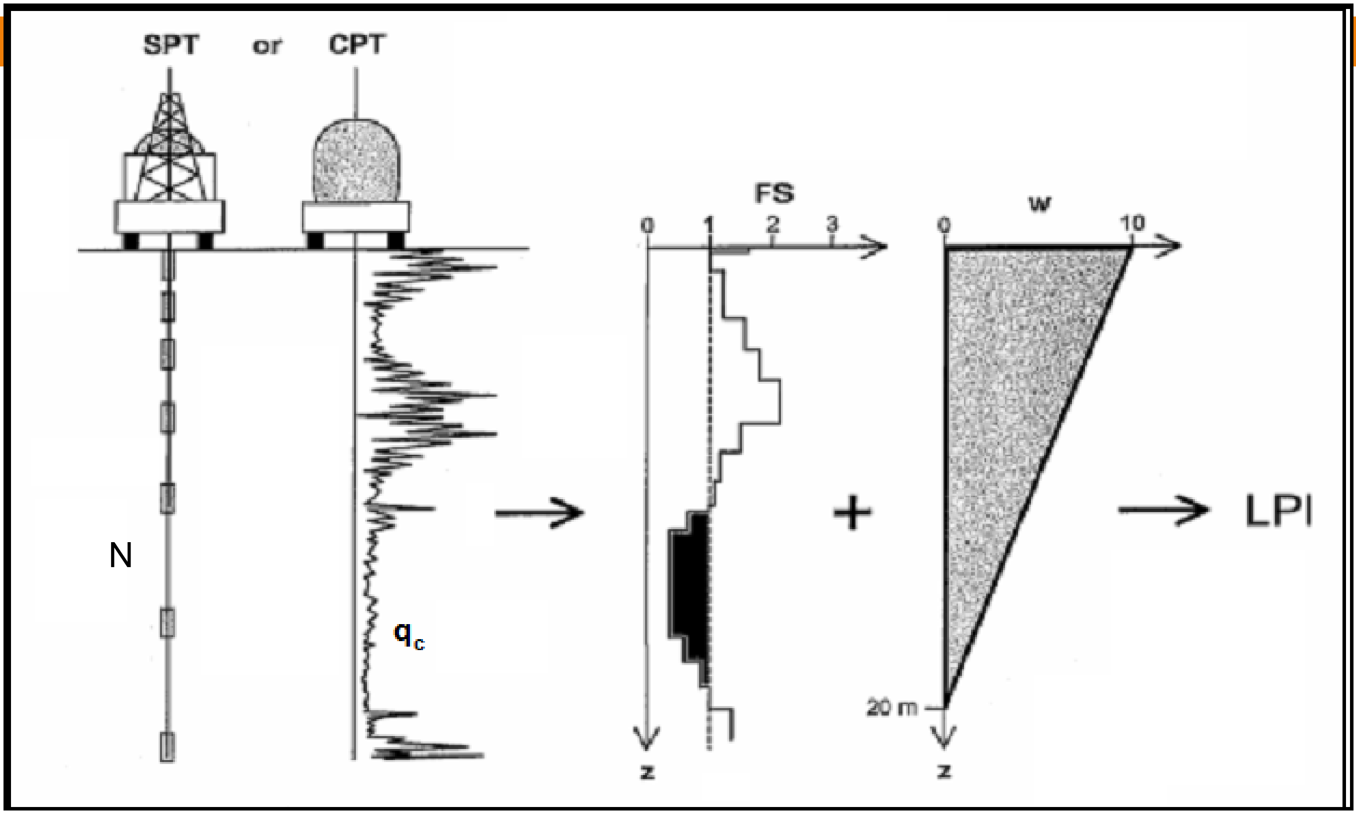
Liquefaction Damage Potential

Liquefaction Potential Index



$$LPI = \int_0^{20\ m} w(z) \cdot f(z)\, dz$$

$$f(z) = 0 \quad \rightarrow \quad for \quad FS(z) > 1$$

$$f(z) = 1 - FS(z) \quad \rightarrow \quad for \quad FS(z) \leq 1$$

$$w(z) = 10 - 0.5z;\ z\ in\ m$$

(Iwasaki et al. 1978)

Liquefaction Potential (Damage) Index

$$LPI = \int_{0}^{20\ m} w(z) \cdot f(z)\, dz$$

Limits: $LPI_{min} = 0$ (FS > 1 for $0 \leq z \leq 20$ m)

$LPI_{max} = 100$ (FS = 0 for $0 \leq z \leq 20$ m)

Damage: *Sand boils: LPI* ≥ 5 ($3 \leq$ LPI ≤ 10)

Lateral spreading: LPI ≥ 12 ($5 \leq$ LPI ≤ 17)

(Holzer et al. 2006)

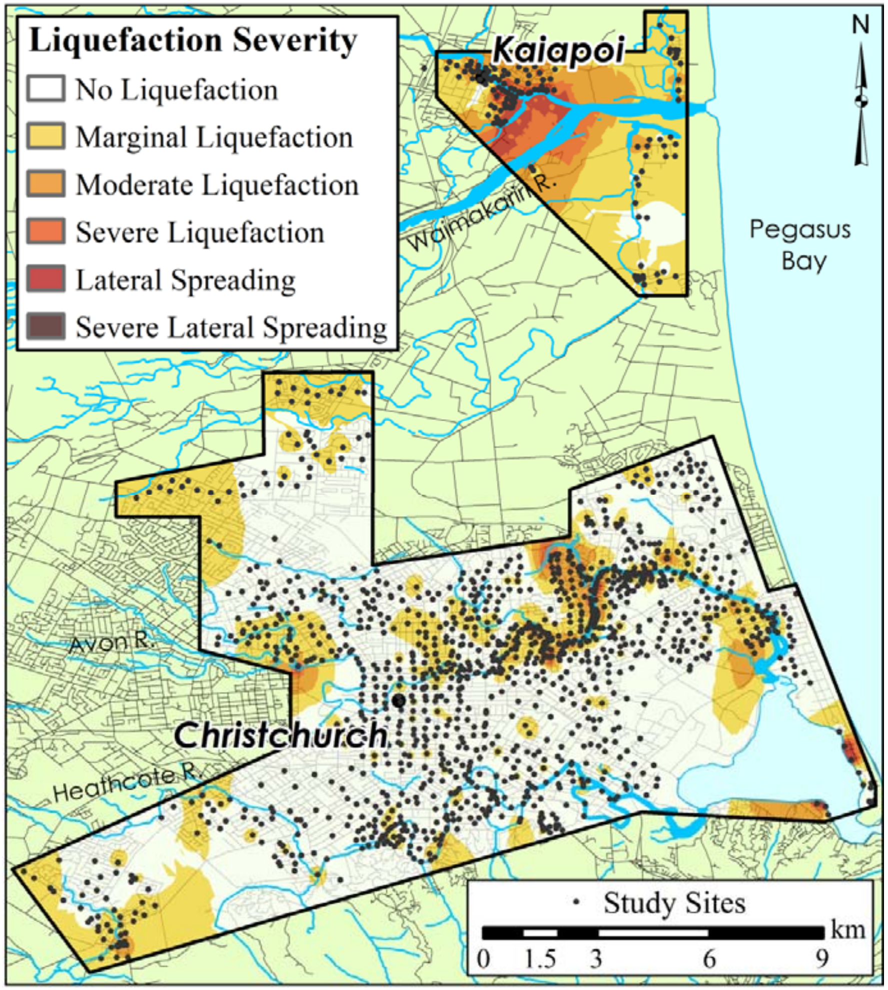
Liquefaction Severity

Classification	Criteria
No Manifestation	No surficial liquefaction manifestation or lateral spread cracking
Marginal Manifestation	Small, isolated liquefaction features; streets had traces of ejecta or wet patches less than a vehicle width; < 5% of ground surface covered by ejecta
Moderate Manifestation	Groups of liquefaction features; streets had ejecta patches greater than a vehicle width but were still passable; 5-40% of ground surface covered by ejecta
Severe Manifestation	Large masses of adjoining liquefaction features, streets impassible due to liquefaction; >40% of ground surface covered by ejecta
Lateral Spreading	Lateral spread cracks were predominant manifestation and damage mechanism, but crack displacements < 200 mm
Severe Lateral Spreading	Extensive lateral spreading and/or large open cracks extending across the ground surface with > 200 mm crack displacement

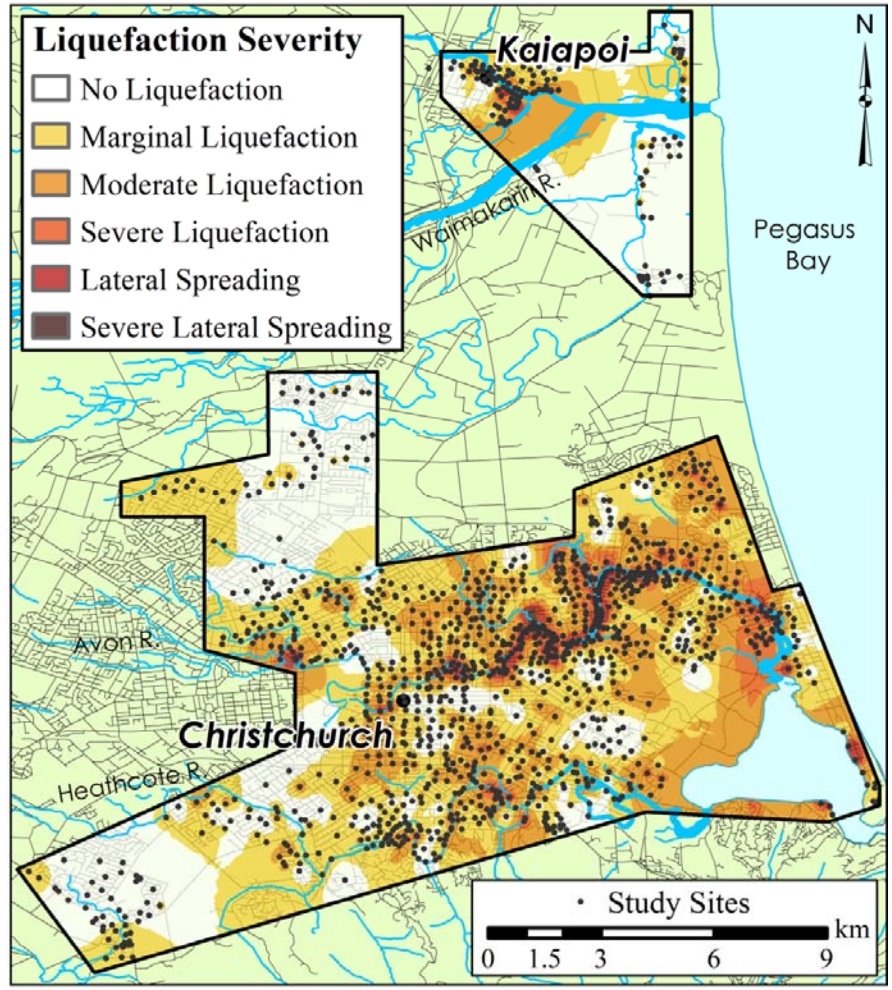
(Maurer et al. 2014a)

Observed Liquefaction Severity

M_w7.1 Darfield Earthquake



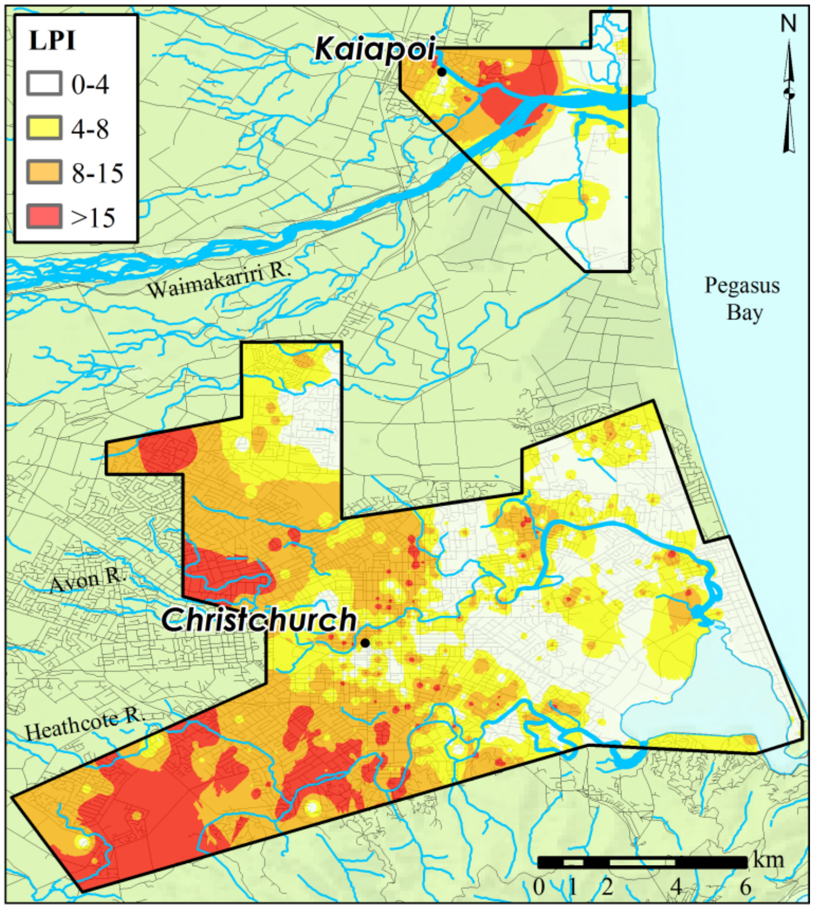
M_w6.2 Christchurch Earthquake



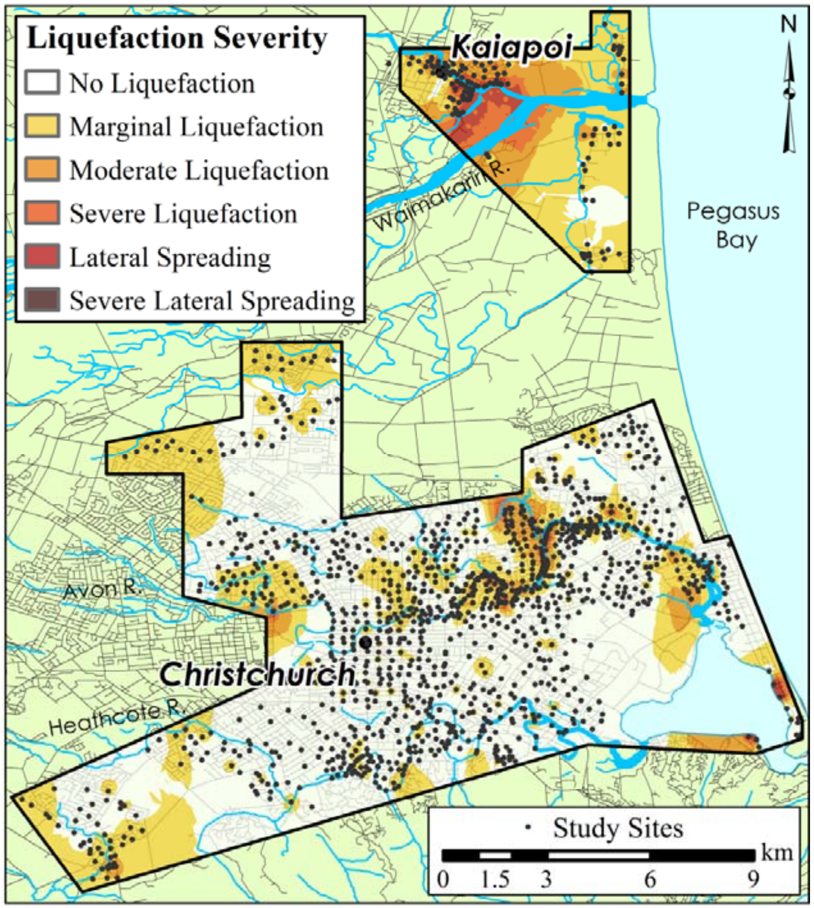
(Maurer et al. 2014a)

Predicted versus Observed Severity

M_w7.1 Darfield Earthquake



Predicted

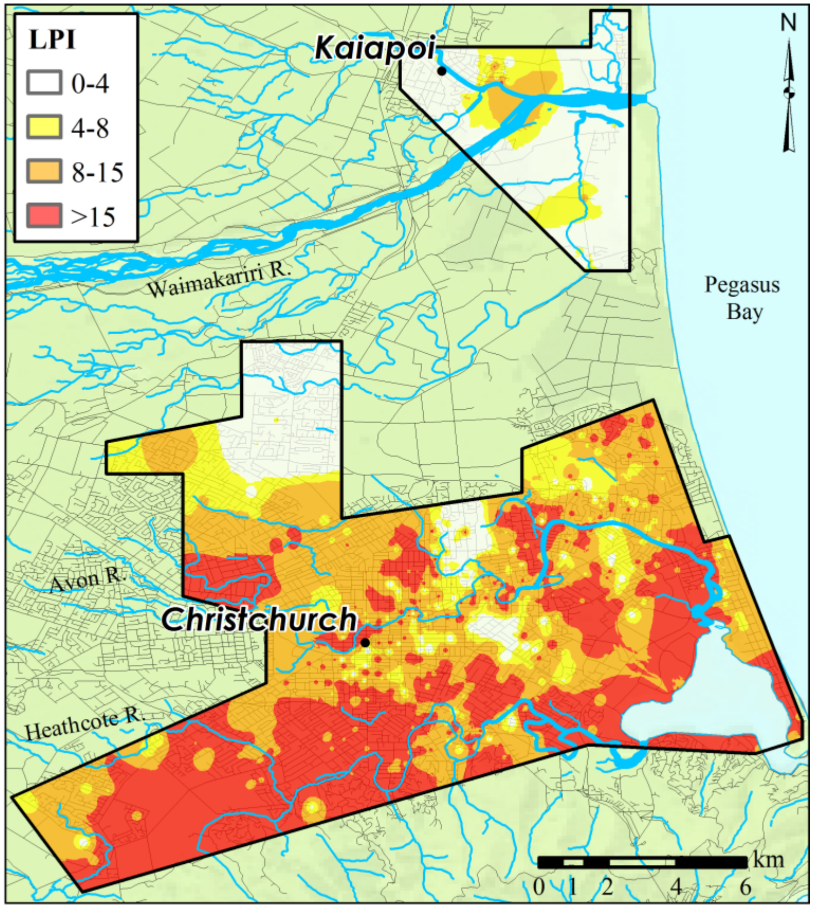


Observed

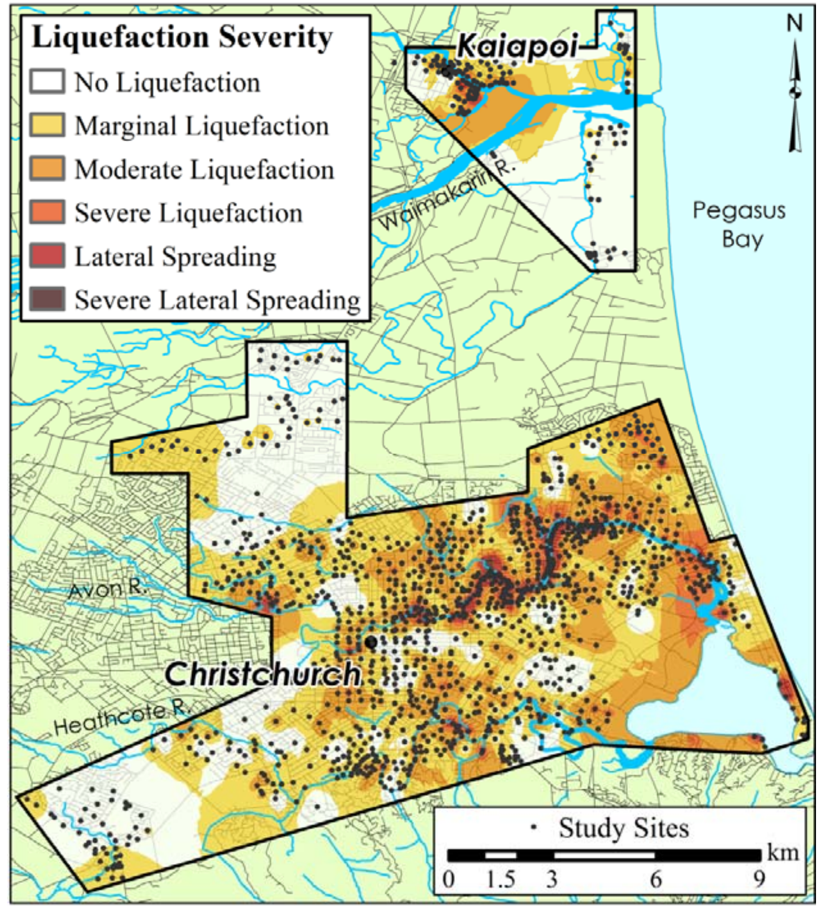
(Maurer et al. 2014a)

Predicted versus Observed Severity

M_w6.2 Christchurch Earthquake



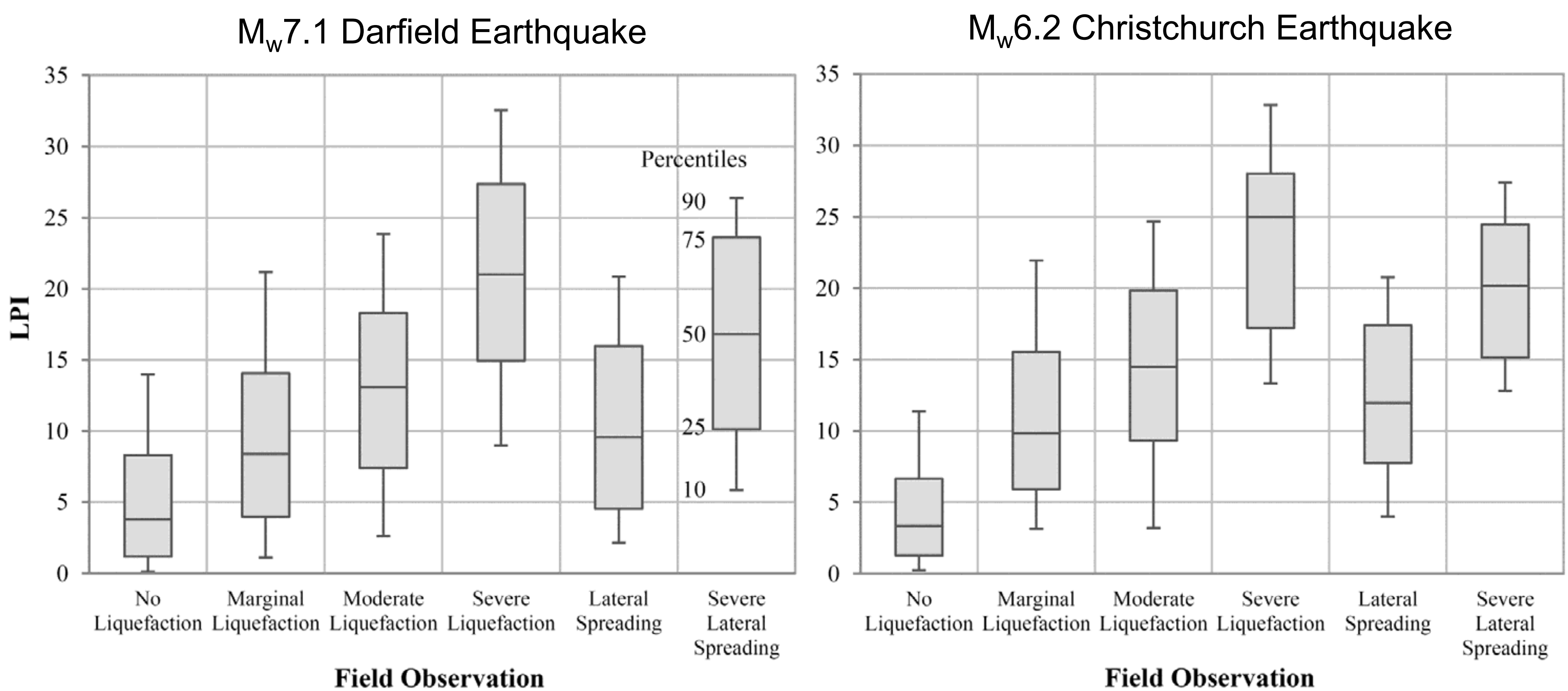
Predicted



Observed

(Maurer et al. 2014a)

LPI: Darfield and Christchurch Earthquakes



(Maurer et al. 2014a)

Liquefaction Potential Index

Damage Classification	Expected LPI Range
No Liquefaction	LPI < 4
Marginal Liquefaction	$4 \leq$ LPI < 8
Moderate Liquefaction	$8 \leq$ LPI < 15
Severe Liquefaction	LPI ≥ 15
Lateral Spreading	LPI ≥ 4
Severe Lateral Spreading	LPI ≥ 4

(Maurer et al. 2014a)

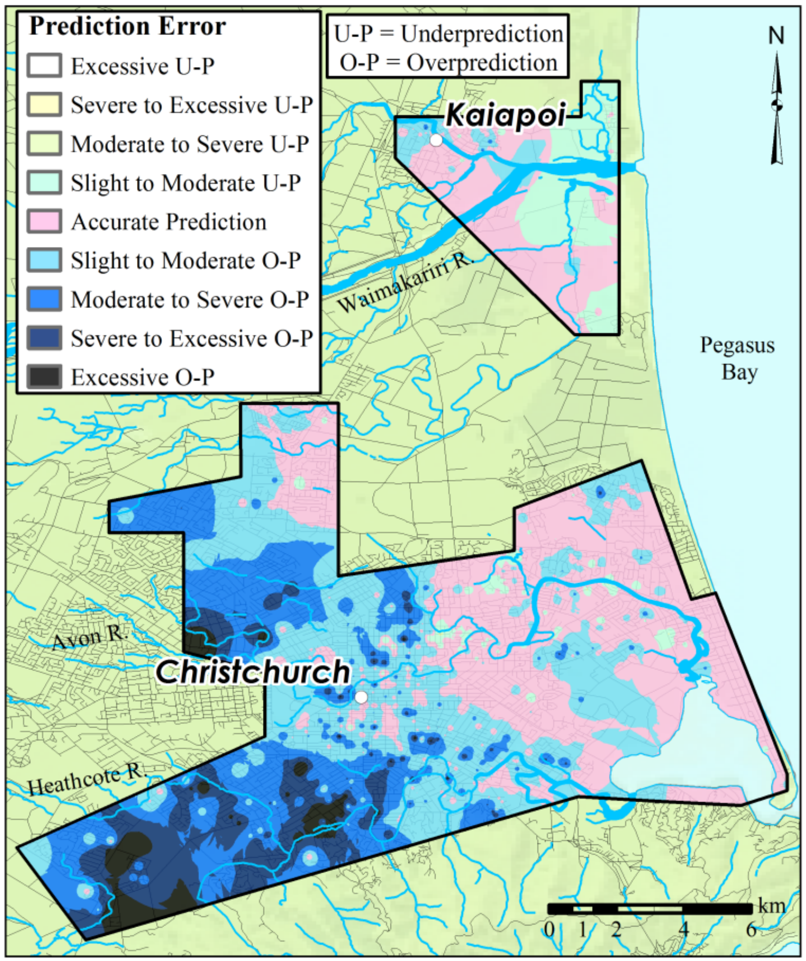
LPI Prediction Error Classification

Error (E) Classification	E (LPI units)
Excessive Underprediction	$E < -15$
Severe to Excessive Underprediction	$-15 \leq E < -10$
Moderate to Severe Underprediction	$-10 \leq E < -5$
Slight to Moderate Underprediction	$-5 \leq E < -1$
Accurate Prediction	$-1 \leq E \leq 1$
Slight to Moderate Overprediction	$1 < E \leq 5$
Moderate to Severe Overprediction	$5 < E \leq 10$
Severe to Excessive Overprediction	$10 < E \leq 15$
Excessive Overprediction	$E > 15$

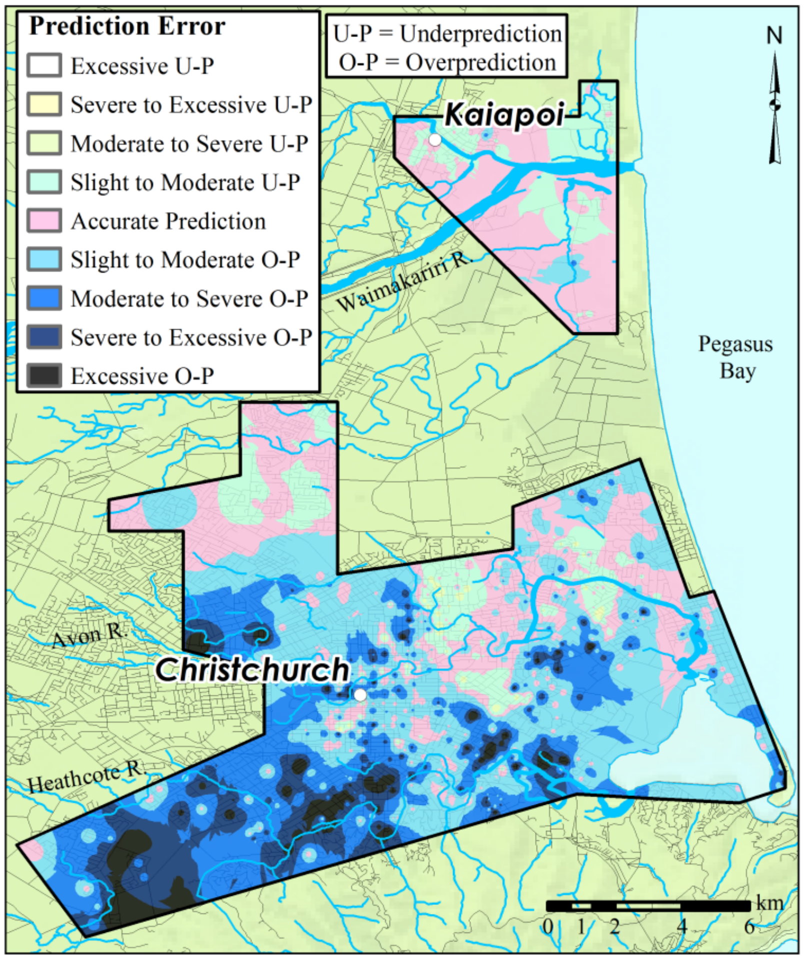
(Maurer et al. 2014a)

Error in LPI Severity Predictions

M_w7.1 Darfield Earthquake



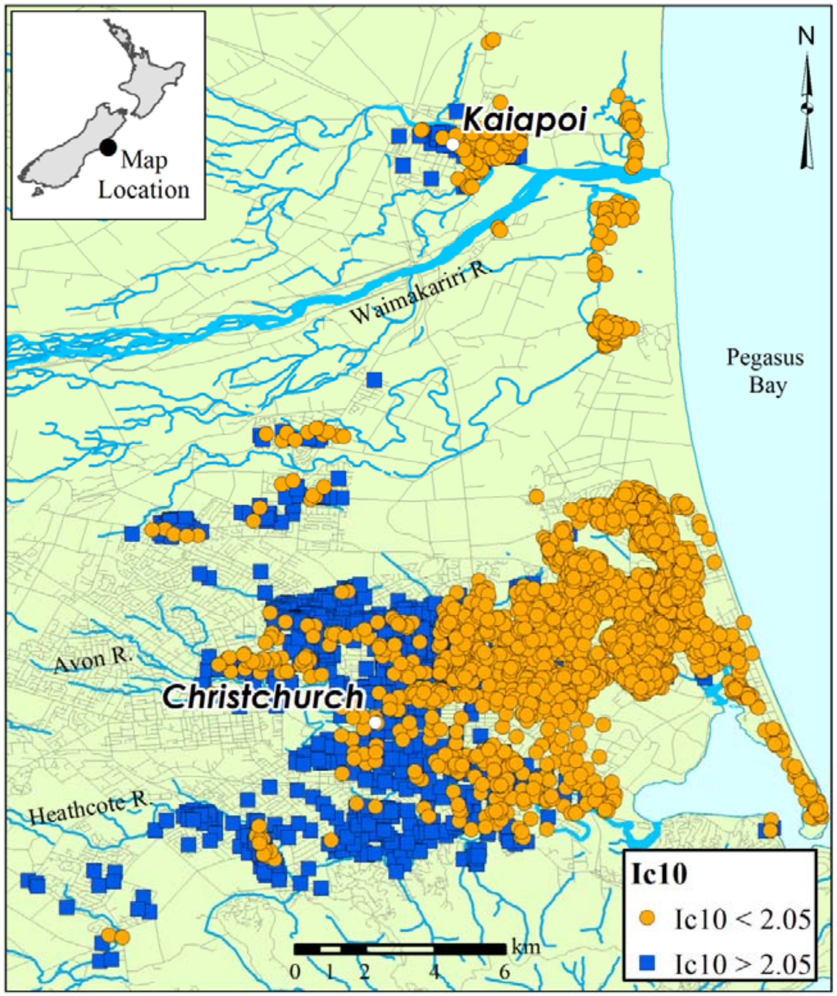
M_w6.2 Christchurch Earthquake



(Maurer et al. 2014a)

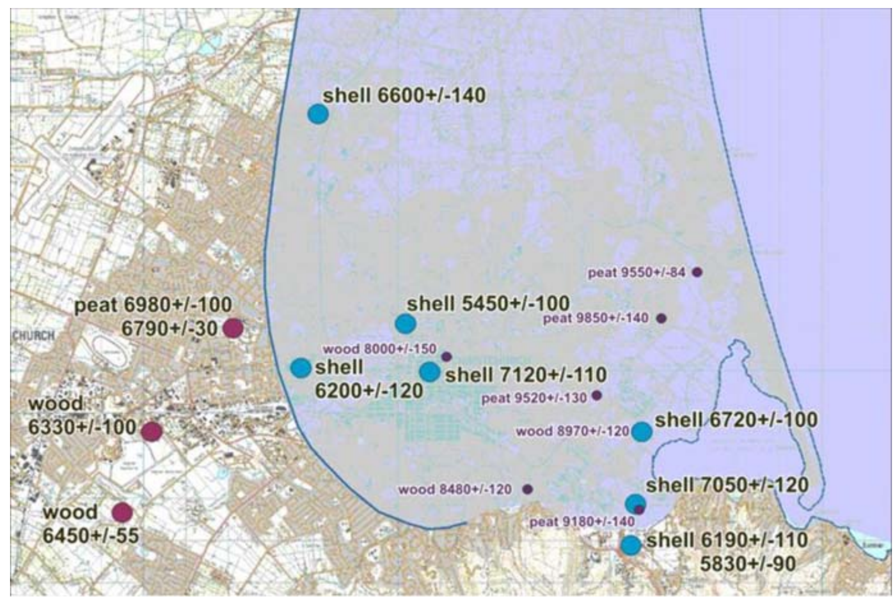
Why is LPI accurate in some regions of Christchurch and not others???

Error in LPI Severity Predictions: Influence of Fines Content

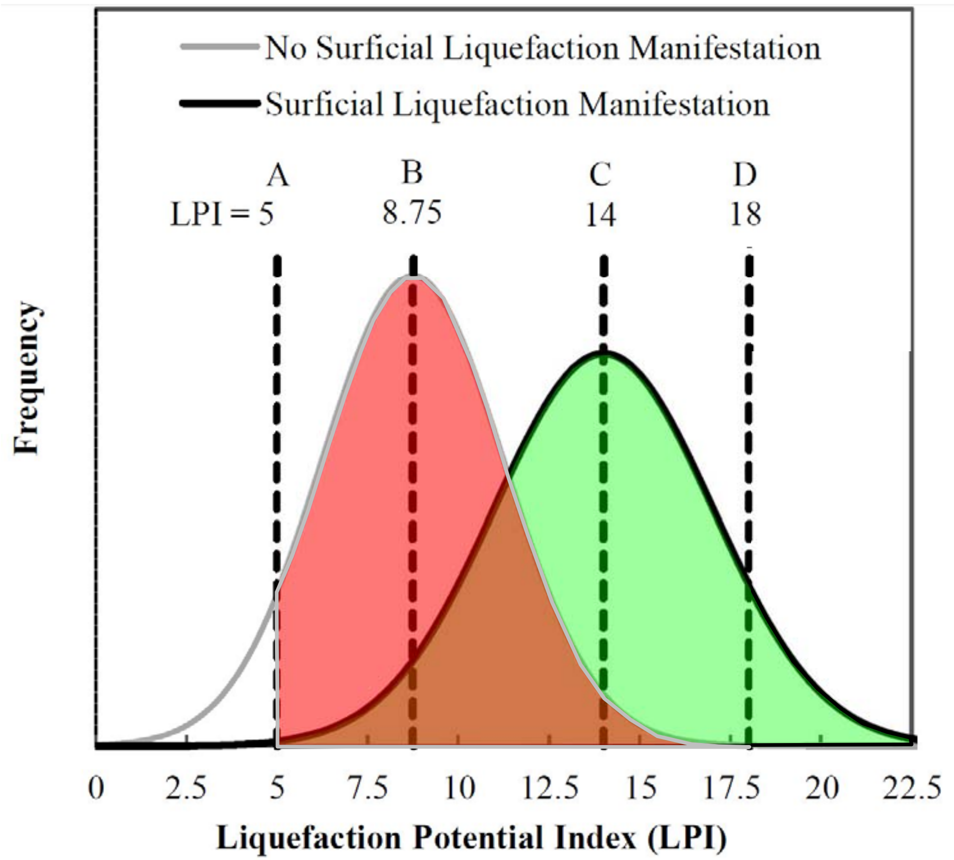


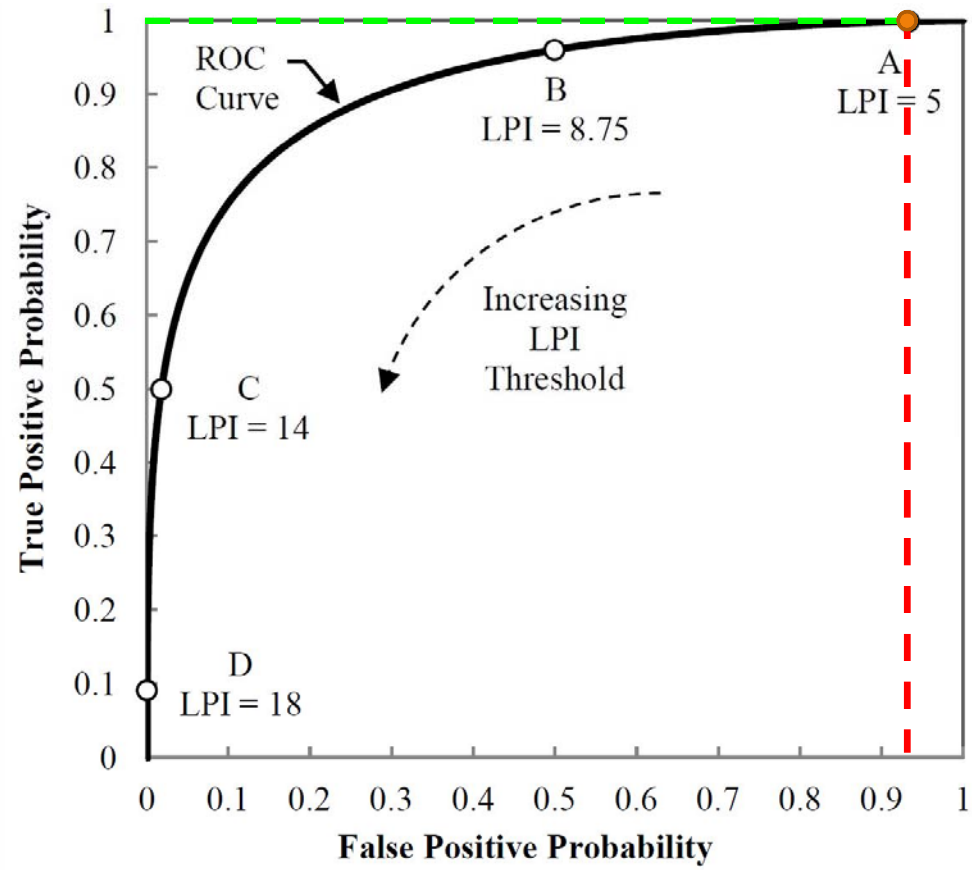
(Maurer et al. 2015b)

Shoreline ~6000 years bp



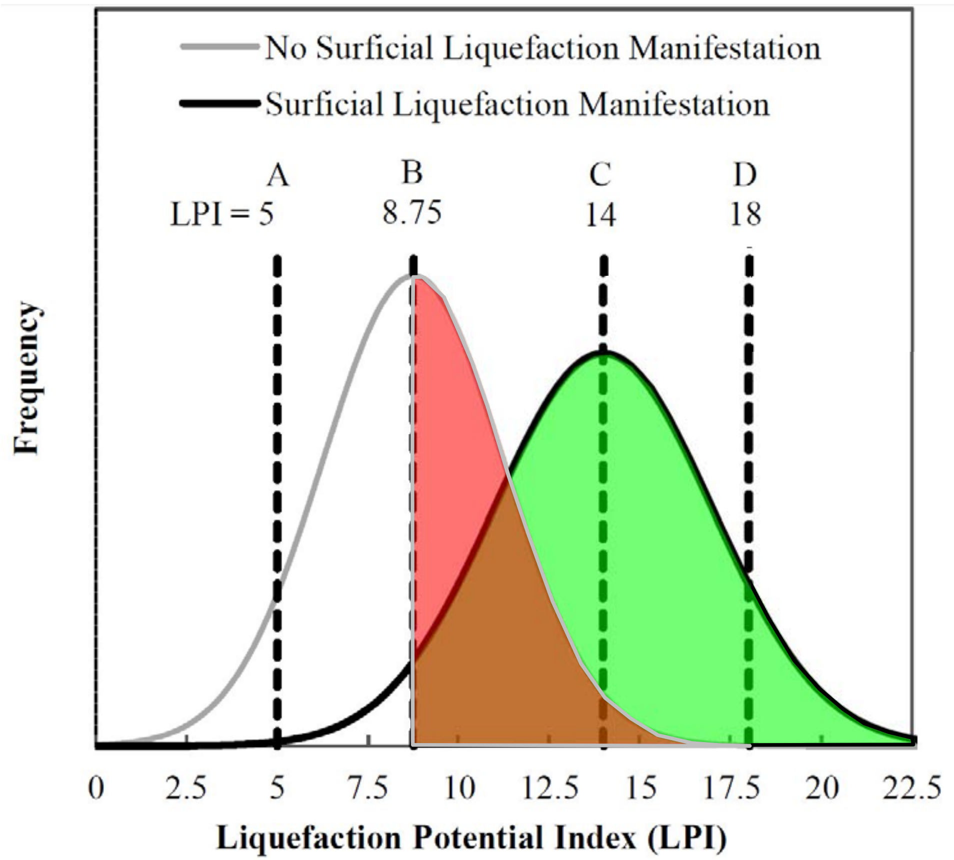
Receiver Operating Characteristic (ROC) Analyses

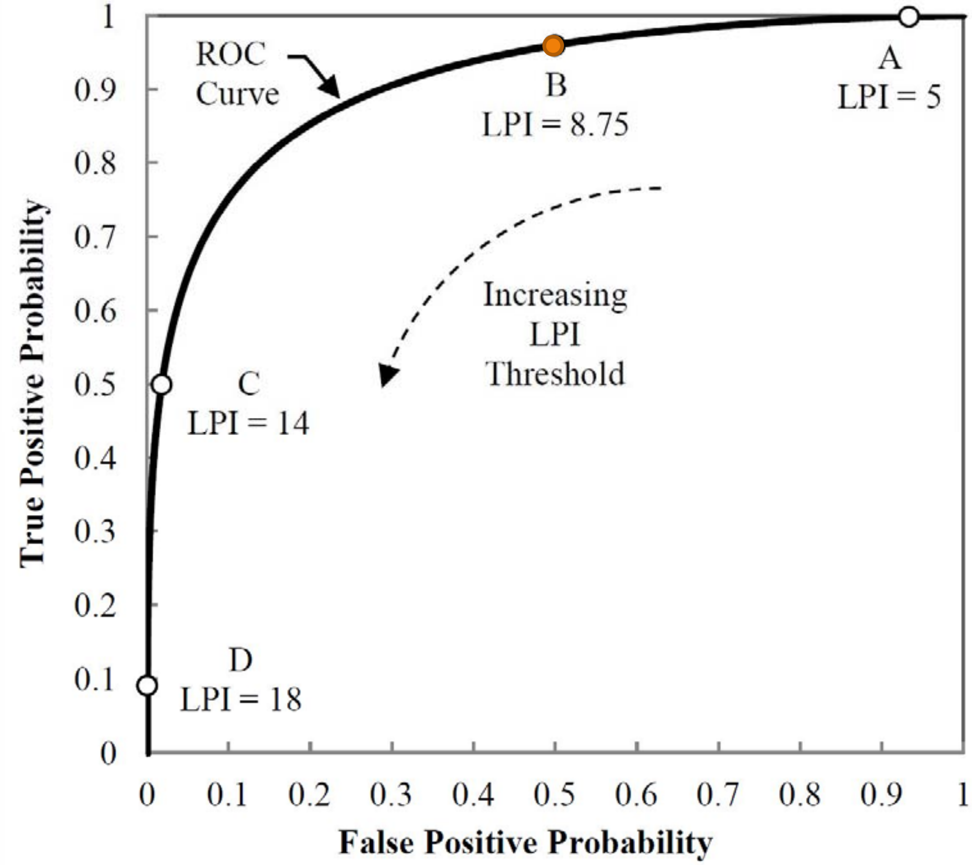




True Positive = Liquefaction Predicted and Observed
False Positive = Liquefaction Predicted but Not Observed

Receiver Operating Characteristic (ROC) Analyses





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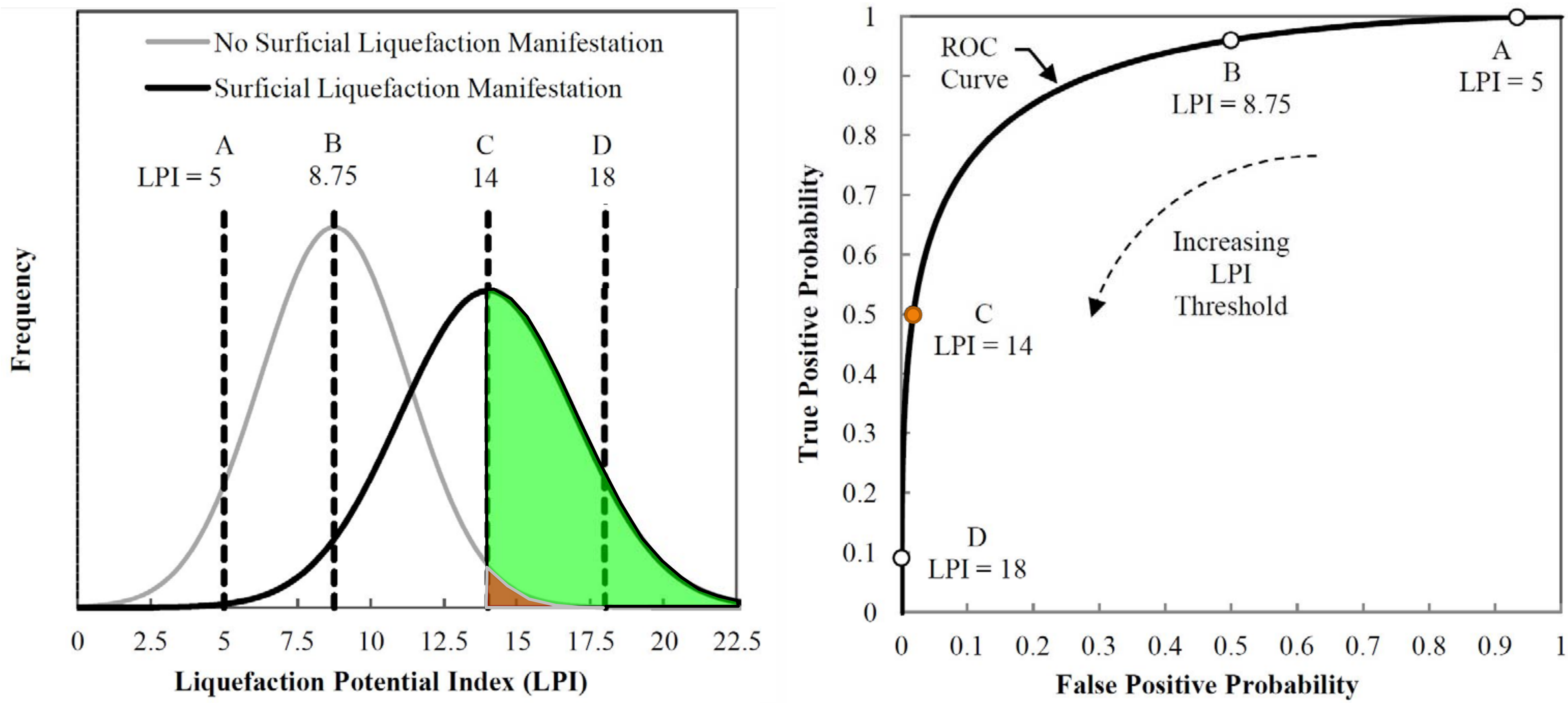

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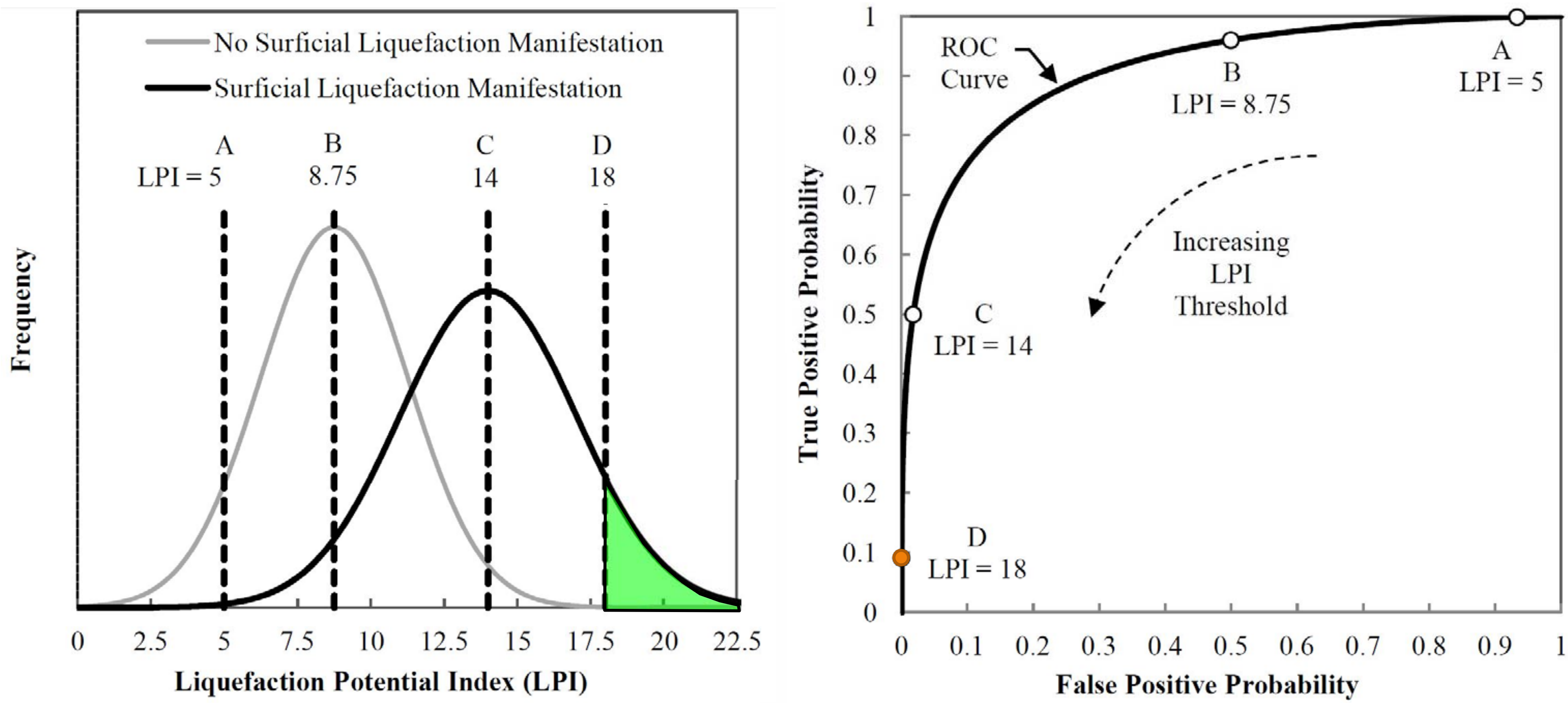

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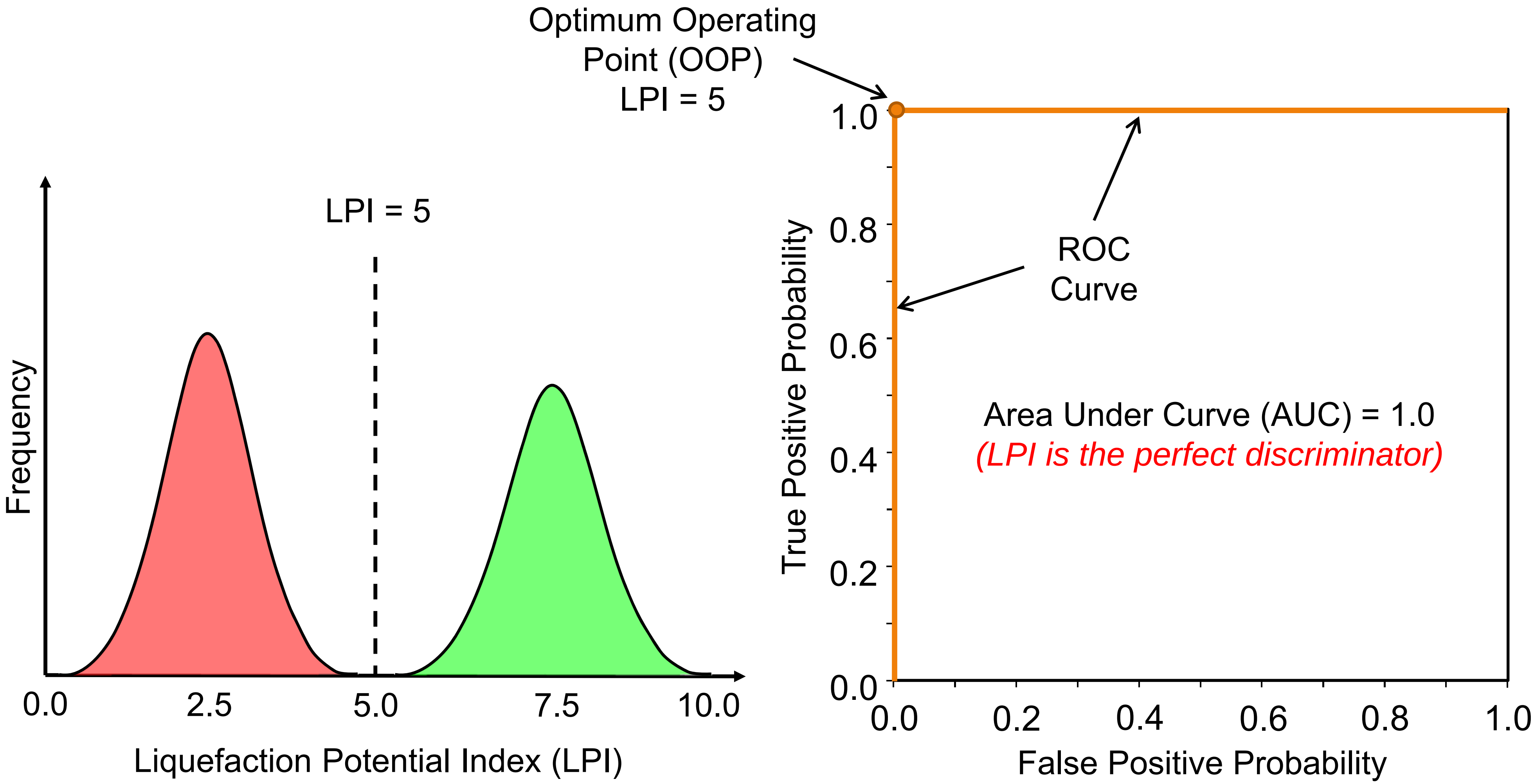
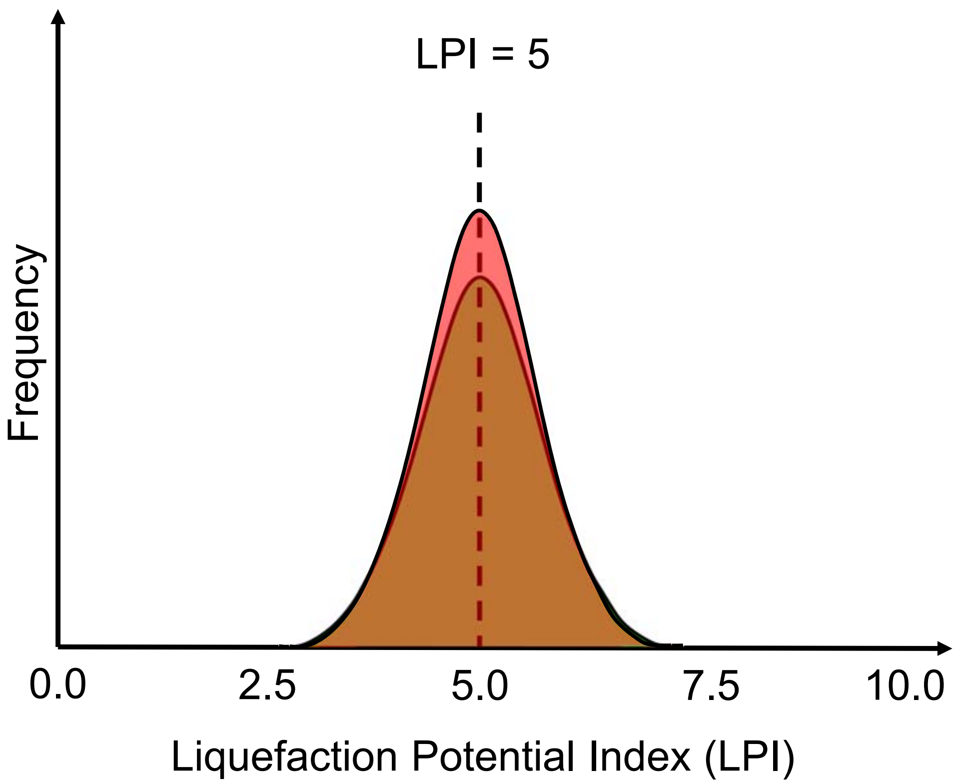
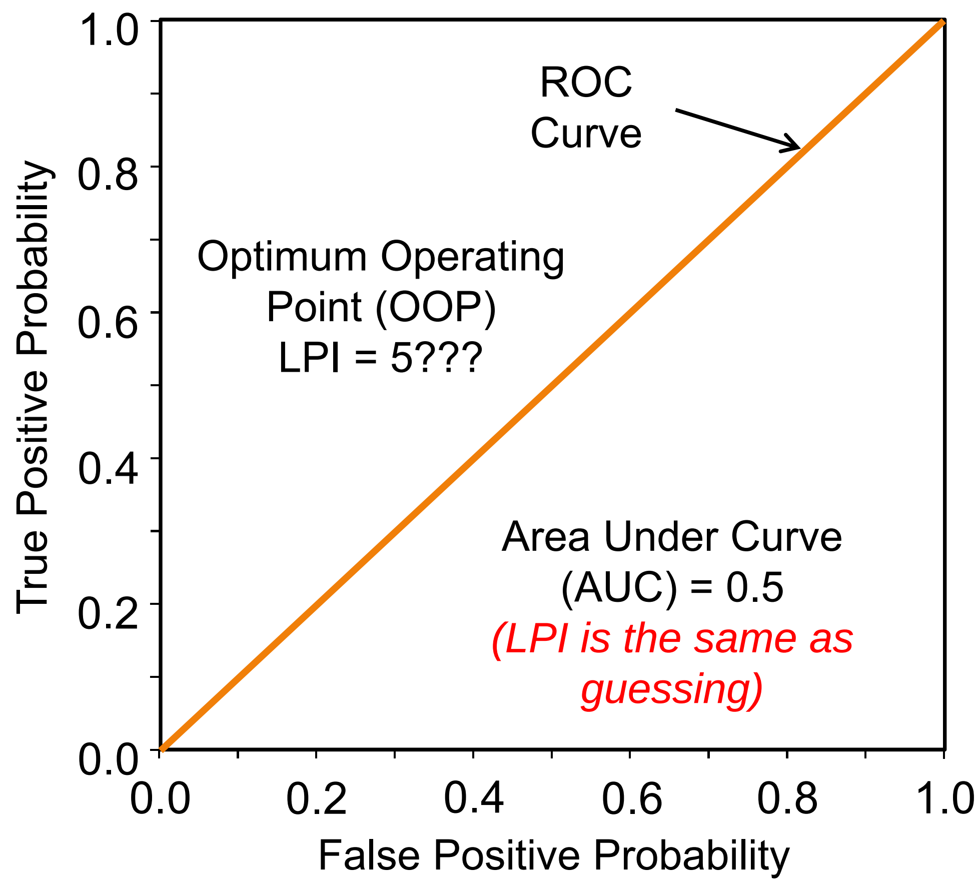
False Positive = Liquefaction Predicted but Not Observed

Receiver Operating Characteristic (ROC) Analyses

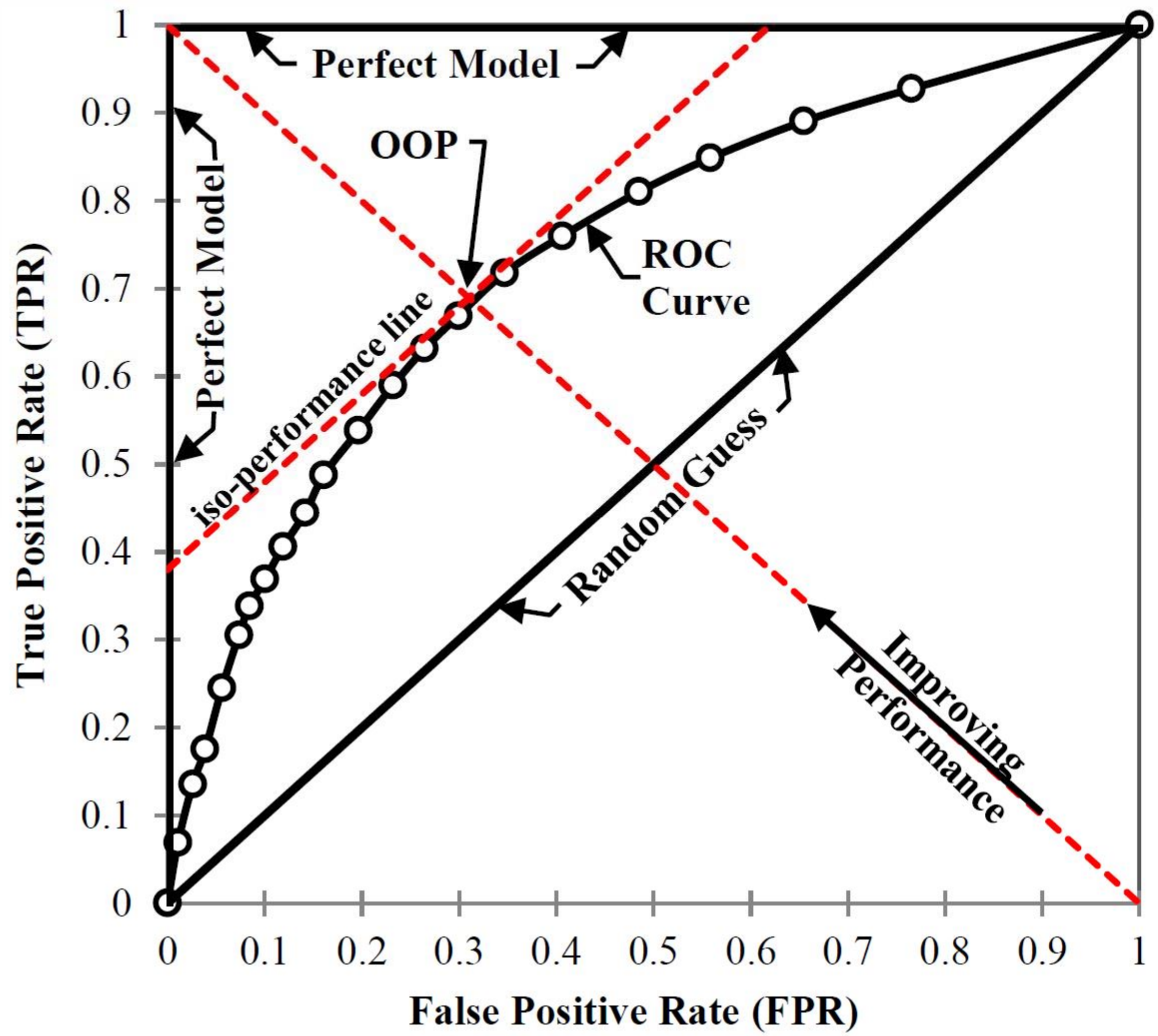


Receiver Operating Characteristic (ROC) Analyses



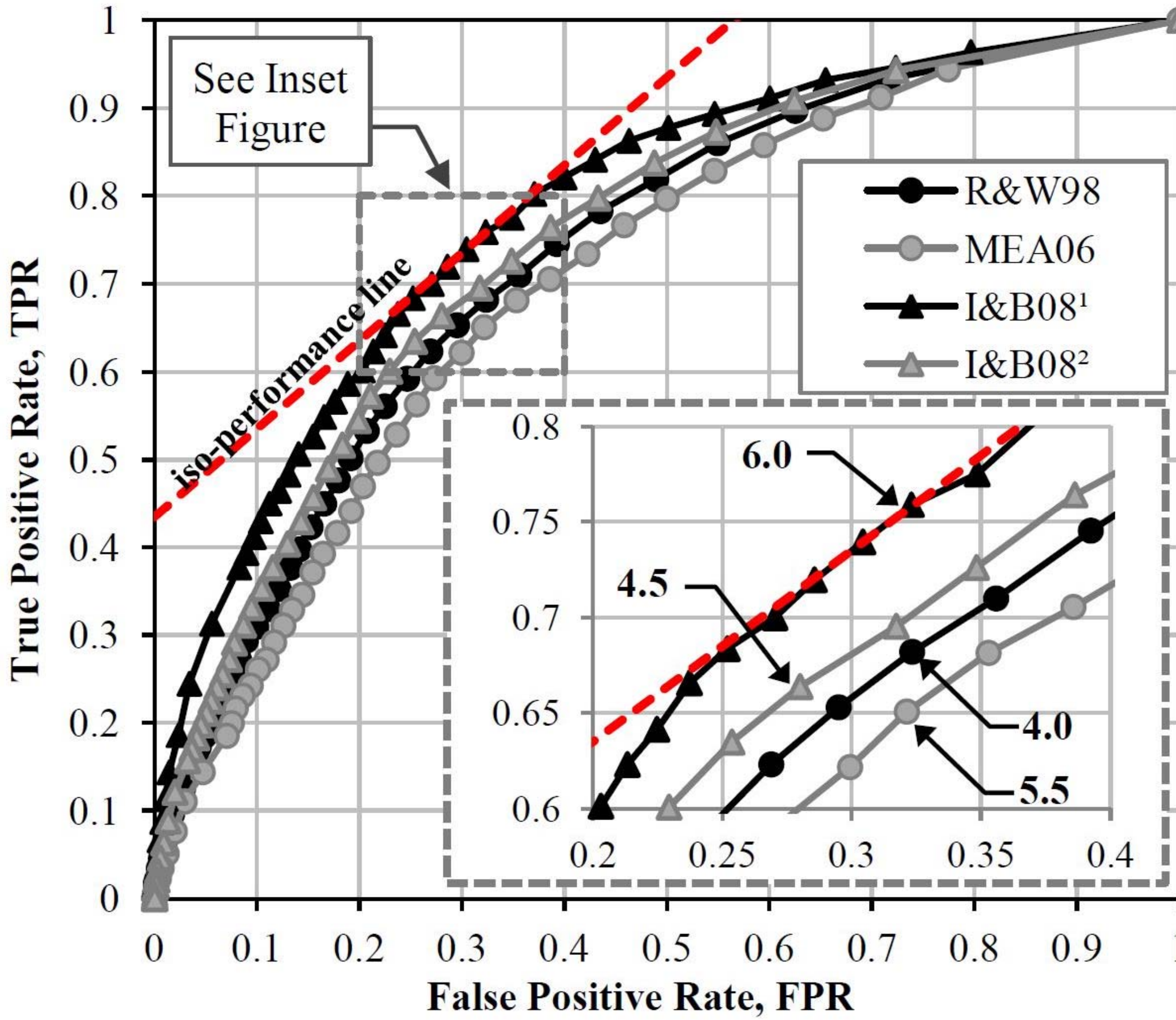


Receiver Operating Characteristic (ROC) Analyses



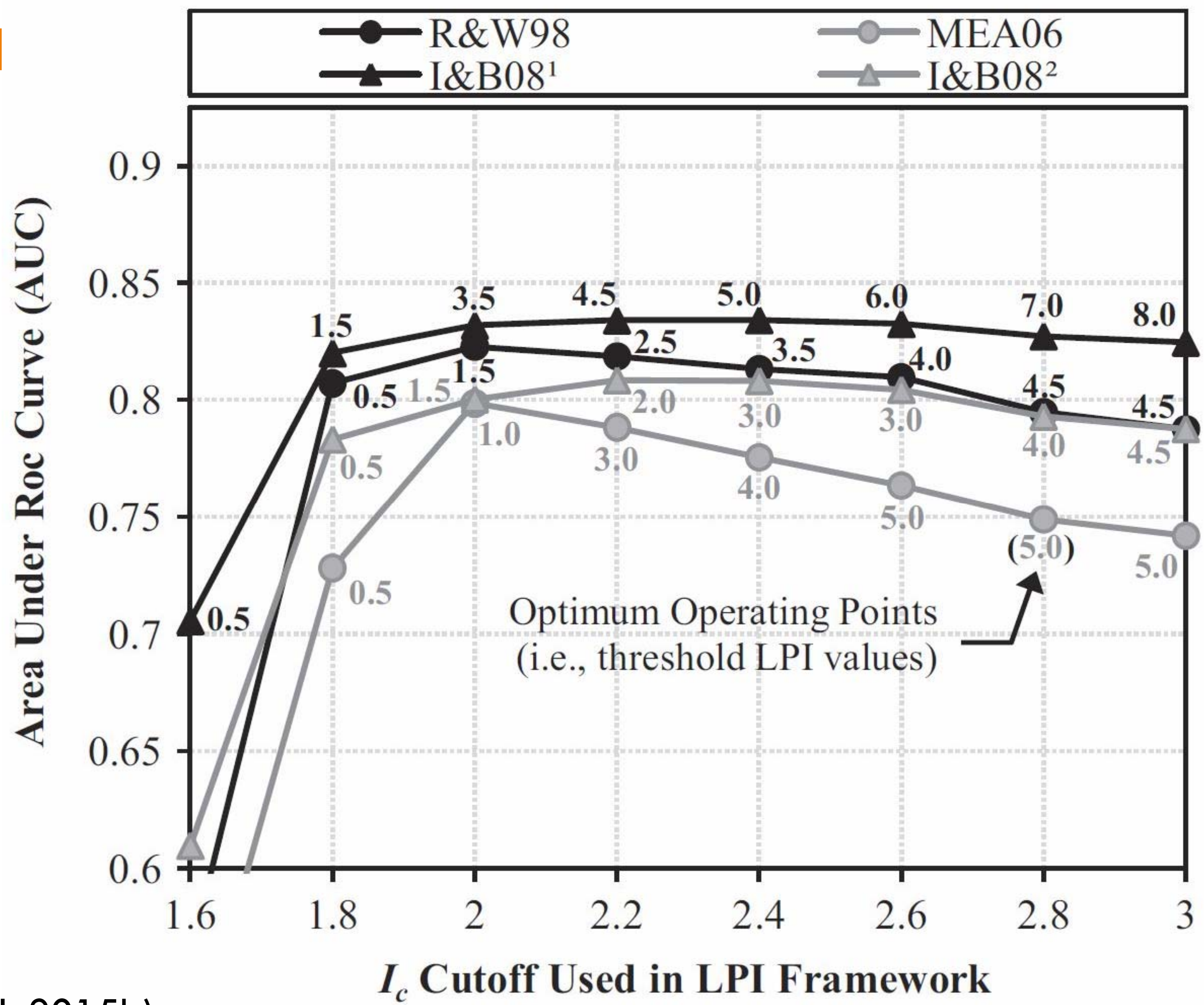
(Maurer et al. 2015b)

ROC Analyses: New Zealand Data



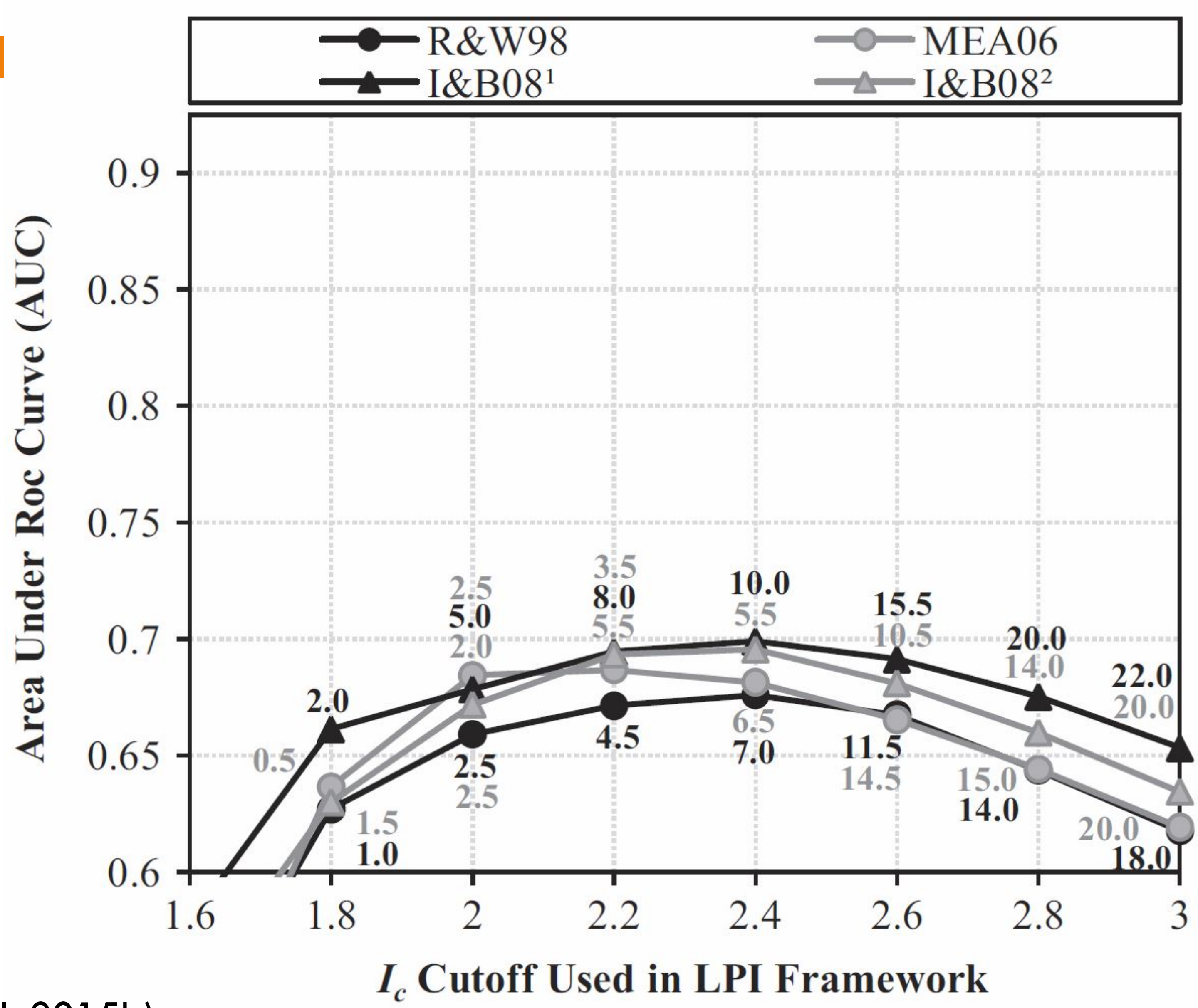
(Maurer et al. 2015a)

Influence of I_c Cutoff: Sites with $I_{c10} < 2.05$



(Maurer et al. 2015b)

Influence of I_c Cutoff: Sites with I_{c10} > 2.05



(Maurer et al. 2015b)

Error in LPI Severity Predictions: Influence of Fines Content

- Result of shortcomings in the FC corrections in the liquefaction evaluation procedures???
- Result of shortcomings in the LPI framework to evaluate severity manifestations for profiles with high FC strata???

(Maurer et al. 2015b)

No-Liq Layers: Low FC (Ic < 2.05)

Dataset Assessed	LPI MODEL							
	R&W98		MEA06		I&B08[1]		I&B08[2]	
	AUC	OOP	AUC	OOP	AUC	OOP	AUC	OOP
Liq: Ic < 2.05	0.79	4.0	0.76	5.0	0.83	6.0	0.81	4.0
Liq: Ic > 2.05	0.79	4.0	0.76	5.0	0.82	5.0	0.81	4.5

(Maurer et al. 2015b)

Liq Layers: Low FC (Ic < 2.05)

Dataset Assessed	LPI MODEL							
	R&W98		MEA06		I&B08[1]		I&B08[2]	
	AUC	OOP	AUC	OOP	AUC	OOP	AUC	OOP
No Liq: Ic < 2.05	0.79	4.0	0.76	5.0	0.83	6.0	0.81	4.0
No Liq: Ic > 2.05	0.67	11.5	0.69	13.5	0.69	14.0	0.66	10.5

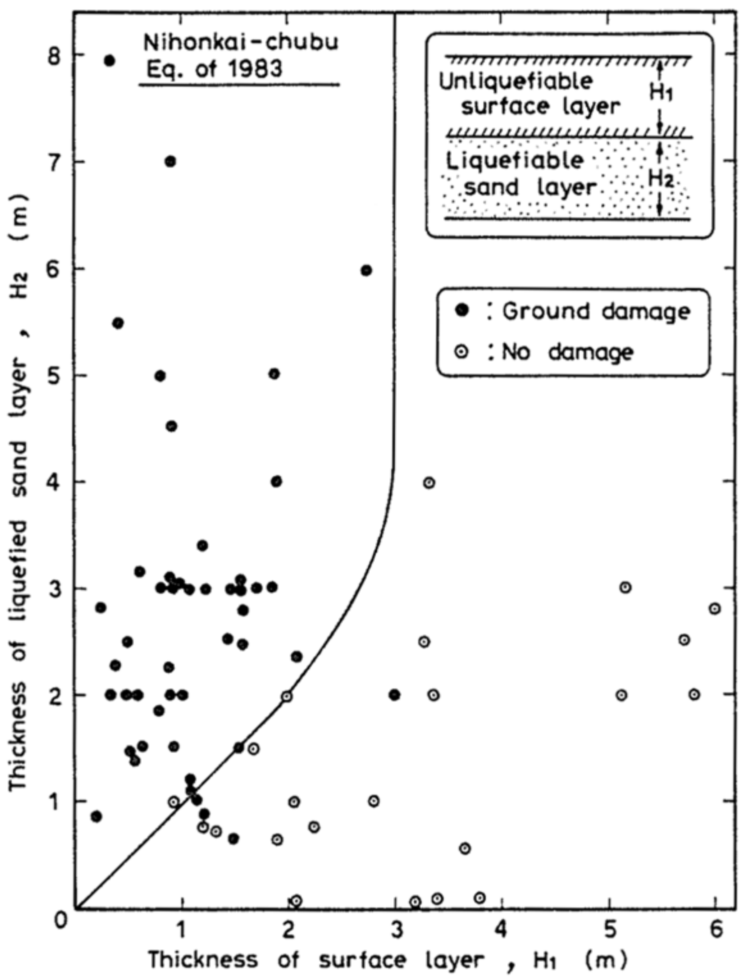
(Maurer et al. 2015b)

Conclusion 2

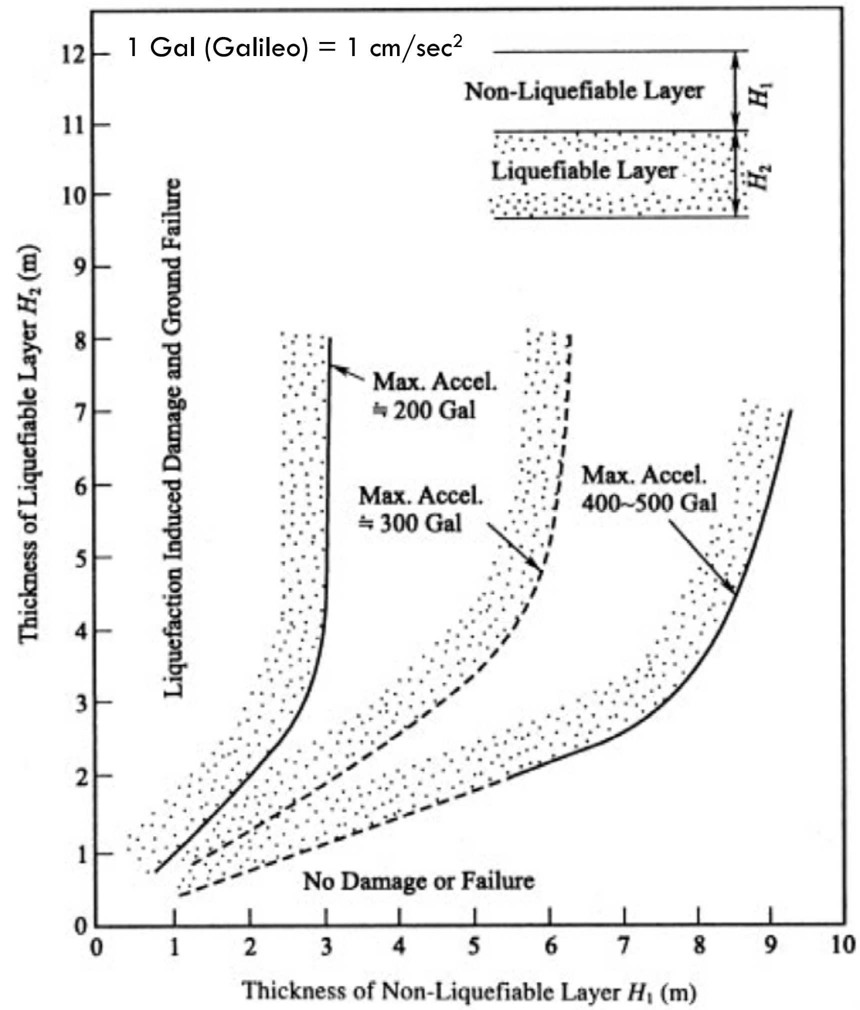
- Based on *thousands* of case history data from the Canterbury Earthquake Sequence:
  - All of the CPT-base procedures do a reasonable job predicting field observations (approx. same AUCs)
  - Idriss and Boulanger (2008) performed better than the other procedures (larger AUC)
- The LPI framework has limitations in predicting severity of surficial liquefaction manifestations for profiles having a fine-grained crust and/or fine-grained layers interbedded with liquefiable layers

(Maurer et al. 2015a,b)

Ishihara H_1-H_2 Charts

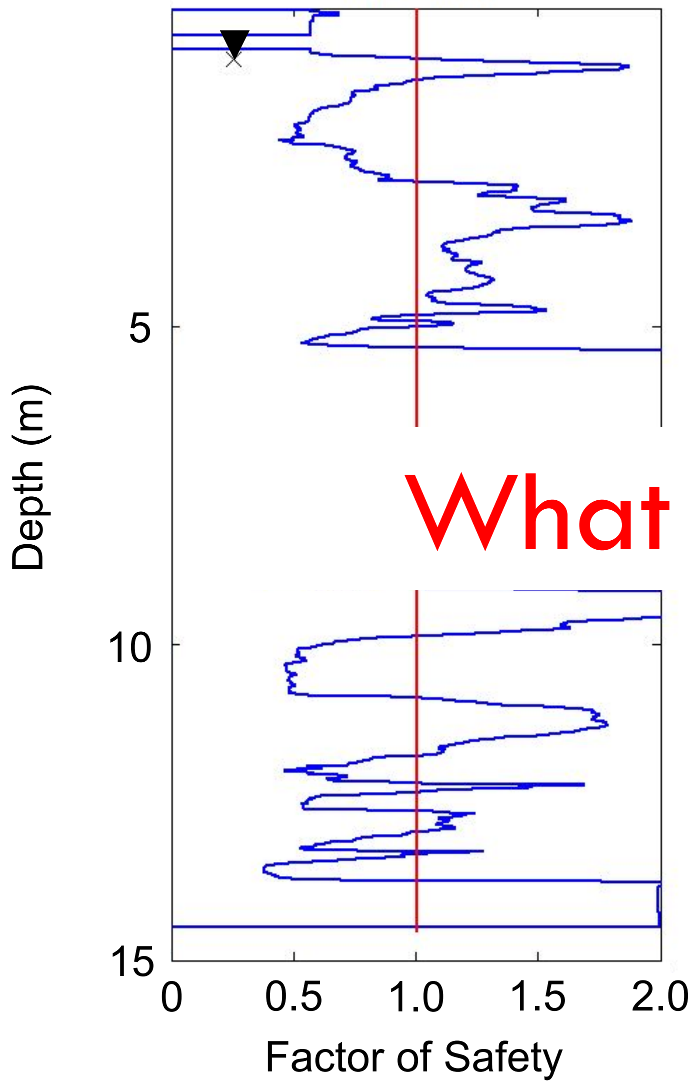


Ishihara (1985)

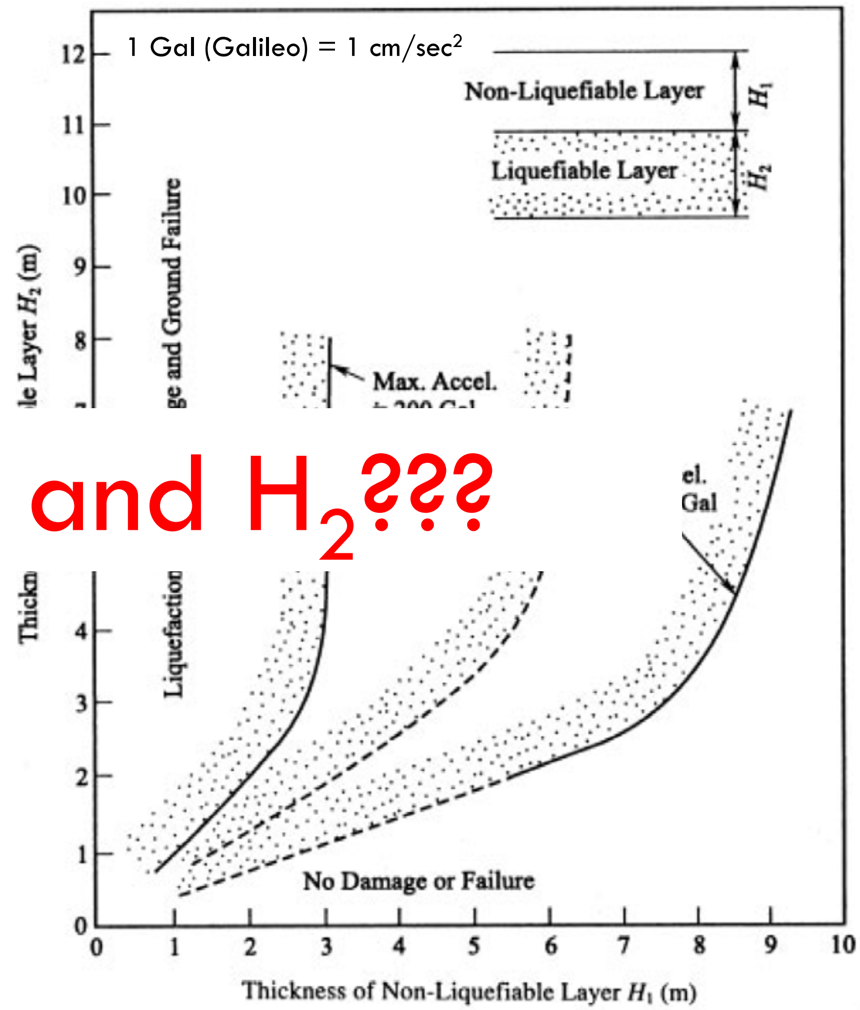


Ishihara (1996)

Ishihara H_1-H_2 Charts

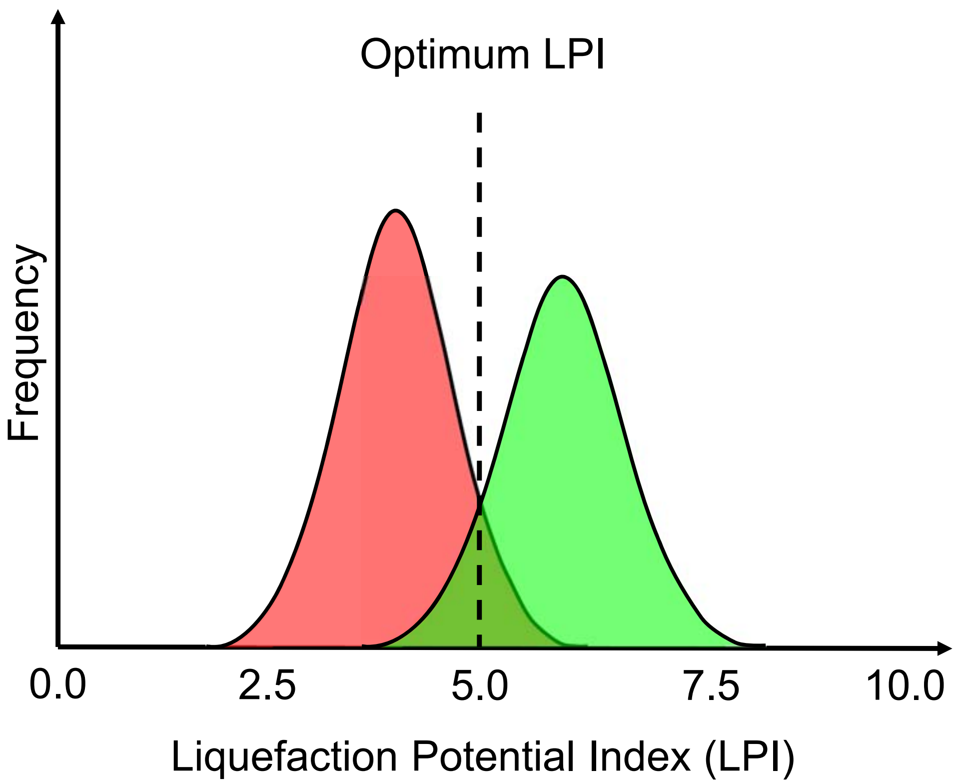


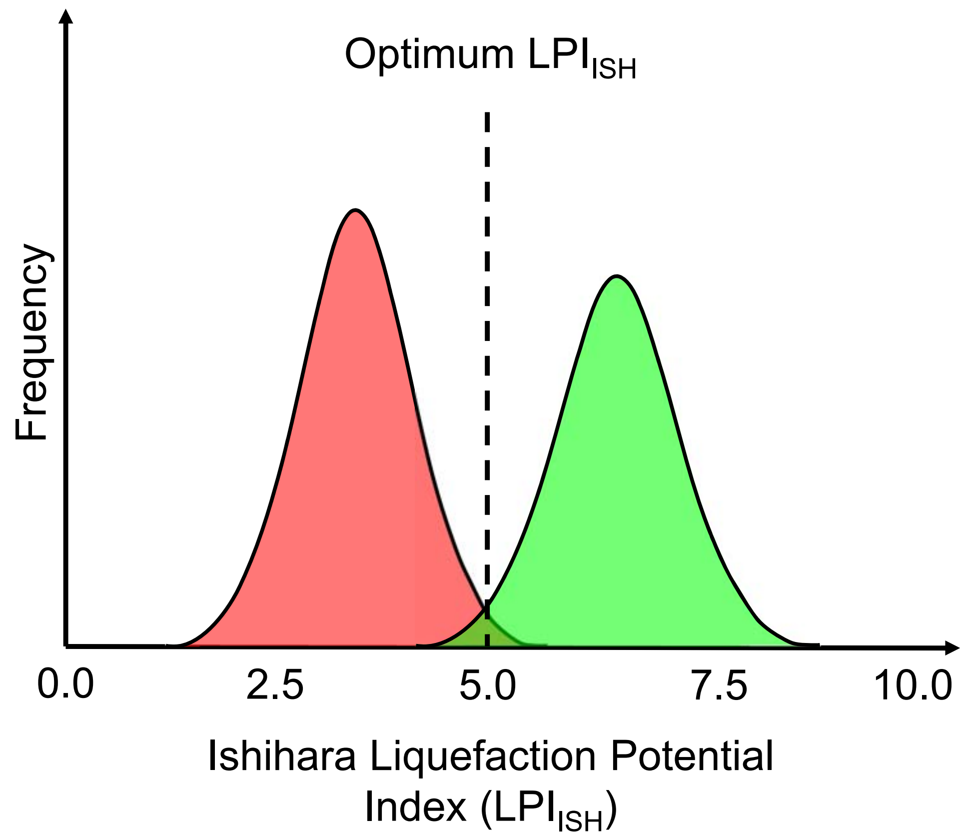
What are H_1 and H_2???



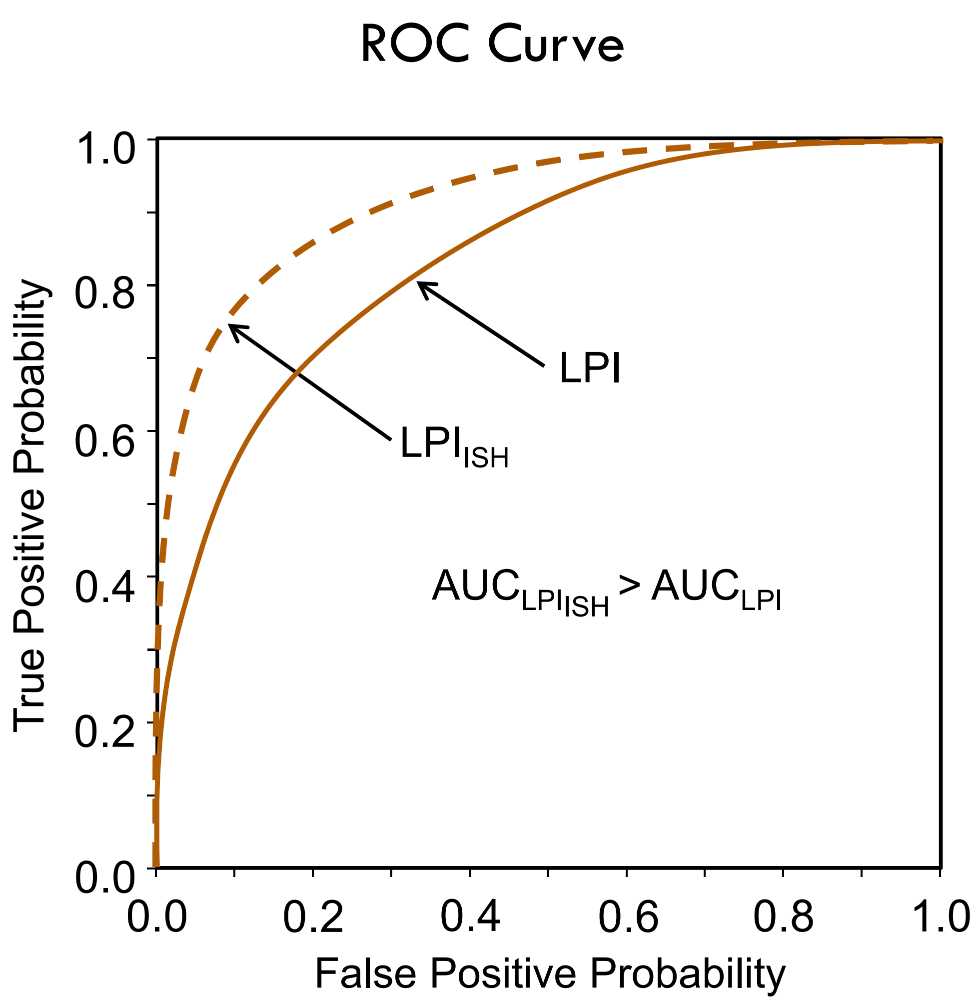
Ishihara (1996)

LPI + Ishihara H_1-H_2 Chart = LPI_{ISH}

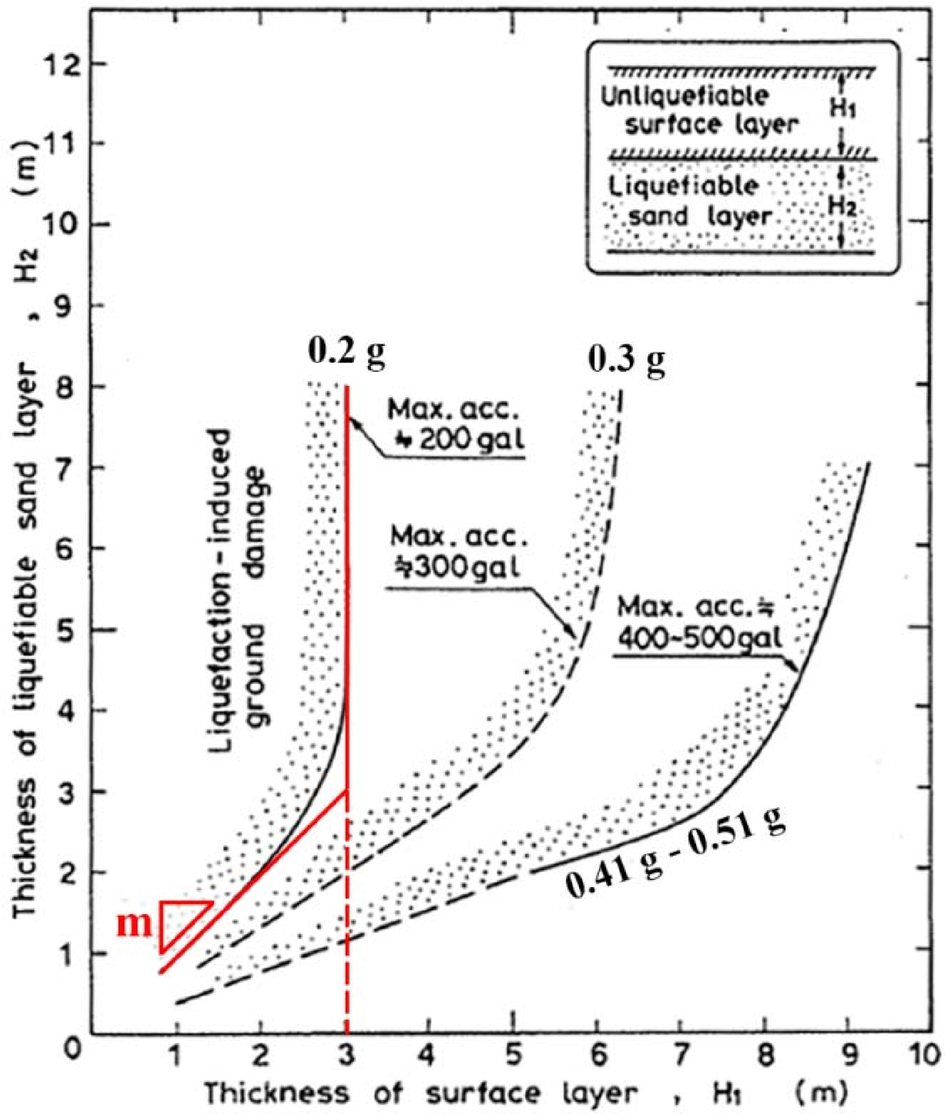




Ishihara LPI (LPI_{ISH})



Ishihara LPI (LPI_{ISH})



(Maurer et al. 2015c)

Ishihara LPI (LPI_{ISH})

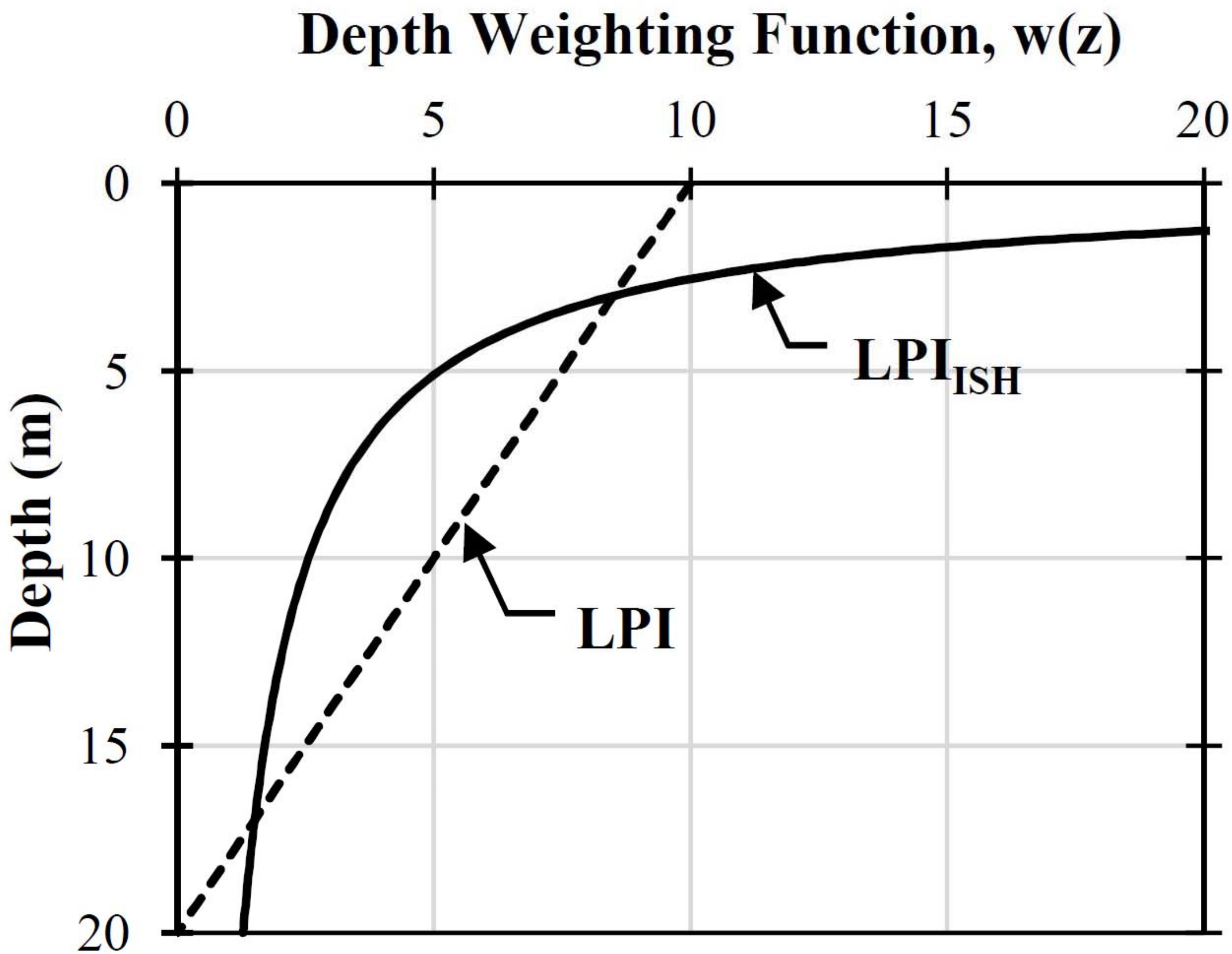
$$LPI_{ISH} = \int_{H_1}^{20\,m} F(FS)\,\frac{25.56}{z}\,dz$$

$$F(FS) = \begin{cases} 1 - FS & if\ FS \leq 1 \cap H_1 \cdot m(FS) \leq 3 \\ 0 & otherwise \end{cases}$$

$$m(FS) = exp\left(\frac{5}{25.56(1-FS)}\right) - 1$$

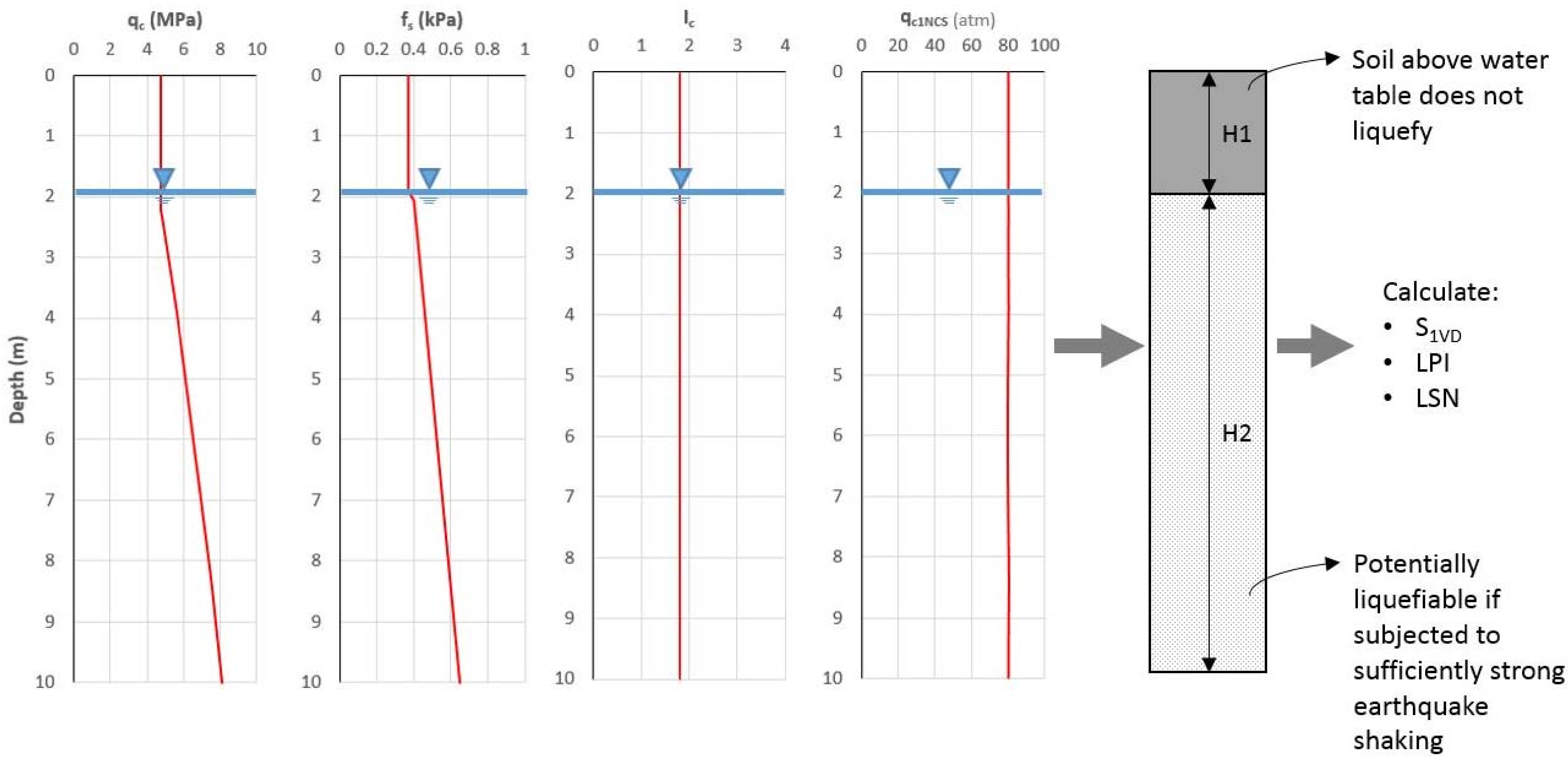
(Maurer et al. 2015c)

Ishihara LPI (LPI_{ISH})



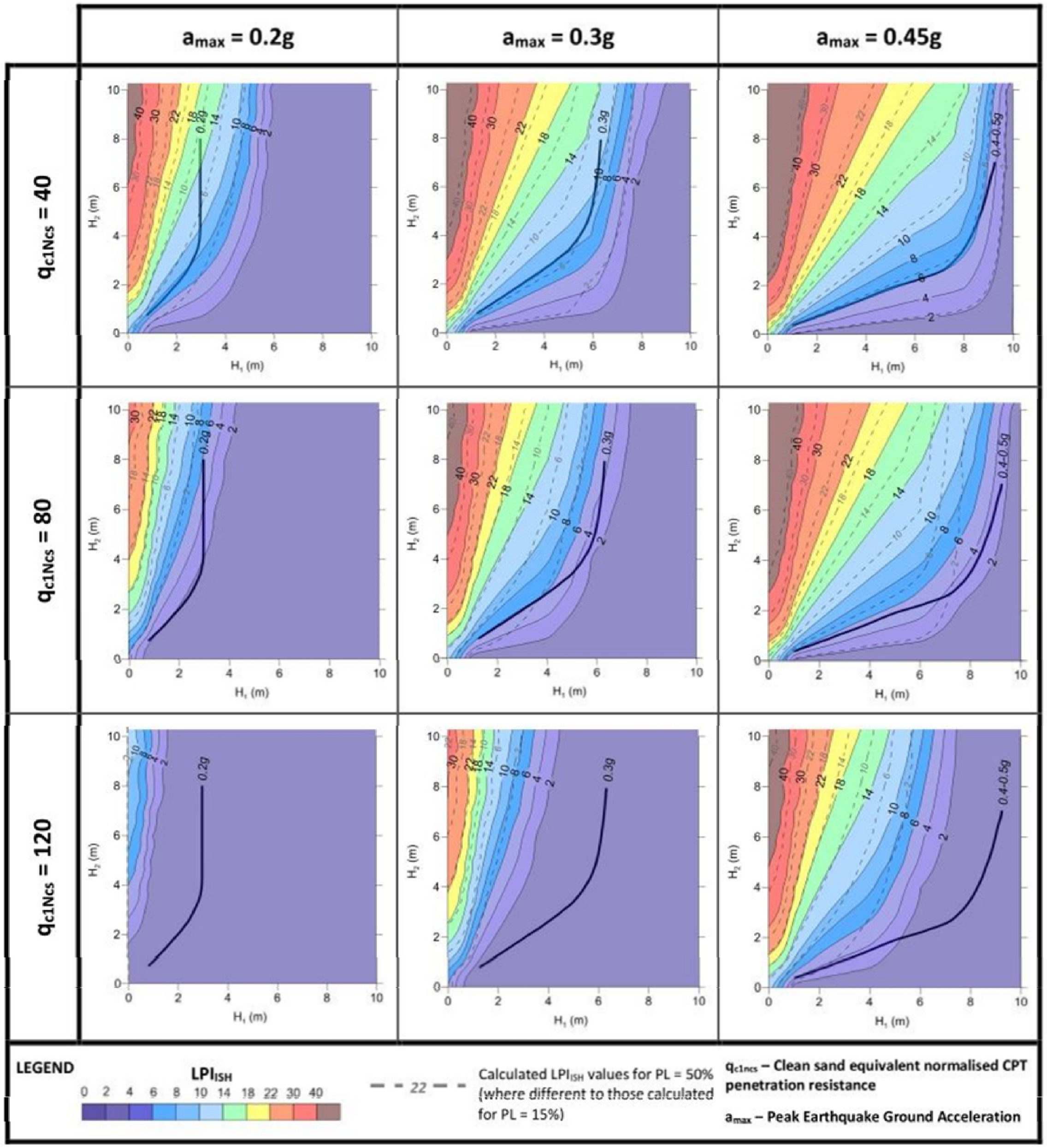
(Maurer et al. 2015c)

Ishihara LPI (LPI_{ISH})



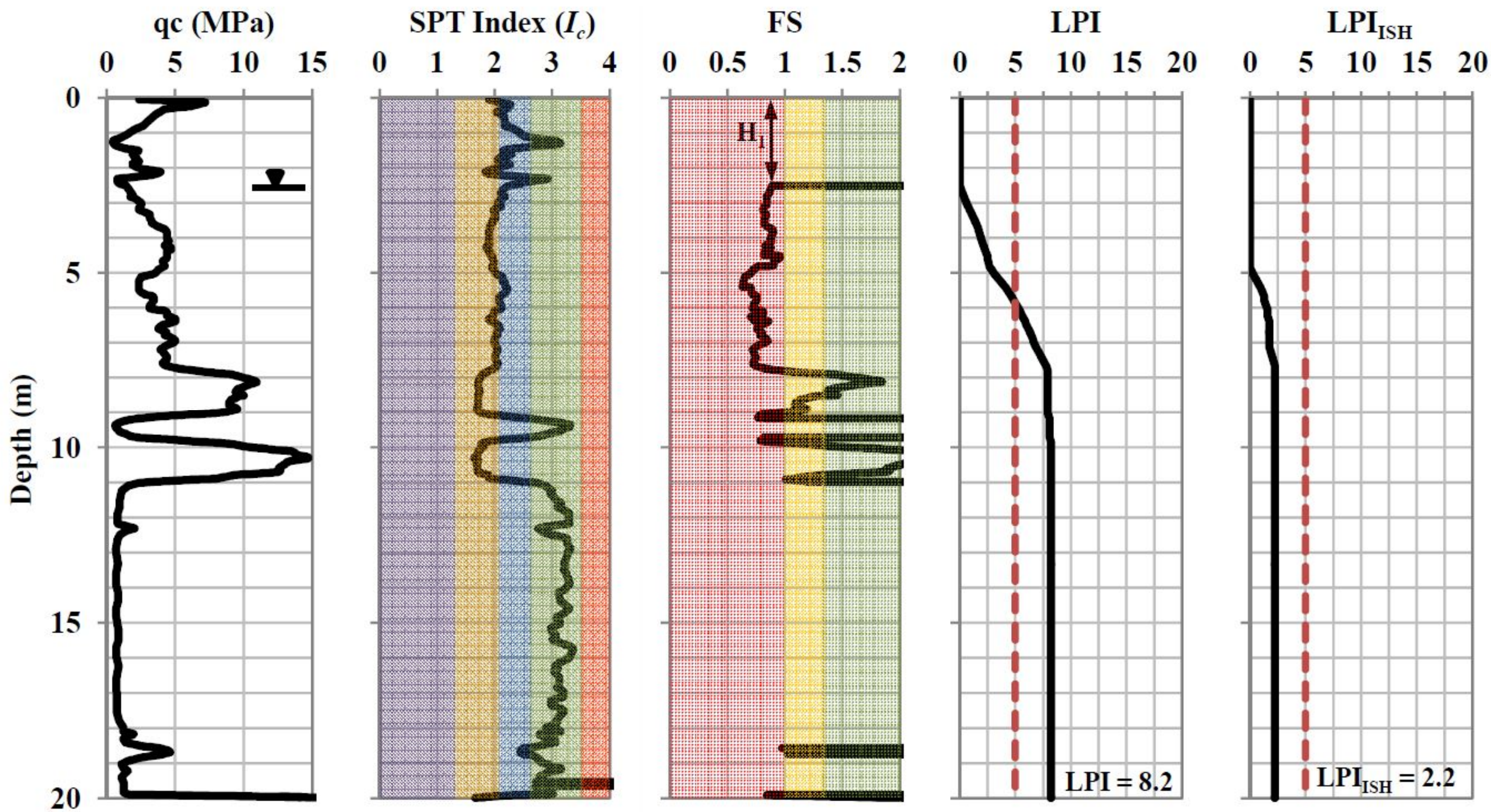
(van Ballegooy et al. 2015)

Ishihara LPI (LPI_{ISH})



(van Ballegooy et al. 2015)

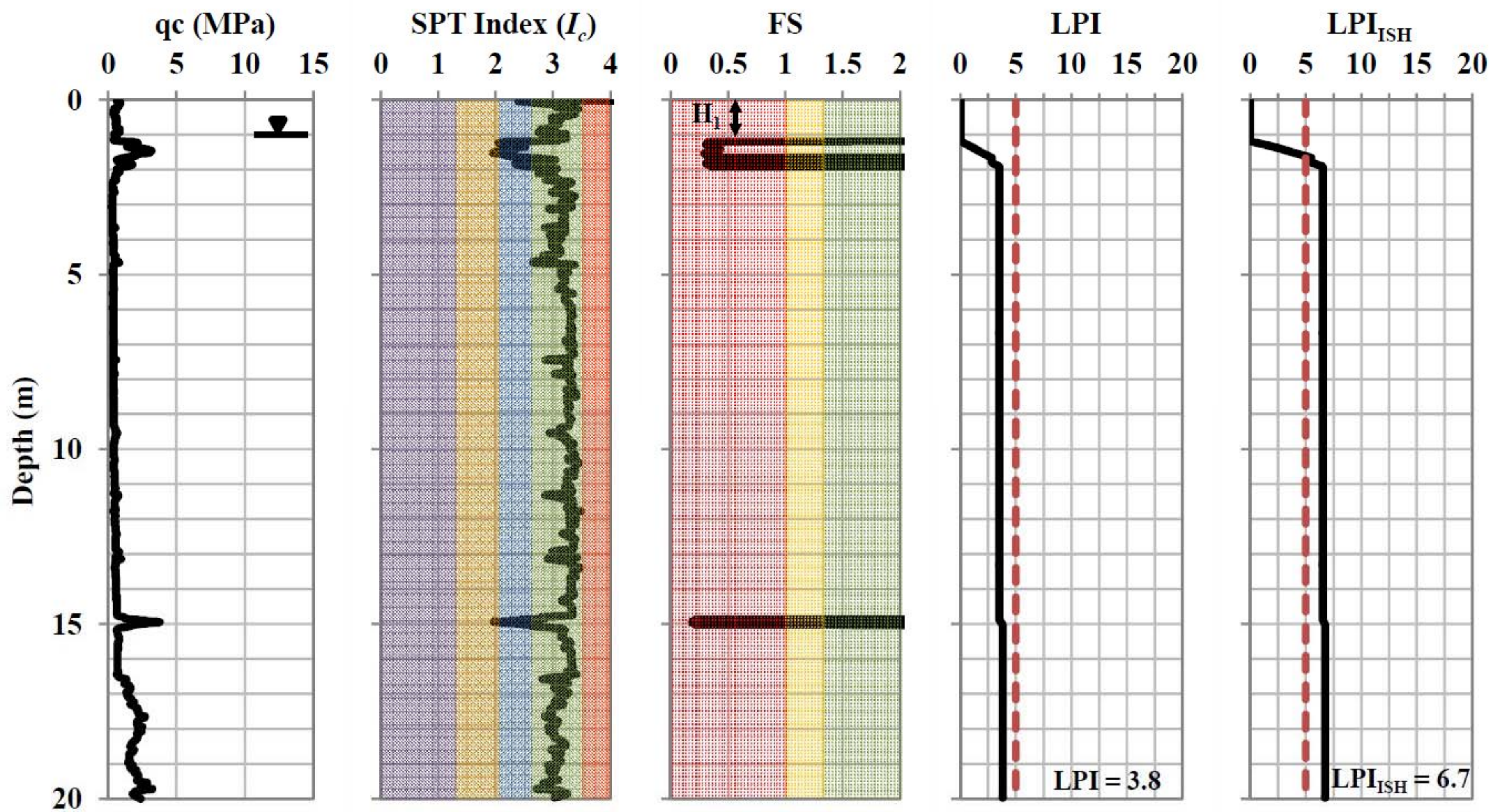
Ishihara LPI (LPI_{ISH})



Loma Prieta earthquake: Site LEN-37 – no observed surficial manifestations

(Maurer et al. 2015c)

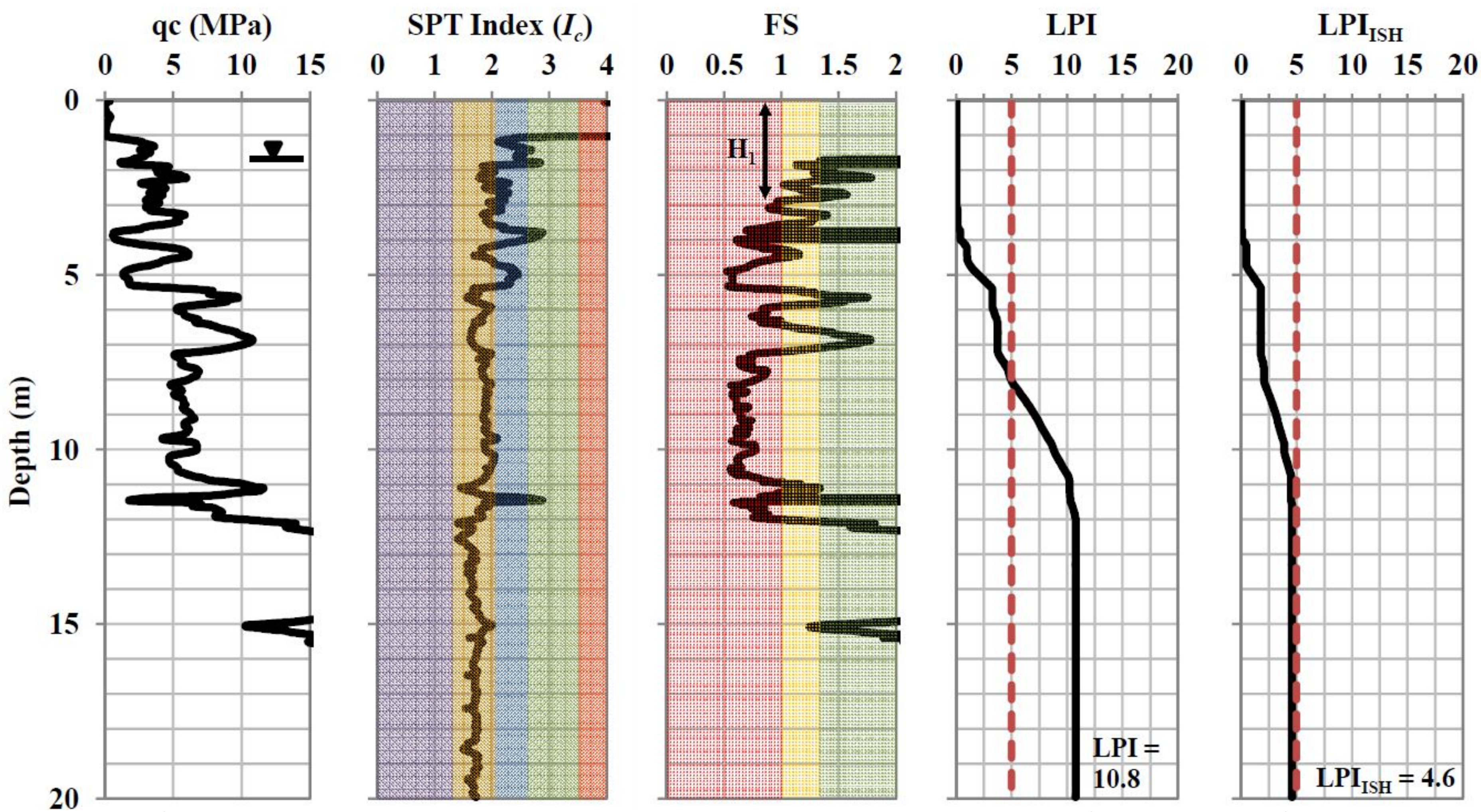
Ishihara LPI (LPI_{ISH})



Kocaeli earthquake: Site SF-5 – surficial manifestations observed

(Maurer et al. 2015c)

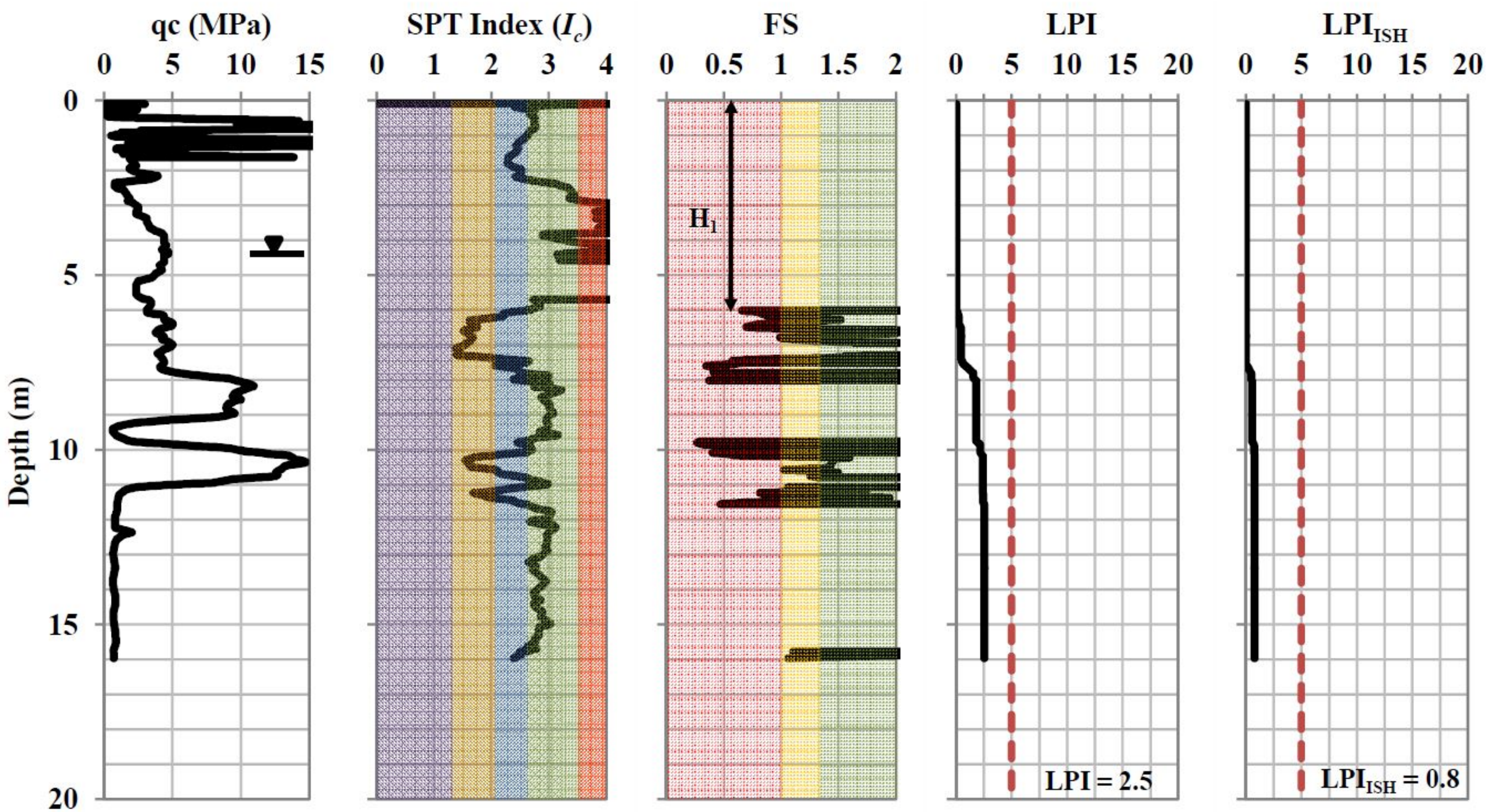
Ishihara LPI (LPI_{ISH})



Darfield earthquake: Site AVD-49 – no observed surficial manifestations

(Maurer et al. 2015c)

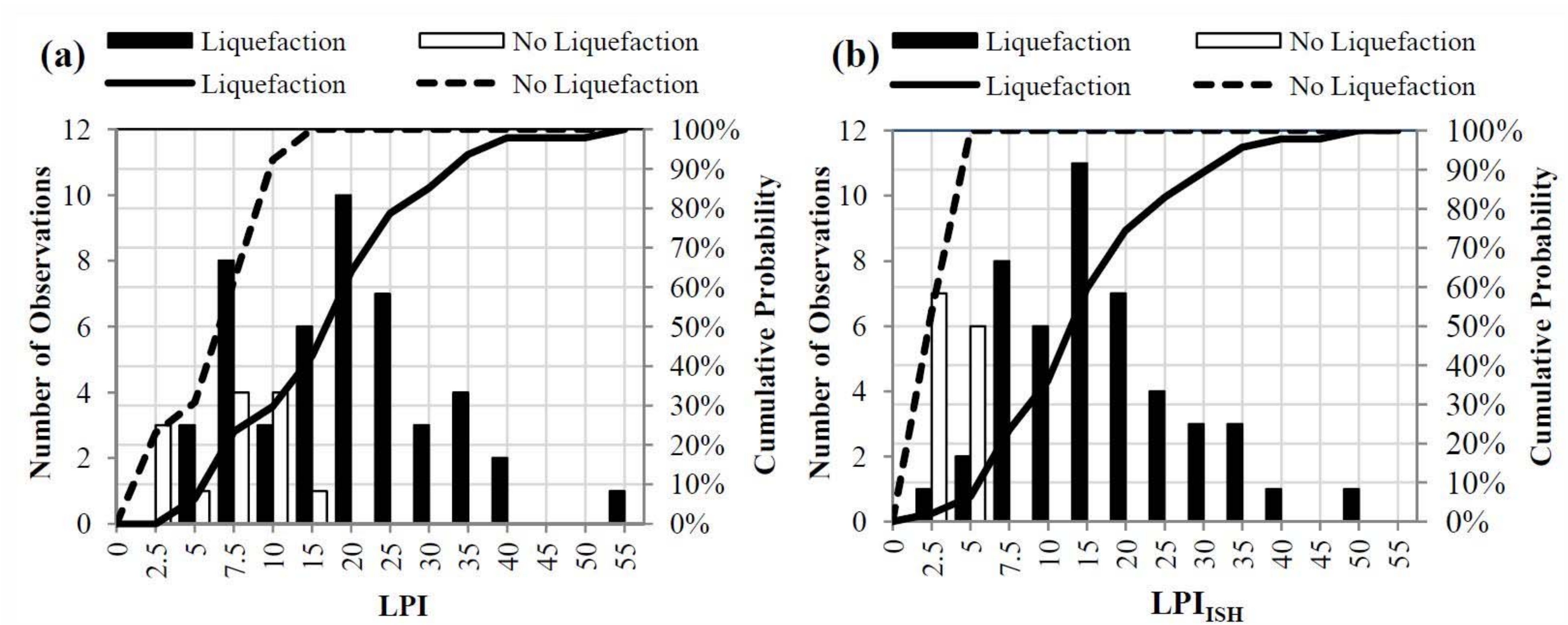
Ishihara LPI (LPI_{ISH})



Northridge earthquake: Site WYN-5a – surficial manifestations observed

(Maurer et al. 2015c)

Ishihara LPI (LPI_{ISH})



Analysis of 60 cases from around the world

(Maurer et al. 2015c)

Conclusion 3

- Based on *sixty* worldwide case histories:
  - LPI_{ISH} results in predictions that are more inline with field observations than LPI.
  - LPI_{ISH} accounts for the influence of the thickness of the non-liquefiable crust, but it does not fully account for fine-grained layers interbedded with liquefiable layers.

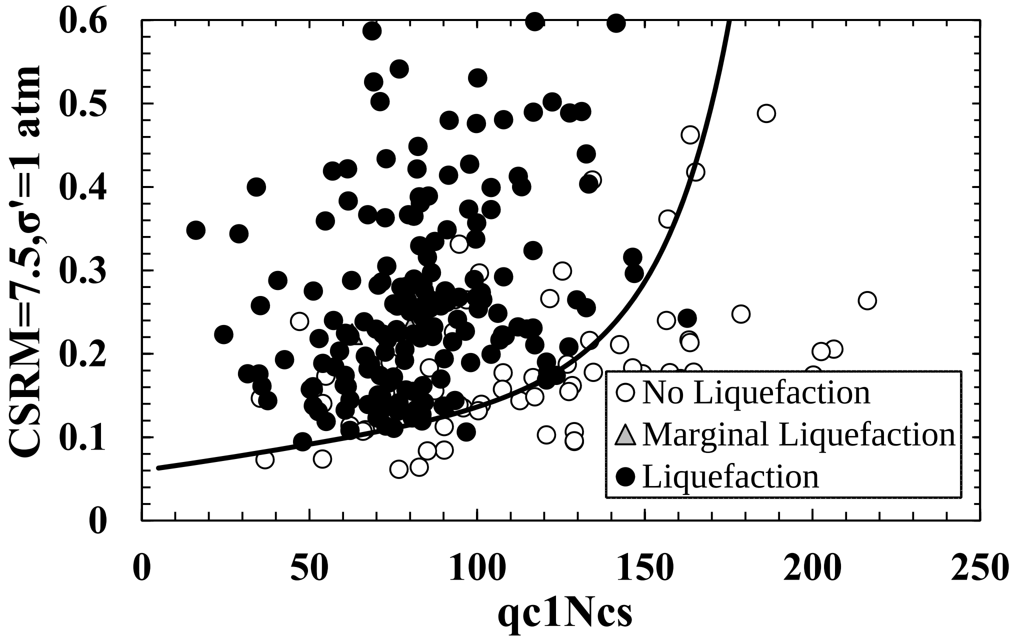
(Maurer et al. 2015c)

Aging Effects on Liquefaction

- Temporal gains in the shear strength and stiffness of sands (e.g., increase in CRR)
- Liquefaction triggering curves developed from liquefaction case-histories in Holocene deposits.
  - Adjustments needed for deposits with ages outside range of case-history database

(Maurer et al. 2014b)

Aging Effects on Liquefaction



- Position of triggering curves controlled by youngest, most susceptible deposits
- Reference age likely on order of ~1 to100 years

$$\mathbf{CRR}_{K} = \mathbf{CRR} \text{ x } K_{\mathbf{DR}}$$

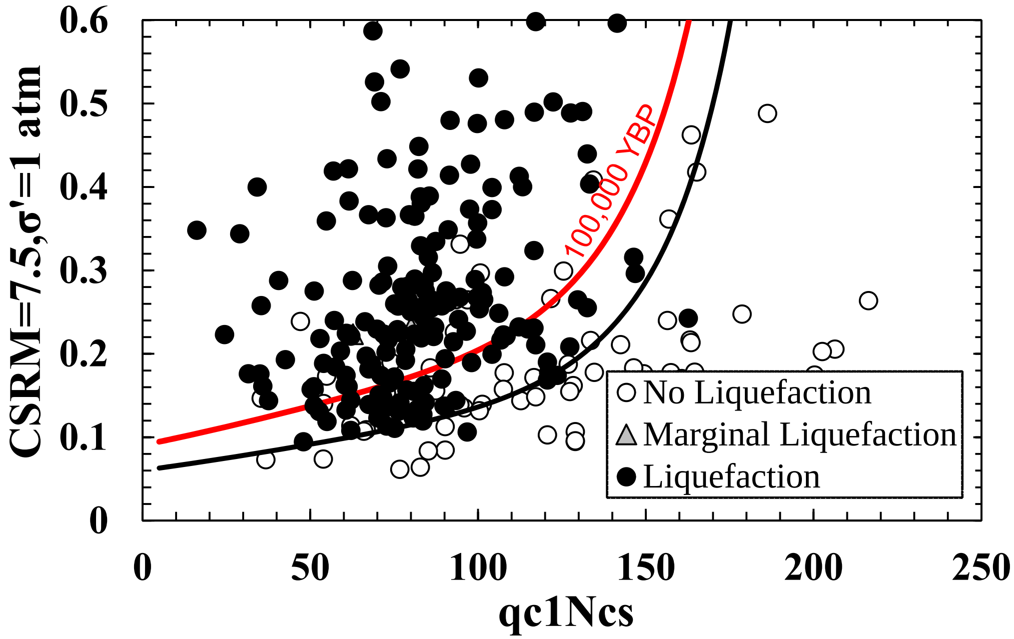
age-corrected CRR

$$\frac{\text{CRR at age } t_1}{\text{CRR at "reference age" } t_0}$$

(Maurer et al. 2014b)

Aging Effects on Liquefaction

$K_{DR} > 1$



- Position of triggering curves controlled by youngest, most susceptible deposits
- Reference age likely on order of ~1 to100 years

$$\mathbf{CRR}_{K} = \mathbf{CRR\ x}\ \boldsymbol{K}_{\mathbf{DR}}$$

age-corrected CRR

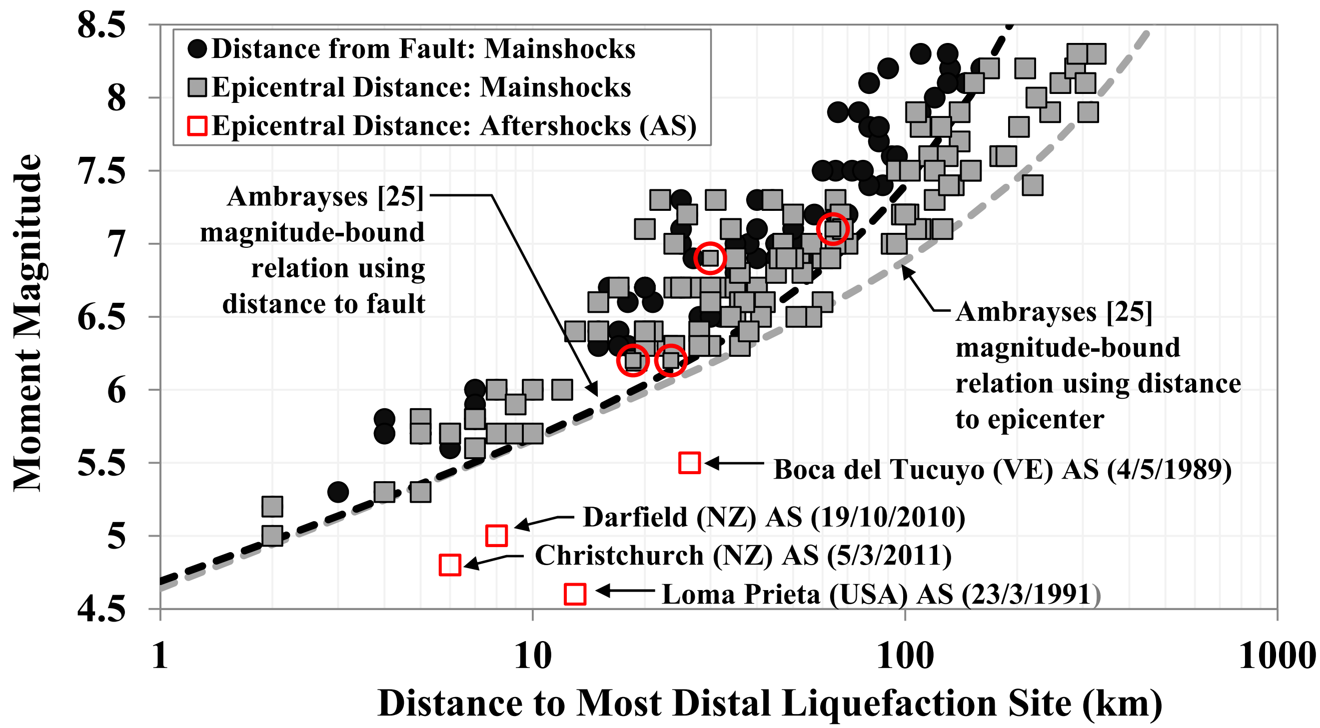
$$\frac{\text{CRR at age } t_1}{\text{CRR at “reference age” } t_0}$$

(Maurer et al. 2014b)

Aging Effects on Liquefaction

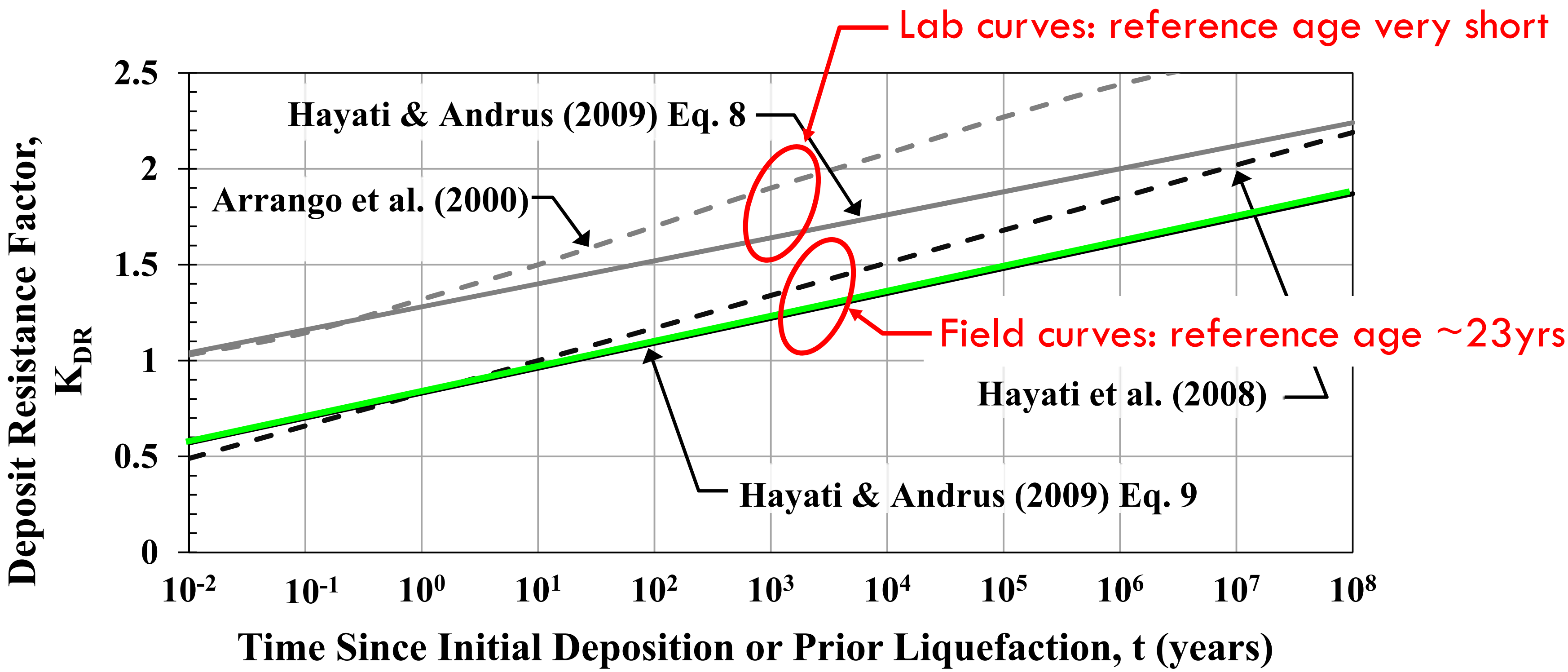
Aftershocks: CRR may be reduced after recent liquefaction

$K_{DR} < 1$



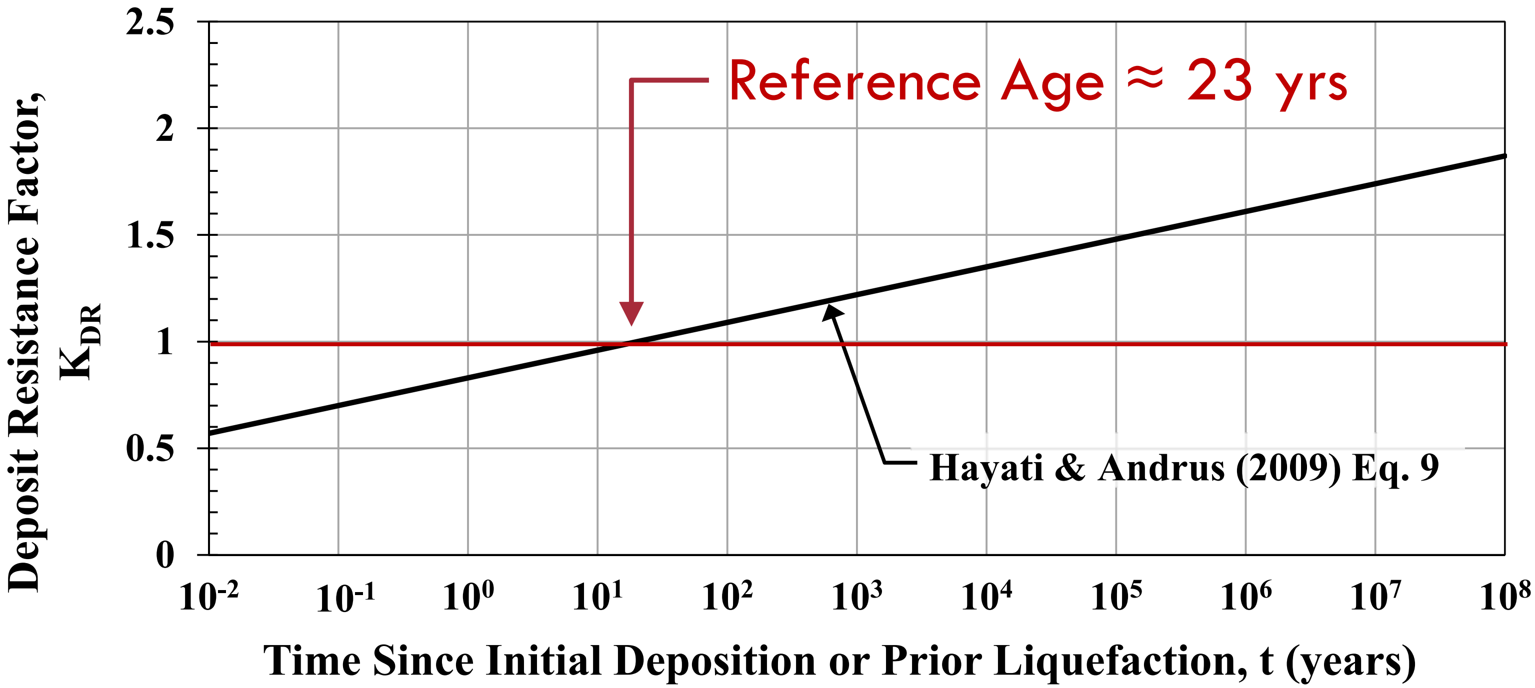
(Maurer et al. 2014b)

Aging Effects on Liquefaction



(Maurer et al. 2014b)

Aging Effects on Liquefaction

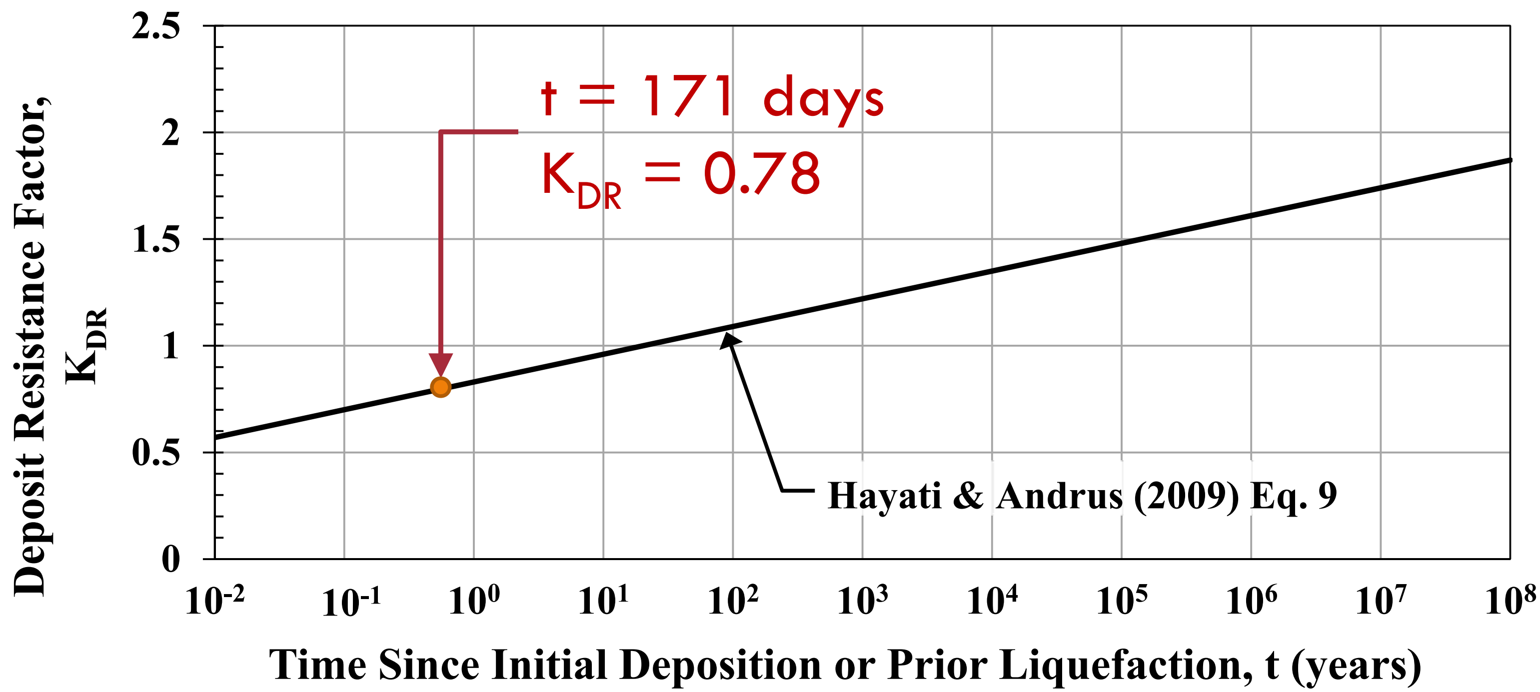


(Maurer et al. 2014b)

Aging Effects on Liquefaction

CPT Soundings
PGA
Liquefaction Evaluation
Aging Correction Factors
Liquefaction Severity

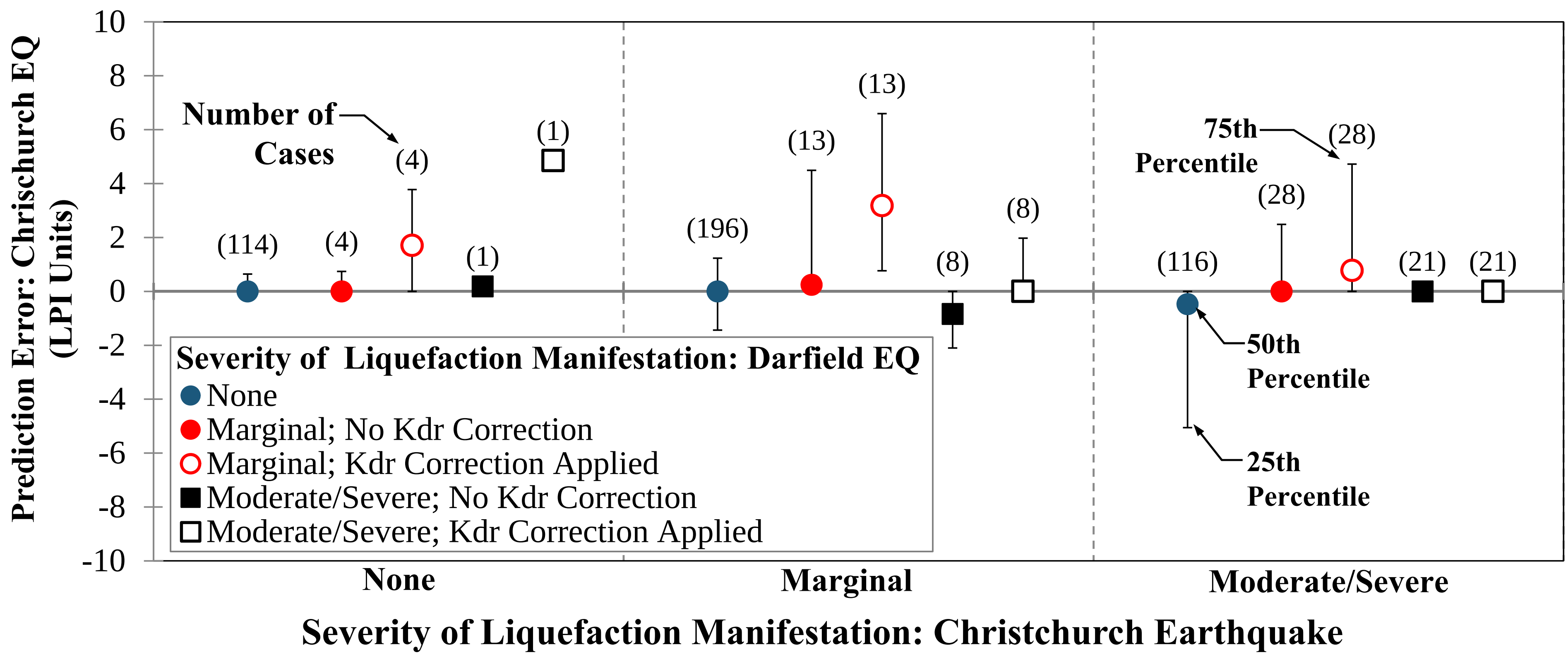
LPI → Do $K_{DR} < 1$ corrections improve accuracy of hazard assessment?



(Maurer et al. 2014b)

Aging Effects on Liquefaction

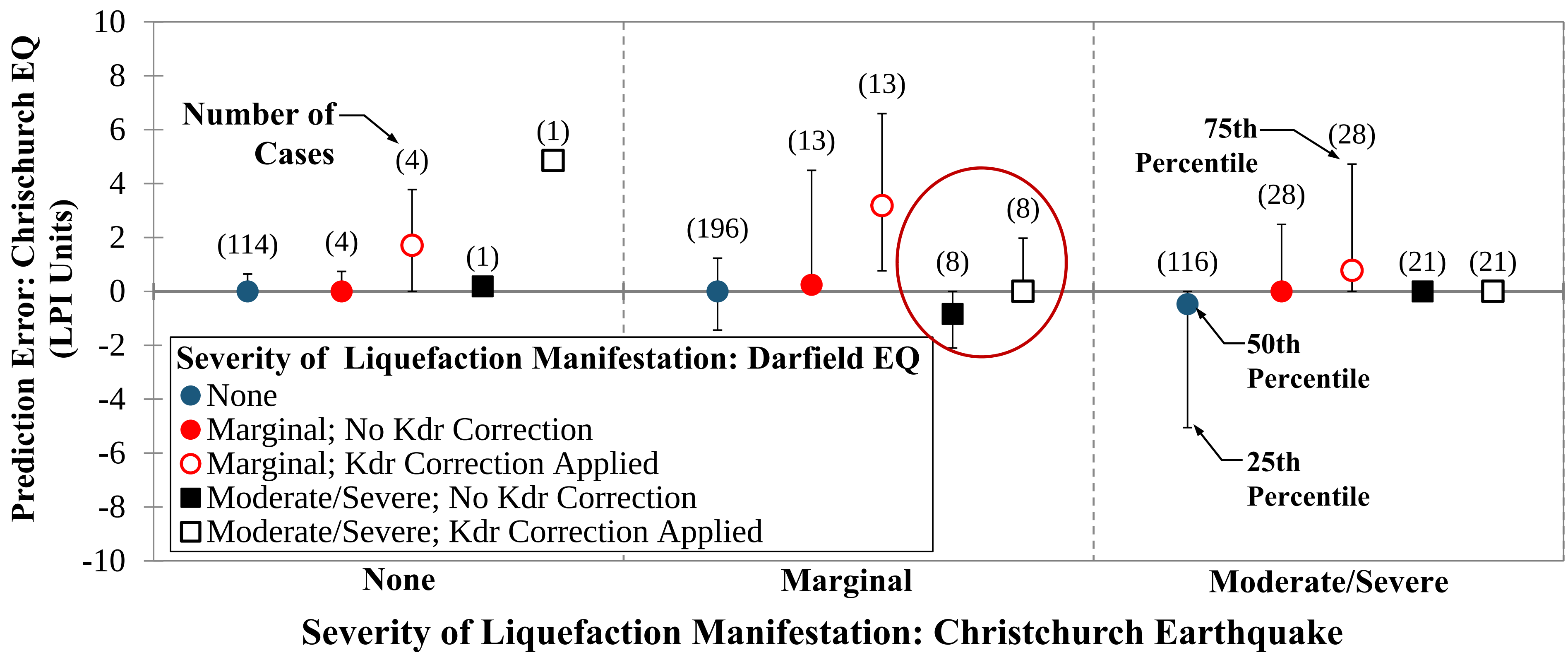
Distribution of LPI prediction errors (with/without K_{DR})



(Maurer et al. 2014b)

Aging Effects on Liquefaction

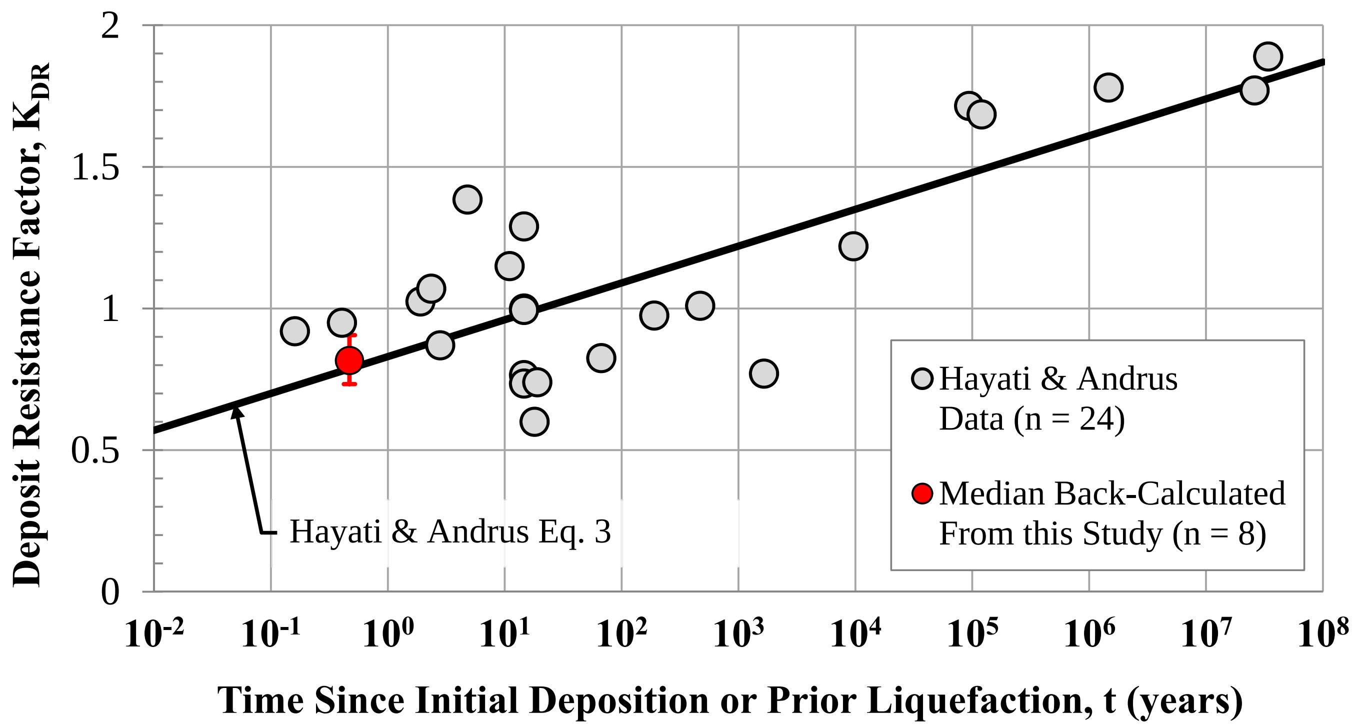
Distribution of LPI prediction errors (with/without K_{DR})



(Maurer et al. 2014b)

Aging Effects on Liquefaction

K_{DR} correction factors back-calculated such that predictions match the range consistent with marginal manifestation (i.e., 5 < LPI < 8)



(Maurer et al. 2014b)

Conclusion 4

- Based on *eight* case histories from the Canterbury Earthquake Sequence:
  - Hazard generally under-predicted without K_{DR} correction
  - K_{DR} correction from Hayati and Andrus (2009) typically improved prediction accuracy

(Maurer et al. 2014b)

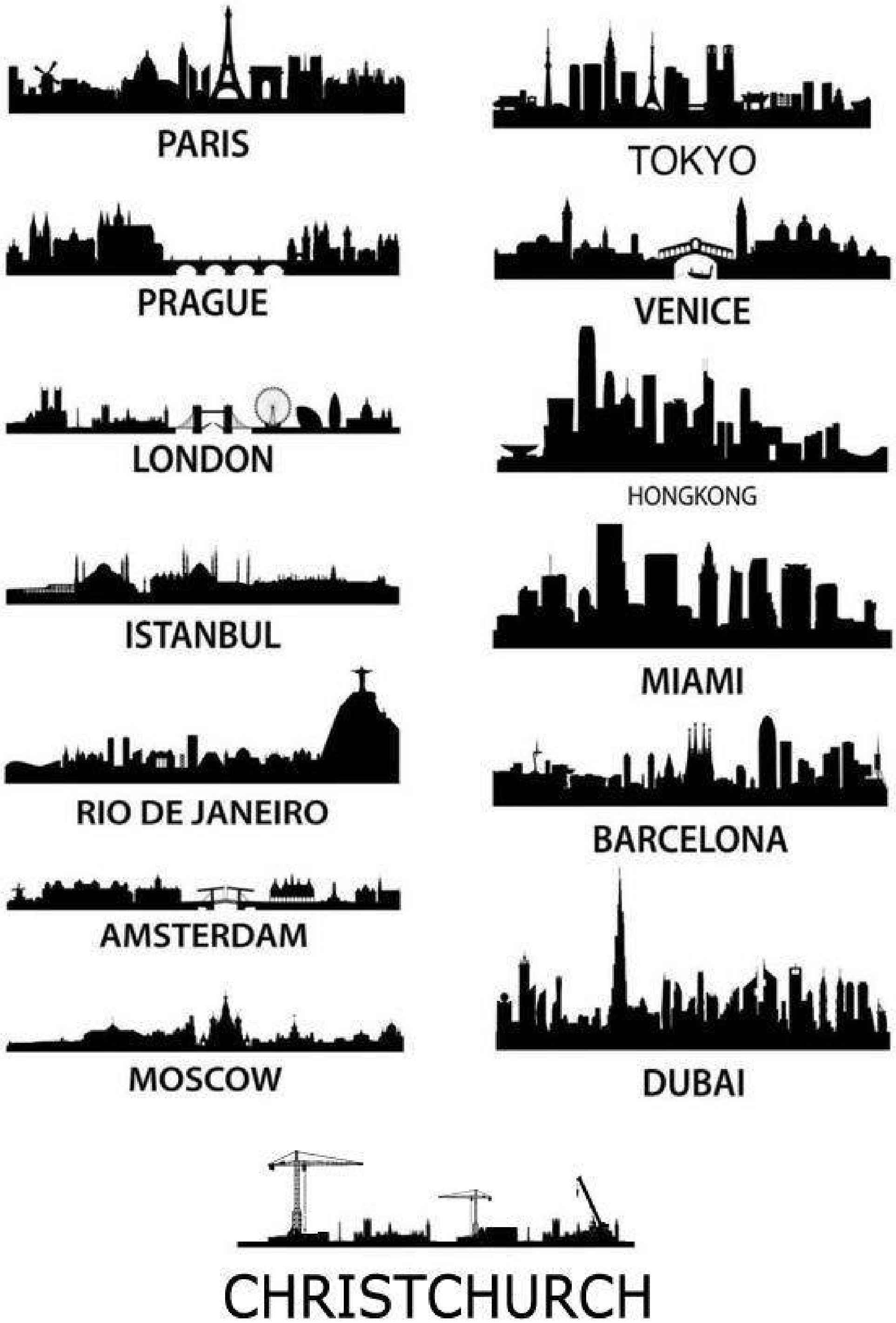
Summary of Conclusions

- All of the CPT-base procedures do a reasonable job predicting field observations.
- Idriss and Boulanger (2008) performed better than the other procedures.
- The LPI framework has limitations in predicting severity of surficial liquefaction manifestations for profiles having a fine-grained crust and/or fine-grained layers interbedded with liquefiable layers
- LPI_{ISH} results in predictions that are more inline with field observations than LPI, but does not fully account for fine-grained layers interbedded with liquefiable layers.
- K_{DR} aging correction from Hayati and Andrus (2009) typically improved prediction accuracy for sites of recurrent liquefaction during the Canterbury Earthquake Sequence

Work in Progress/Future Directions

- Develop a new liquefaction severity index that:
  - Accounts for both the fine-grained crust and fine-grained layers interbedded with liquefiable layers
  - Has depth weighting factors for liquefaction damage potential to shallow and deep foundations and embankments
  - Is completely compatible with liquefaction triggering curve
  - Gives a full quantification of uncertainty

Thank You


PARIS
TOKYO
PRAGUE
VENICE
LONDON
HONGKONG
ISTANBUL
MIAMI
RIO DE JANEIRO
BARCELONA
AMSTERDAM
MOSCOW
DUBAI
CHRISTCHURCH

References

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Maurer, B.W., Green, R.A., Cubrinovski, M., and Bradley, B.A. (2014a). “Evaluation of the Liquefaction Potential Index for Assessing Liquefaction Hazard in Christchurch, New Zealand”, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 140(7).

Maurer, B.W., Green, R.A., Cubrinovski, M., and Bradley, B.A. (2014b). “Assessment of Aging Correction Factors for Liquefaction Resistance at Sites of Recurrent Liquefaction: A Study of the Canterbury (NZ) Earthquake Sequence”, *Proc. 10th National Conference on Earthquake Engineering* (10NCEE), Anchorage, AK, 21-25 July.

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Maurer, B.W., Green, R.A., Cubrinovski, M., and Bradley, B.A. (2015b). “Fines-Content Effects on Liquefaction Hazard Evaluation for Infrastructure in Christchurch, New Zealand”, *Soil Dynamics and Earthquake Engineering*. (*in press*) doi:10.1016/j.soildyn.2014.10.028

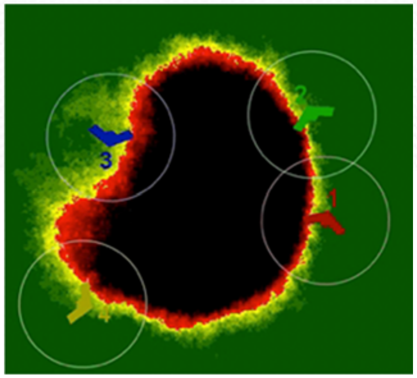
Maurer, B.W., Green, R.A., and Taylor, O.S. (2015c). “Moving Towards an Improved Index for Assessing Liquefaction Hazard: Lessons from Historical Data”, *Soils and Foundations*, JGS. (*in review*)

van Ballegooy, S., Green, R.A., Lees, J., Wentz, F., and Maurer, B.W. (2015). “Assessment of Various CPT Based Liquefaction Severity Index Frameworks Relative to the Ishihara (1985) H_1-H_2 Boundary Curves”, *Soil Dynamics and Earthquake Engineering*. (*in review*)

Next Generation Liquefaction Field Reconnaissance: Unmanned Aerial Vehicles

Kevin Franke, Ph.D., P.E.
Assistant Professor, CEEn
Brigham Young University

Center for Unmanned Aircraft Systems (C-UAS)



Cooperative Control

- Cooperative timing problems
- Cooperative persistent imaging
- Cooperative fire monitoring
- Consensus seeking

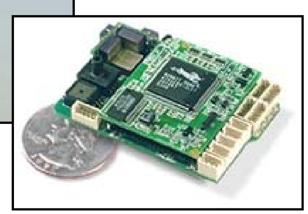
Path Planning
Trajectory Generation

- 3D Waypoint path planning
- Wind compensation
- Collision avoidance
    - Optic flow sensor
    - Laser ranger
    - EO cameras

Image Directed Control

- Image stabilization
- Geo-location
- Vision-aided tracking & engagement

Autonomous Vehicles



- Autopilot design for small UAVs
- Attitude estimation
- Adaptive control
- Tailsitter guidance & control

What is C-UAS? (http://c-uas.byu.edu/)

- C-UAS: Center for Unmanned Aircraft Systems
- Sponsored by National Science Foundation under I/UCRC program *and* industry members
- Three universities involved:
  - Brigham Young University
    - Tim McLain, Randy Beard, Mike Goodrich, Eric Mercer, Karl Warnick, John Hedengren, Kevin Franke, Gus Williams
  - University of Colorado
    - Eric Frew, Brian Argrow
  - Virginia Tech is joining us this year!!

Current Industry Membership

- 2D3 Sensing
- AFRL Aerospace Systems Directorate
- AFRL Munitions Directorate
- AAI-Textron
- BP
- Boeing
- Insitu
- L-3 Communications
- NASA Dryden Flight Research Center
- National Oceanic and Atmospheric Administration
- Northrop Grumman
- United Technologies Research Center
- Utopia Compression
- Strong interest from: USBR, Lockheed Martin, URS Corp. Raytheon, Fairweather, and others

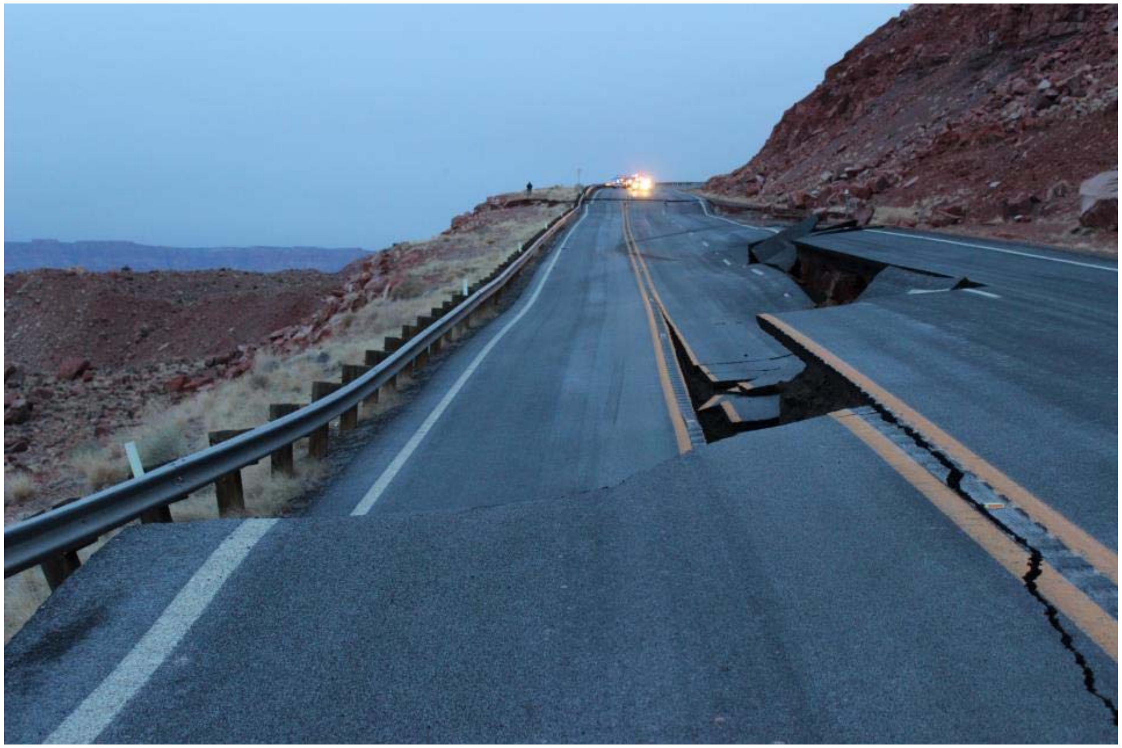
Current Project Collaborators

Dr. Ryan Farrell
Computer Science

Dr. John Hedengren
Chemical Engineering

US-89 Arizona Landslide

On February 20, 2013, a massive dry landslide occurred approximately 20 miles south of Page, Arizona. This landslide critically damaged US-89.



Landslide Modeling and Monitoring

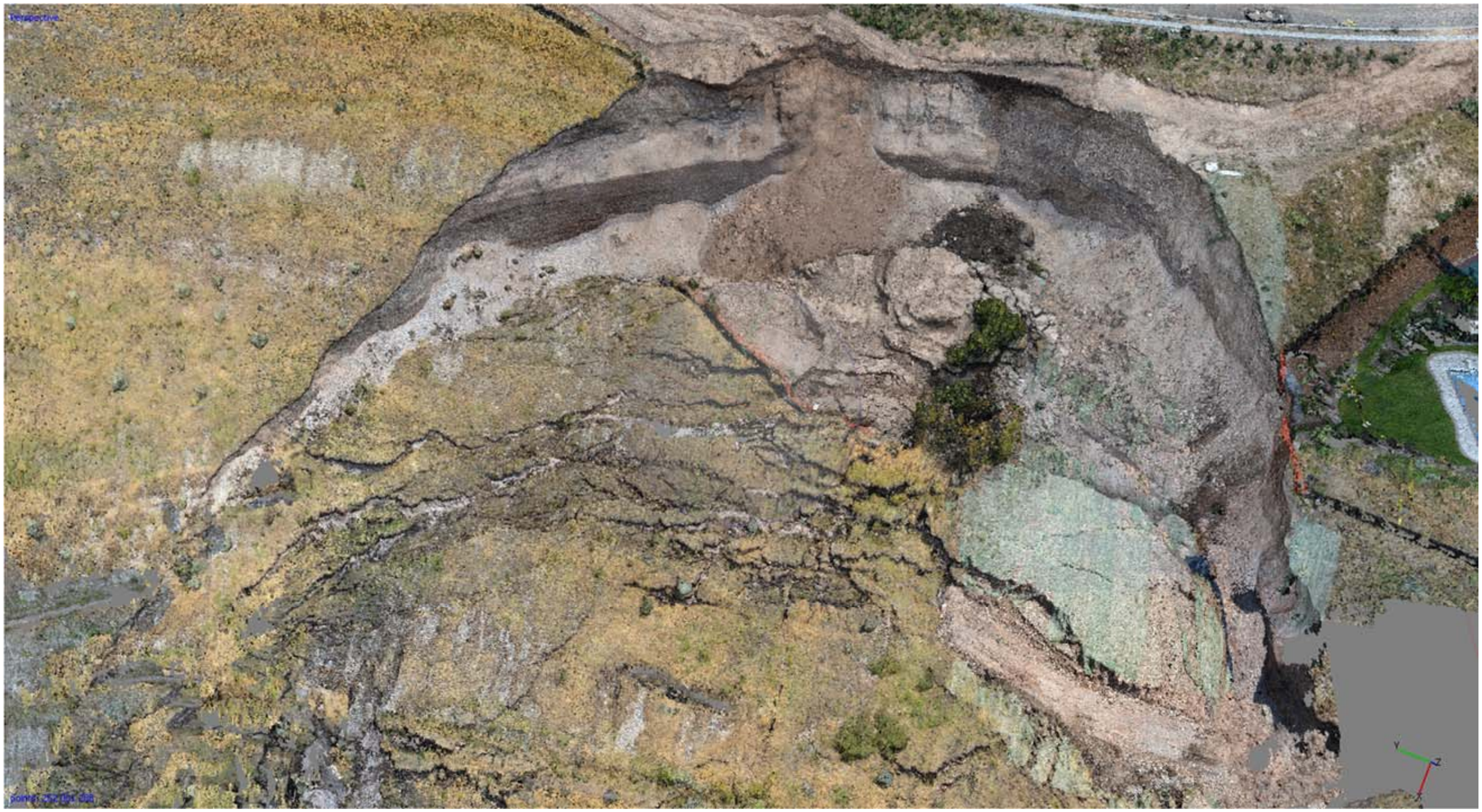
In July 2014, we flew the US-89 landslide with a UAV carrying a digital SLR camera. This is an image of the the resulting 3D point cloud model.

Landslide Modeling and Monitoring

Recent re-processing of those images produced a model with nearly 950M points (1cm resolution) and median accuracy of 3cm..

Landslide Modeling and Monitoring

We partnered with the UGS and North Salt Lake City to model the recent landslide in August 2014.



Landslide Modeling and Monitoring

The UGS and North Salt Lake City asked us to fly and model the recent landslide in August 2014.

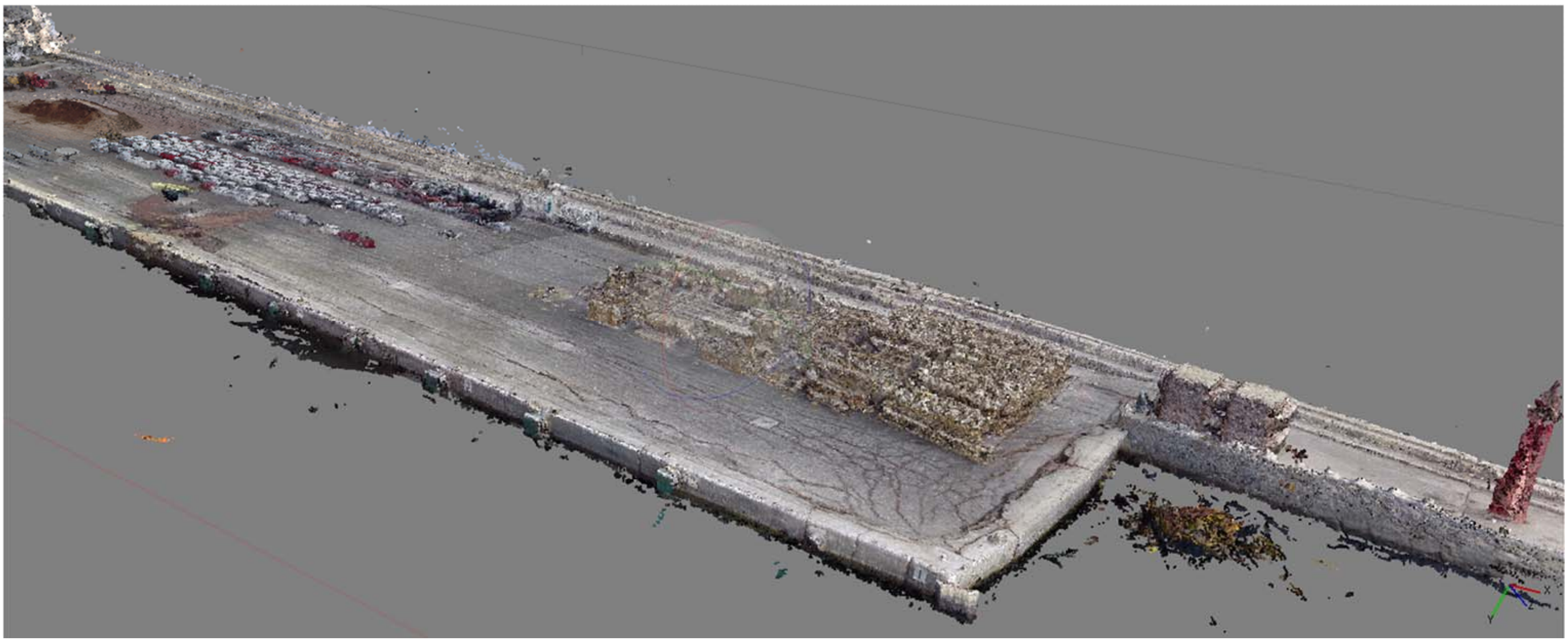
Landslide Modeling and Monitoring

Earthquake Reconnaissance

In April 2014, Dr. Kyle Rollins and I reconnoitered sites in Iquique, Chile following the M8.0 earthquake there. We returned in June with UAVs.

Earthquake Reconnaissance

Here are some screenshots of CV models of liquefaction damage from April 1, 2014 Chile earthquake

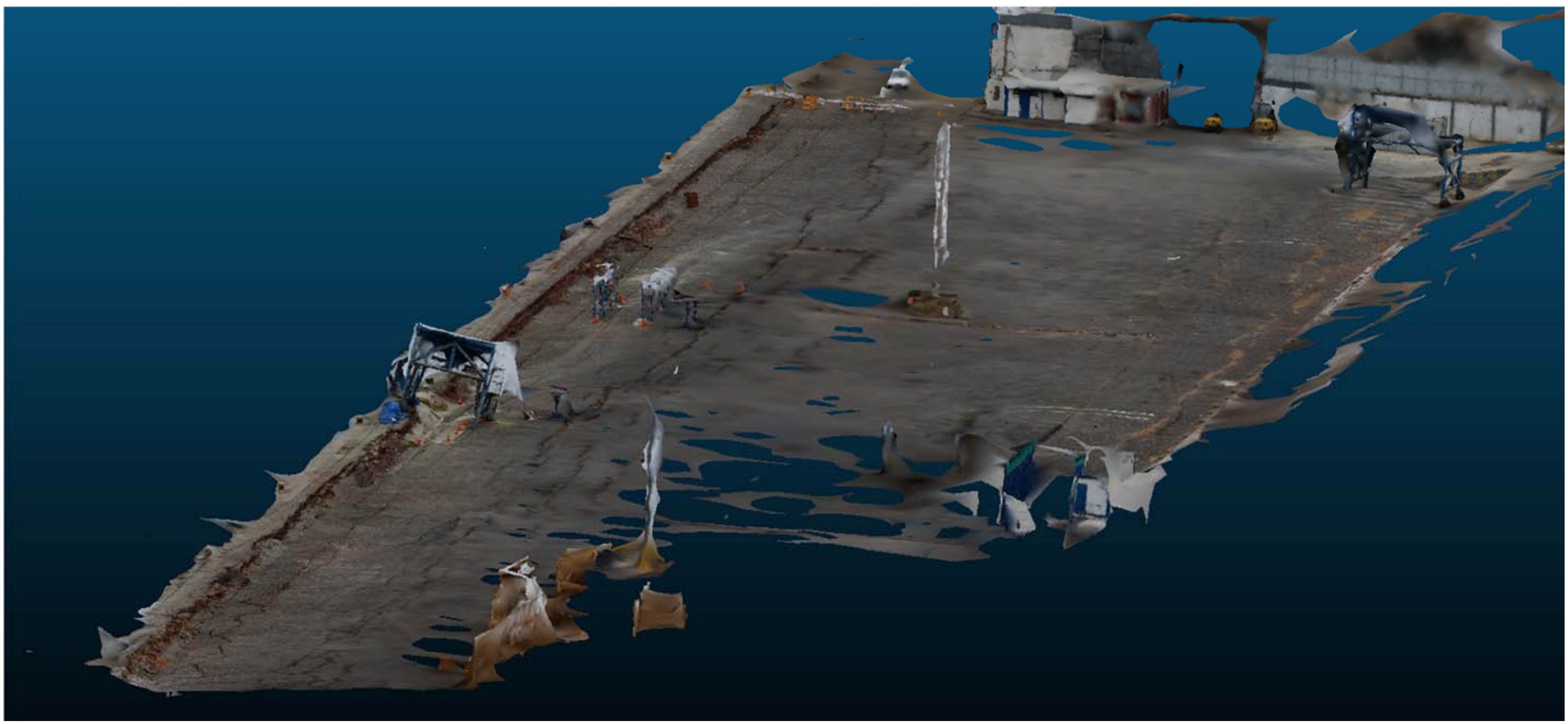


Earthquake Reconnaissance

Here are some screenshots of CV models of liquefaction damage from April 1, 2014 Chile earthquake

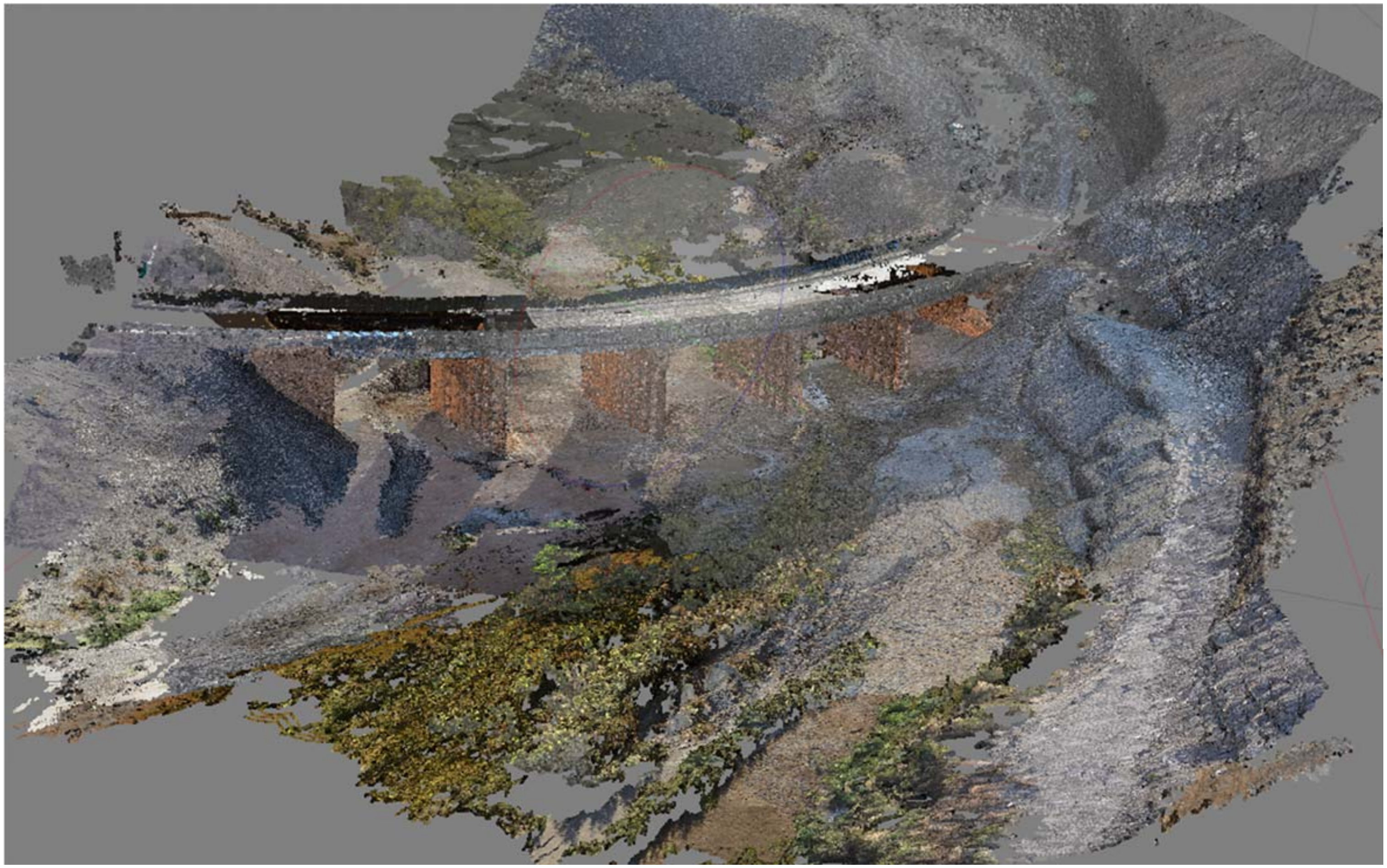
Earthquake Reconnaissance

Compare the UAV models with this model, developed from handheld photographs (…more photos, actually!) The UAV offers much more coverage.



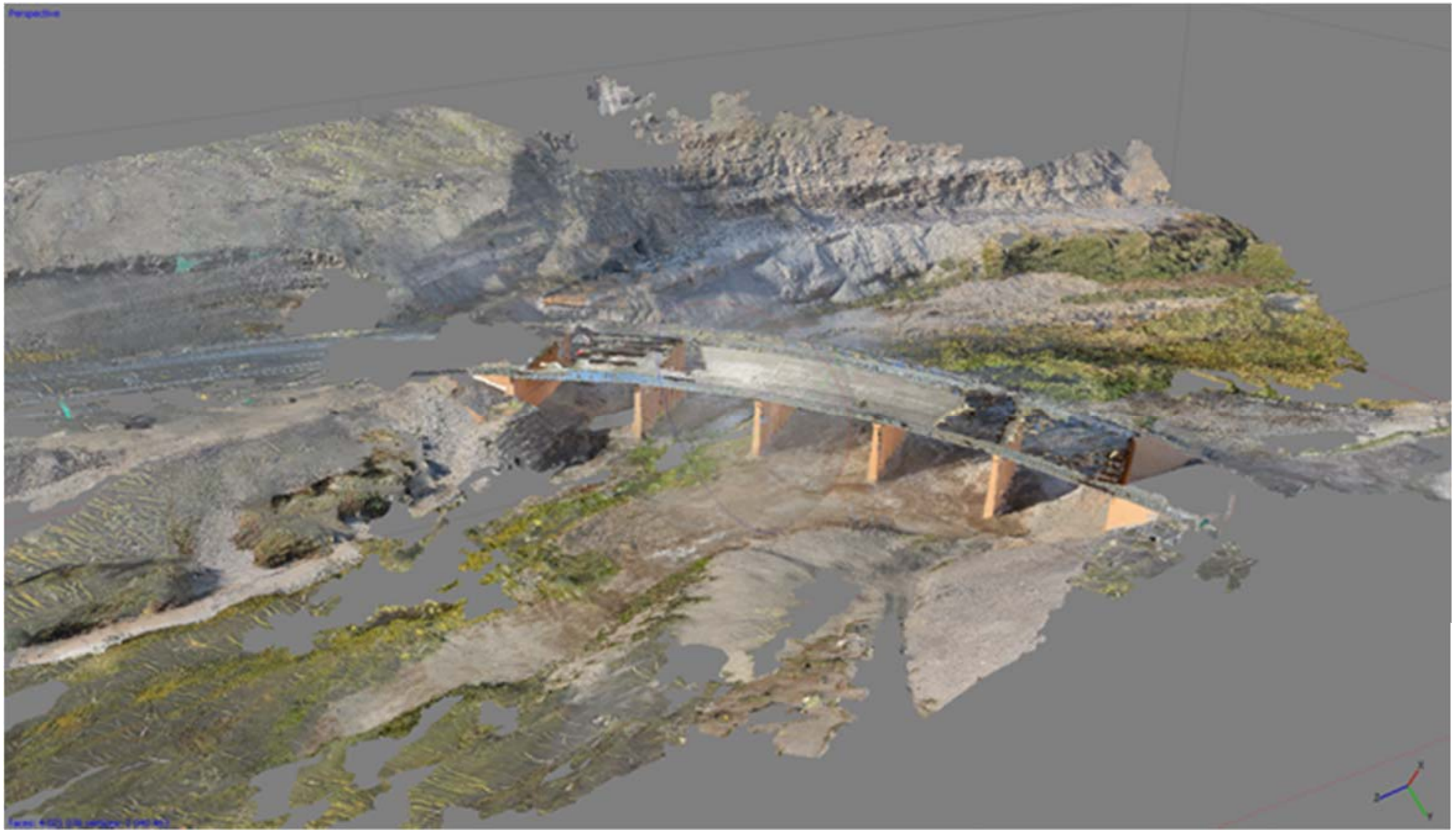
Earthquake Reconnaissance

Here are some screenshots of CV models of liquefaction damage from April 1, 2014 Chile earthquake



Earthquake Reconnaissance

Here are some screenshots of CV models of liquefaction damage from April 1, 2014 Chile earthquake

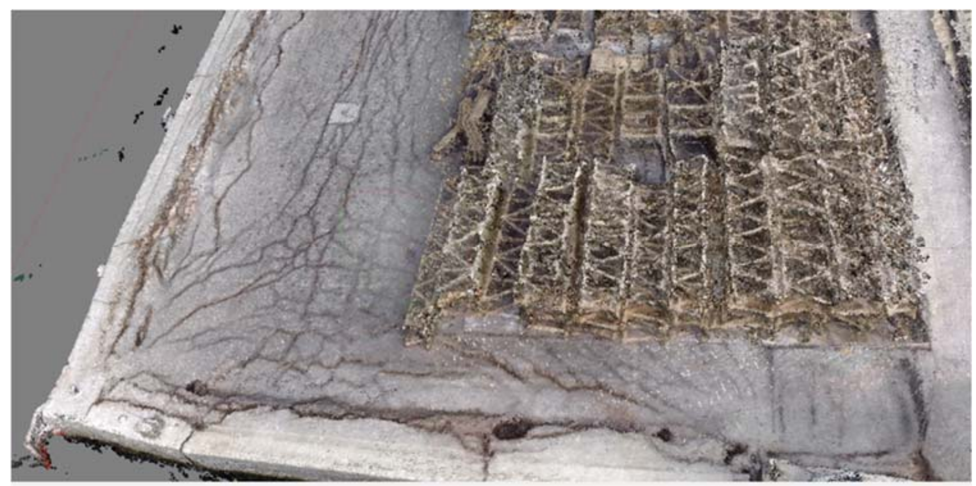


Earthquake Reconnaissance

Here is a screenshot of a CV model of a lateral spread from April 1, 2014 Chile earthquake

Conclusion

- UAVs improve our ability to gather data from post-liquefaction damage sites.
- A large site can typically be reconnoitered and “scanned” in less than 2 hours.
- Utah might consider creating a database of pre-earthquake point clouds for select critical structures. Clouds could be developed using LiDAR or computer vision.



Next Generation Liquefaction Field Reconnaissance: Unmanned Aerial Vehicles

Kevin Franke, Ph.D., P.E.
Assistant Professor, CEEn
Brigham Young University

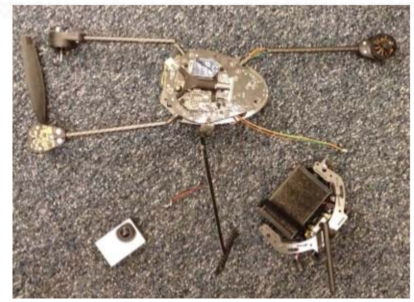
My Current UAV Platforms:

Rightwing 81" ZXL (a.k.a. "Big Bird")

- 81" wingspan (very stable!)
- Can fly in 45+ mph winds
- Carries GoPro Hero 3
- Flies at 35-65 mph
- Flight time is 10-20 minutes

Draganfly X-4 Quadcopter

(Before Crash…)



(After Crash…)

- 4 rotor system
- Very mobile, but squirrely in wind
- Carries GoPro Hero 3 or Panasonic still
- Flies at 0-35 mph
- Flight time is 10-20 minutes

Phantom 2

- 4 rotor system
- Very mobile, more stable than X-4
- Carries GoPro Hero 3
- Flies at 0-35 mph
- Flight time is 10-20 minutes

My Current UAV Platforms:

Skyjib 6 (custom built)

- 6 rotor system
- 360-degree gimbled camera
- GPS waypoint-programmable
- Very mobile, more stable than X-4
- Can carry full-size DSLR camera
- Flies at 0-35 mph
- Flight time is 10-20 minutes

DJI S1000 (octa-rotor)

- 8 rotor system
- 360-degree gimbled camera platform
- GPS waypoint-programmable
- Very mobile, more stable than X-4
- Can carry multiple sensors (e.g., camera & LiDAR)
- Flies at 0-35 mph
- Flight time is 10-20 minutes

My Current UAV Platforms:

Our new addition (….no, we haven't named her yet!)

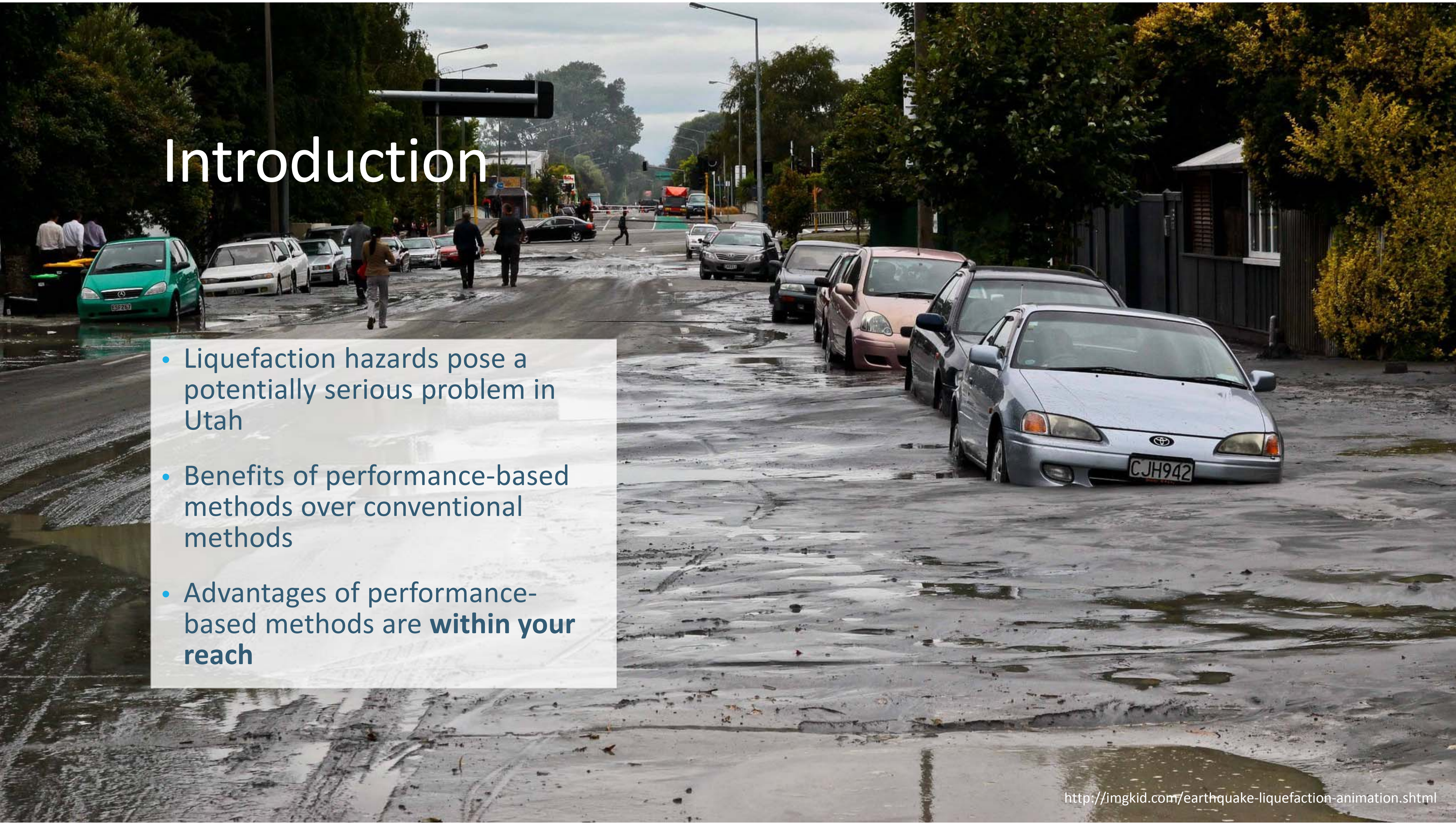
Performance-based Assessment of Liquefaction Triggering and Lateral Spread: A **Simplified** Approach

Levi Ekstrom, Kristin Ulmer, and Dr. Kevin Franke

Utah Liquefaction Advisory Group Meeting

February 9th, 2015

Introduction



- Liquefaction hazards pose a potentially serious problem in Utah
- Benefits of performance-based methods over conventional methods
- Advantages of performance-based methods are **within your reach**

http://imgkid.com/earthquake-liquefaction-animation.shtml

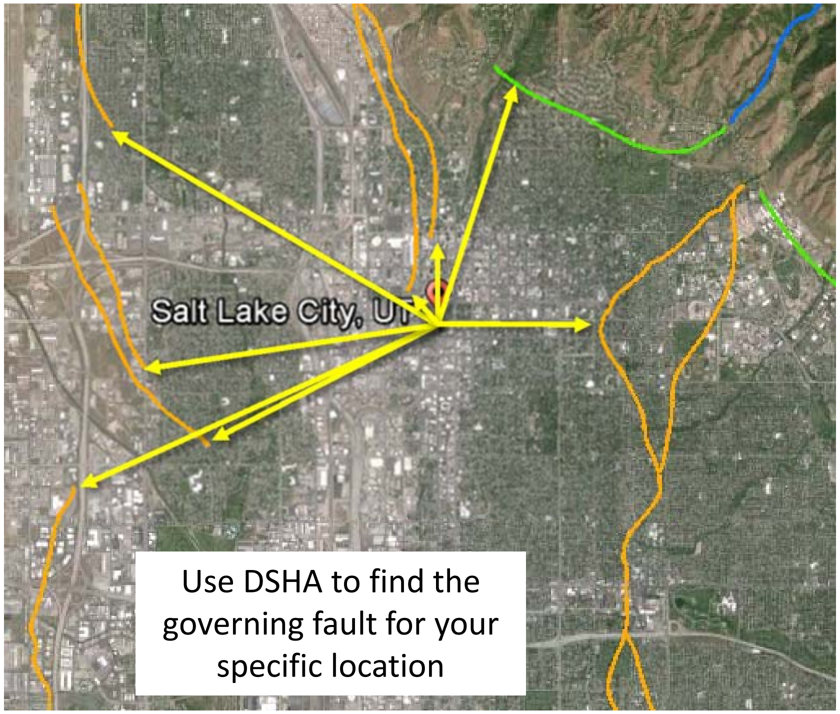
Outline

- Why Performance-based methods?
  - What are PB methods?
  - How do PB methods differ from conventional methods?
  - Advantages and disadvantages
- Introduction to the Simplified Method
  - Purpose
  - How does it work?
  - Maps
- Validation
- What this means for you

http://liquefactionmitigation.weebly.com/

Why Performance-based Methods?

- **Deterministic** approach: Deterministic Seismic Hazard Analysis (DSHA)



Use DSHA to find the governing fault for your specific location

Estimate 50th or 84th percentile PGA, Mean M_w, and Distance

	Seismic Source	Dist (km)	M	PGA
1	Wasatch Fault, SLC Section	1.02	7	0.5911
2	West Valley Fault Zone	2.19	6.48	0.5694
3	Morgan Fault	25.04	6.52	0.0989
4	Great Salt Lake Fault zone, Antelope Section	25.08	6.93	0.1016
5	Oquirrh-Southern, Oquirrh Mountain Fault	30.36	7.17	0.0958

Why Performance-based Methods?

- **Deterministic** approach

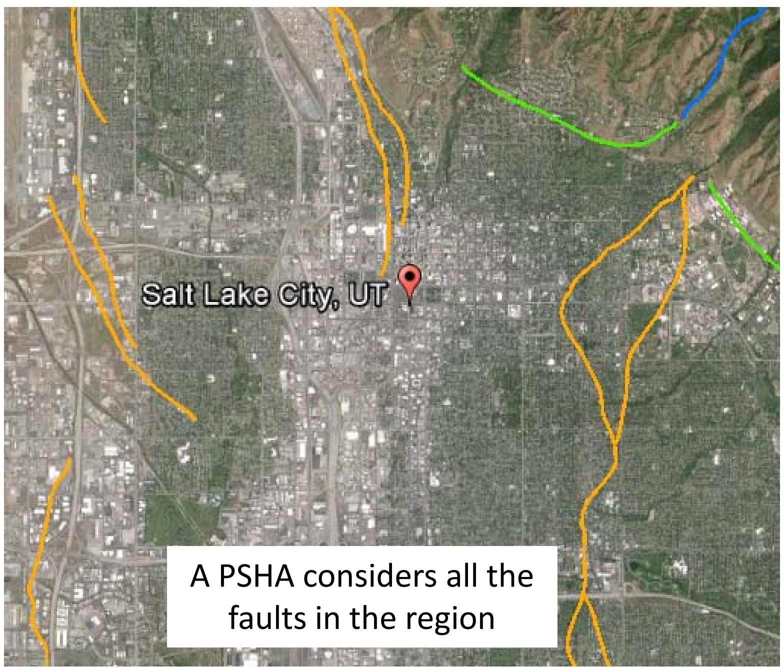
Estimate 50th or 84th percentile PGA, Mean M_w, and Distance

	Seismic Source	Dist (km)	M	PGA
1	Wasatch Fault, SLC Section	1.02	7	0.5911
2	West Valley Fault Zone	2.19	6.48	0.5694
3	Morgan Fault	25.04	6.52	0.0989
4	Great Salt Lake Fault zone, Antelope Section	25.08	6.93	0.1016
5	Oquirrh-Southern, Oquirrh Mountain Fault	30.36	7.17	0.0958

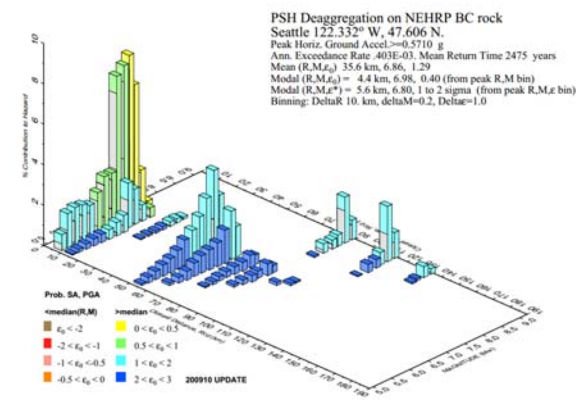
Deterministic Equations

Why Performance-based Methods?

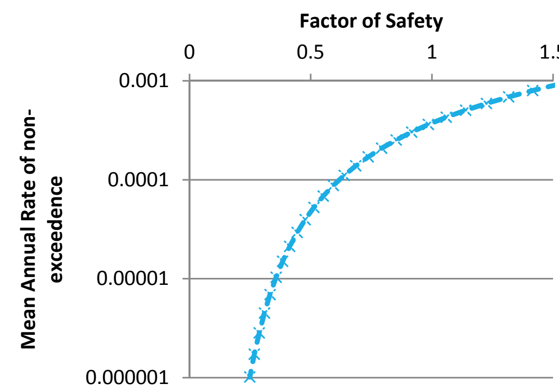
- **Performance-based Methods**
  - Consider multiple scenarios (R = ?, M_w = ?, a_{max} = ?) and their respective likelihoods



Probabilistic Seismic Hazard Analysis (PSHA): develop deaggregations with magnitude, distance, and % contribution

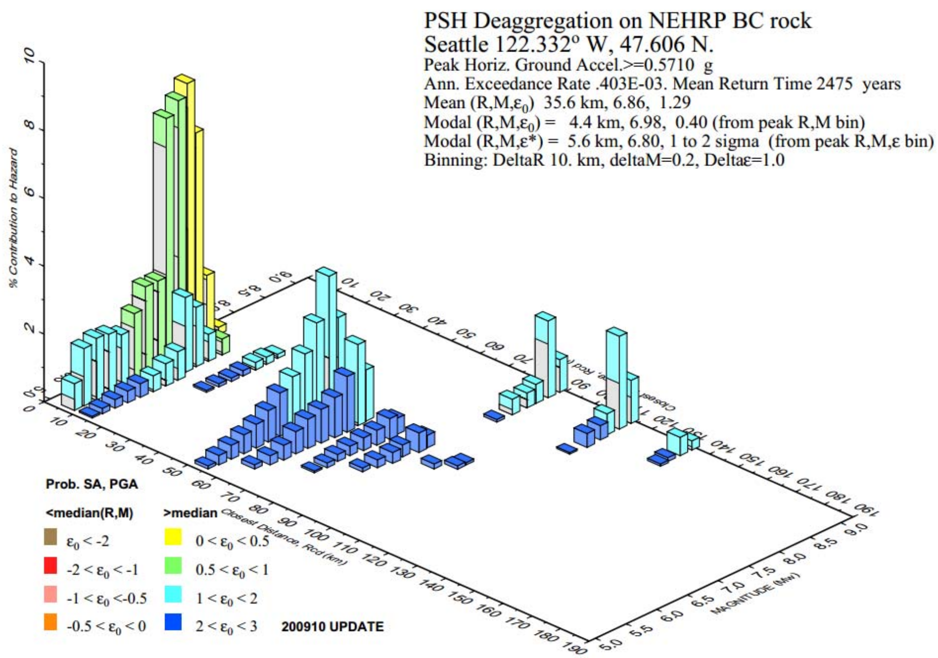


Develop hazard curves for the parameter of interest



Why Performance-based Methods?

- **Pseudo-probabilistic** approach



Retrieve probabilistic estimate of PGA, Mean M_w, and Distance

Deterministic Equations

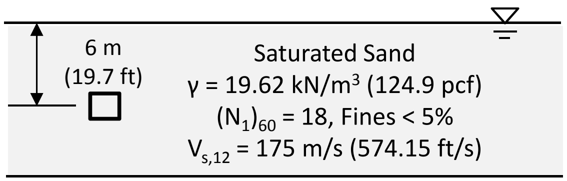
Why Performance-based Methods?

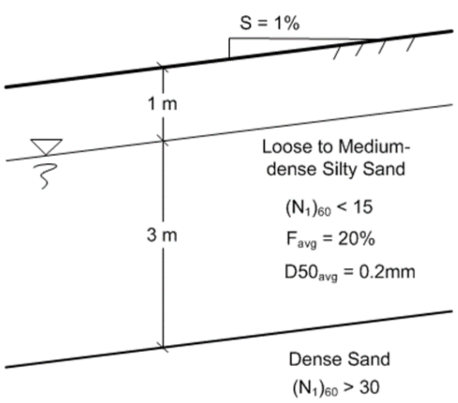
- Advantages
  - Considers multiple scenarios and their respective likelihoods
  - More consistent estimate of hazard
  - Return-period based approach for decision-makers
- Disadvantages
  - Requires special training and expertise
  - Complex analysis requires time
  - Difficult to incorporate into routine projects
  - May overpredict liquefaction hazard in some areas of high seismicity

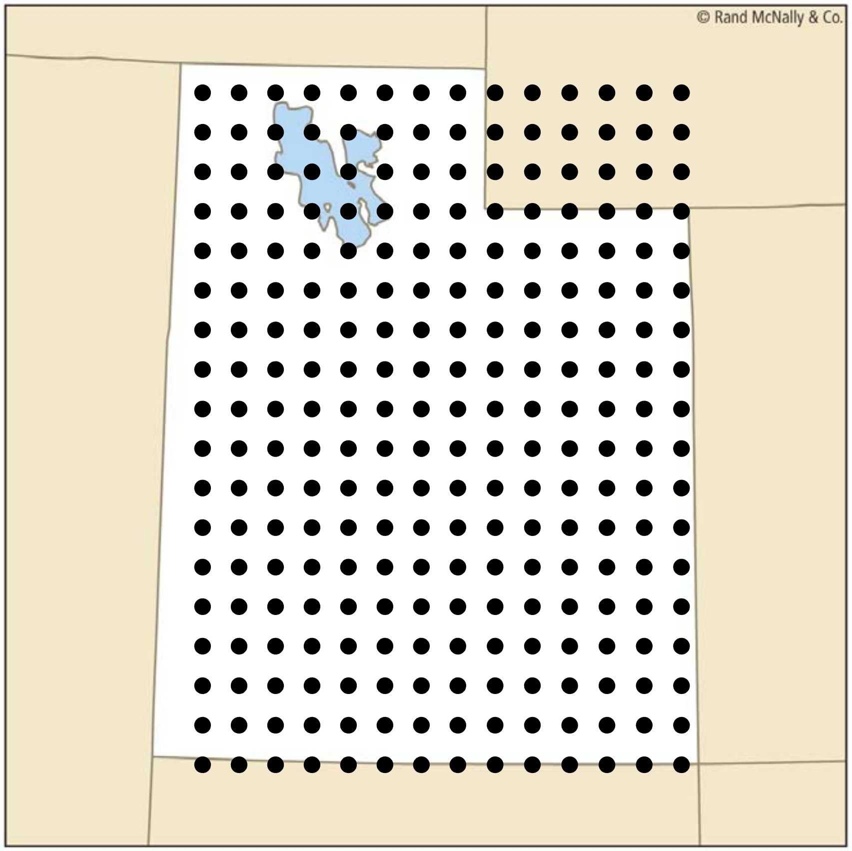
Introduction to the Simplified Method

- Creating the Maps
- Correction Factors
- Parameter Maps vs Hazard Maps
- Comparison of Simplified Methods and Full Performance-Based Methods

The Simplified Method: Creating the Maps

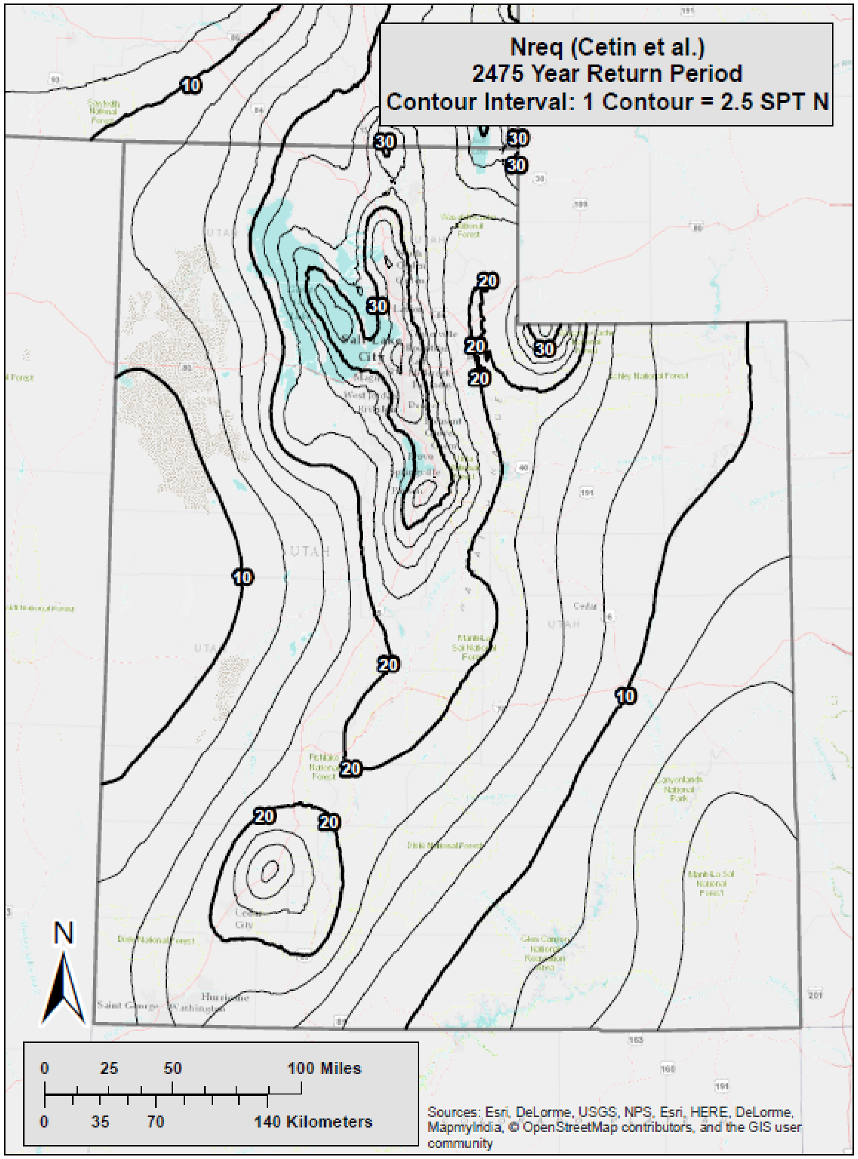






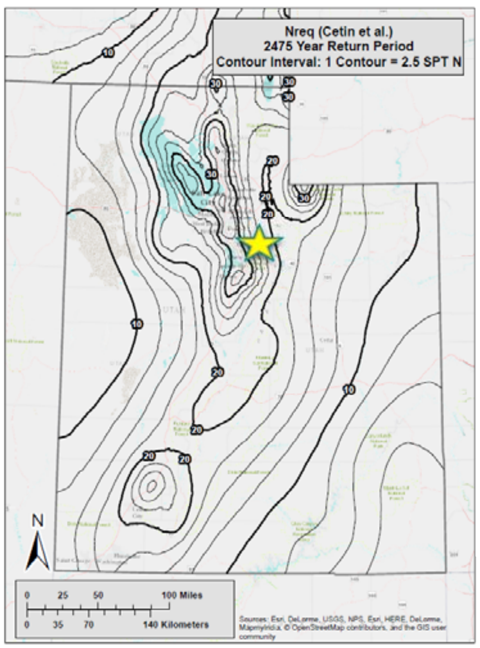
Parameter Maps for:

- Blow counts needed to resist liquefaction (N_{req}^{ref})
- Cyclic Stress Ratio ($CSR\%^{ref}$)
- Lateral Spread Displacement (D_H^{ref})



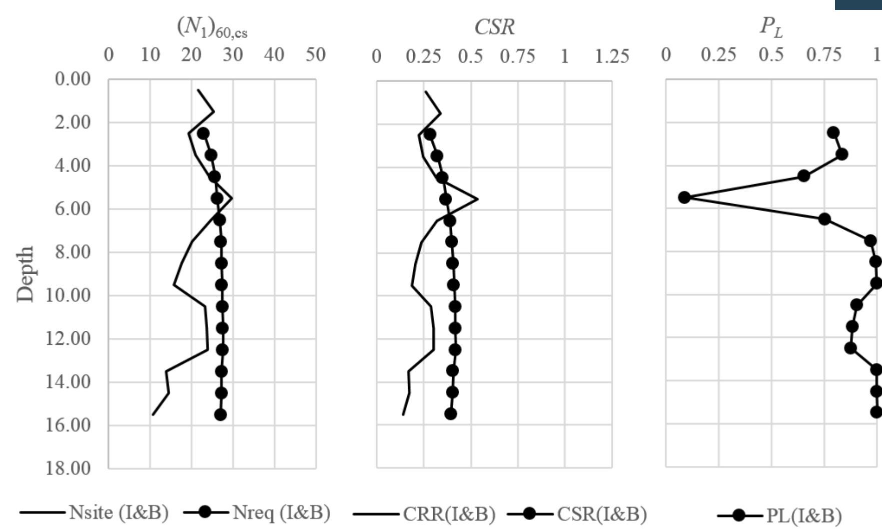
The Simplified Method: Liquefaction Assessment

Hazard-targeted map + Site-specific soil data = Site-specific liquefaction initiation results



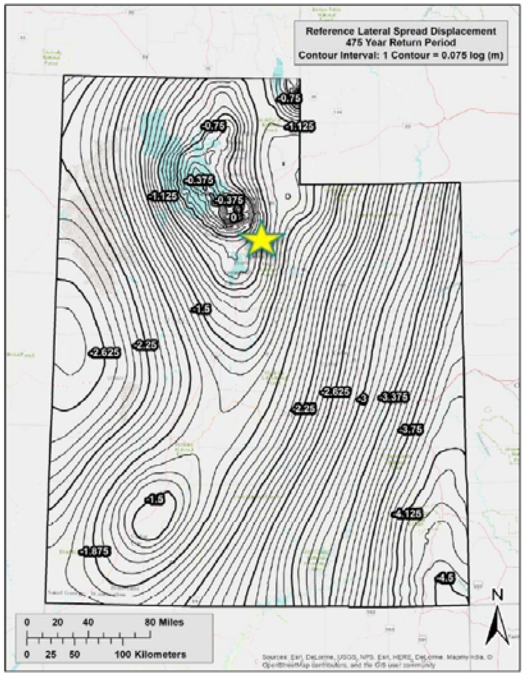
Depth to Water Table = 2 m

Depth (m)	SPT N	γ (kN/m^3)	Fines (%)	Thickness (m)
0.50	10	20.0	2.0	1.0
1.50	12	21.0	2.0	1.0
2.50	11	22.0	2.0	1.0
3.50	13	20.0	4.0	1.0
4.50	16	20.0	4.0	1.0
5.50	20	20.0	4.0	1.0
6.50	18	21.0	5.0	1.0
7.50	16	21.0	5.0	1.0
8.50	15	21.0	5.0	1.0
9.50	14	20.0	8.0	1.0
10.50	20	21.0	8.0	1.0
11.50	21	21.0	8.0	1.0
12.50	22	21.0	5.0	1.0
13.50	15	22.0	6.0	1.0
14.50	16	22.0	6.0	1.0
15.50	13	22.0	6.0	1.0



The Simplified Method: Lateral Spread

Hazard-targeted map + Site-specific data = Site-specific lateral spread results

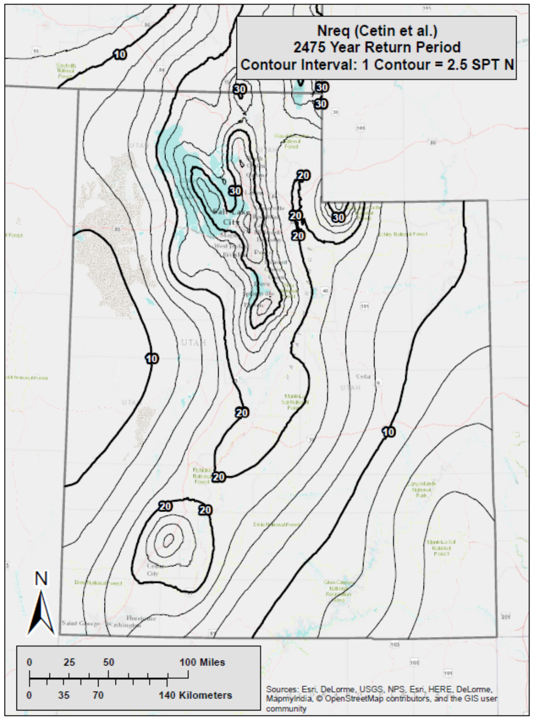


- Slope
- Free-Face Ratio
- Thickness of Liquefiable Layer
- Fines Content
- Mean Grain Size

Lateral Spread Displacement

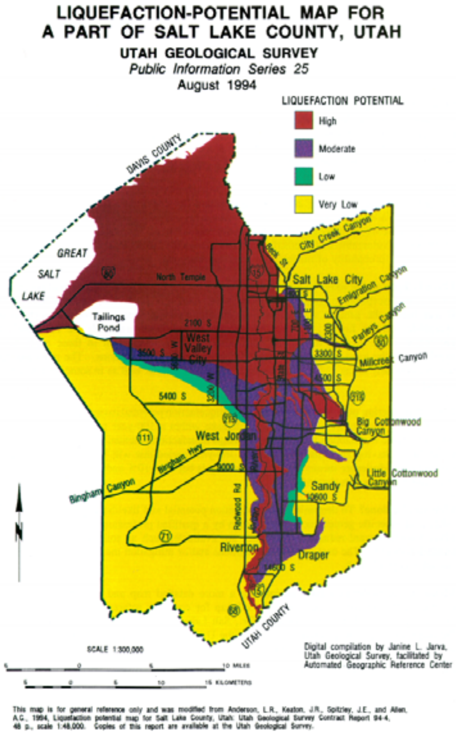
$D_h^{site} = \mathbf{0.126}$ m

Parameter Maps vs Hazard Maps



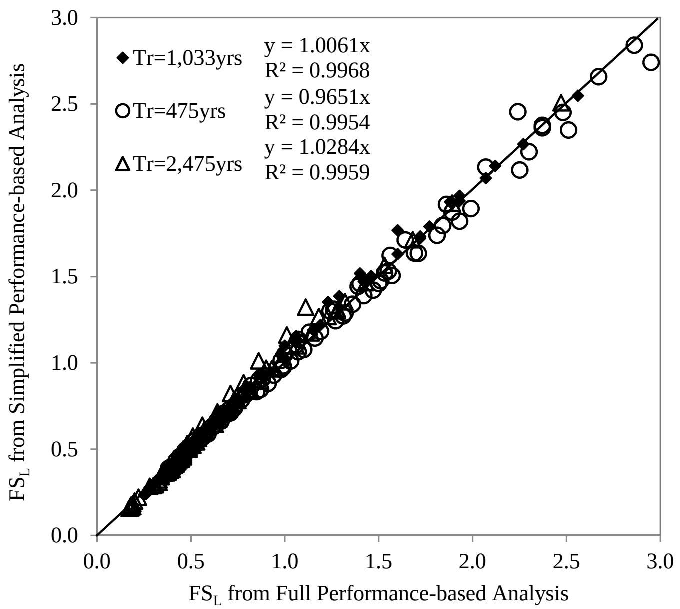
- Single, generic soil profile

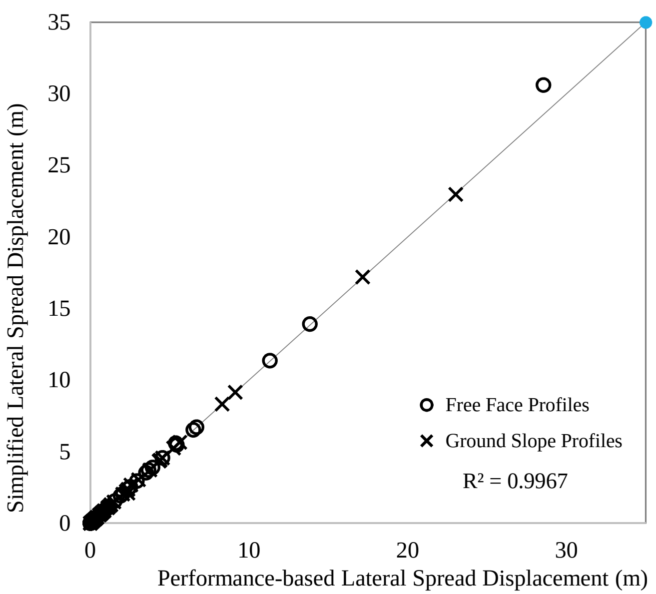
What's the difference?



- Associated with available soil data

Validation – How Accurate is This Method?





What This Means for You…

- You can have the advantages of performance-based methods without the necessary tools, training and expertise
  - With almost none of the disadvantages
- Benefits for Engineers
  - Quickly calculate liquefactions hazards
  - Accurate and simple
- Benefits for Decision-makers
  - Criticality of structure determines hazard level

Questions?

- We would like to acknowledge the DOTs from the following states for supporting our research:
  - Alaska
  - Connecticut
  - Idaho
  - Montana
  - South Carolina
  - Utah

Probabilistic Liquefaction and Lateral Spread Hazard Mapping for Utah County

Jasmyn Harper
Brigham Young University
February 9, 2015

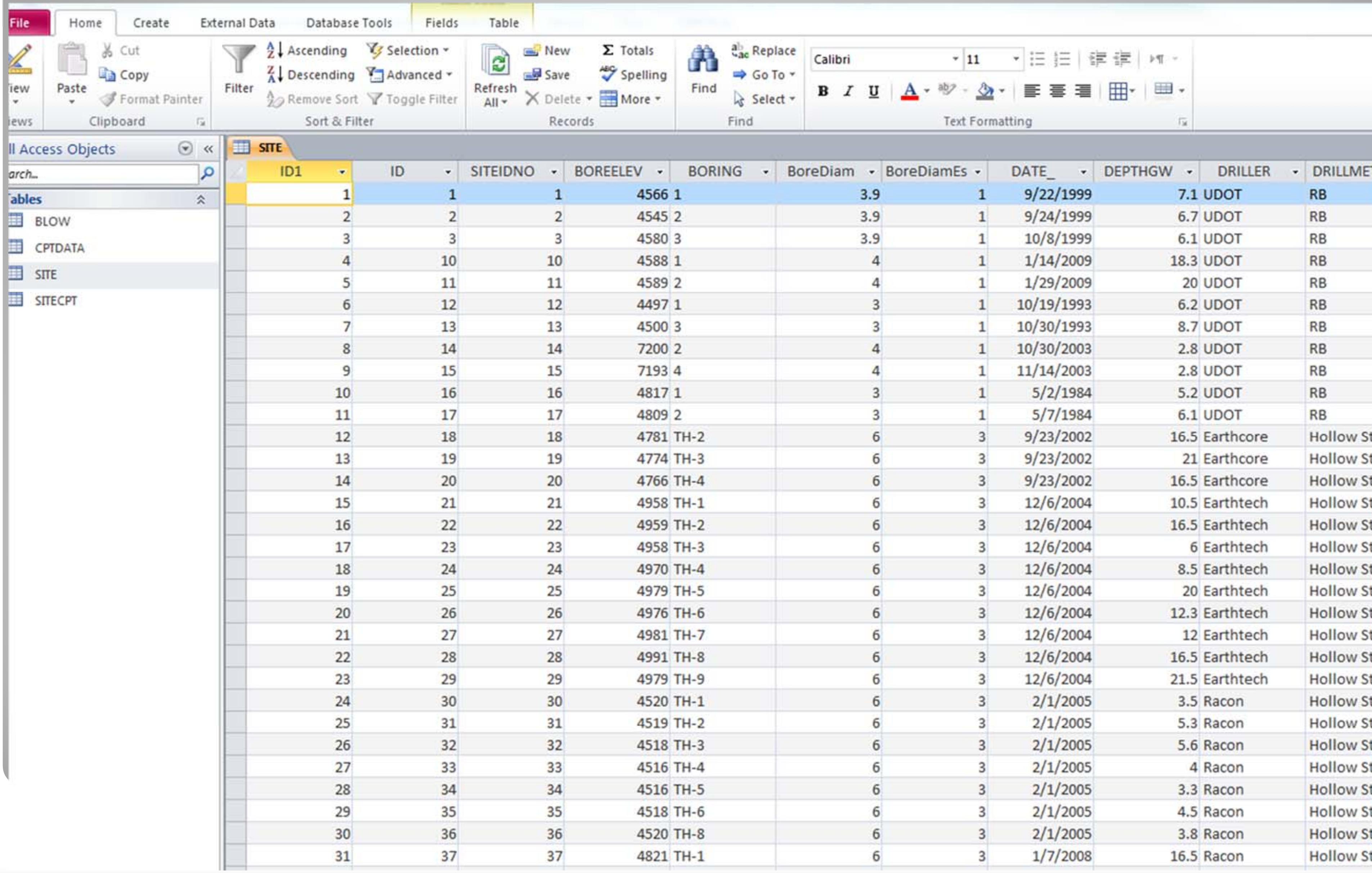
Aspects of research

- Subsurface database construction
- Analysis and map creation

Subsurface Database

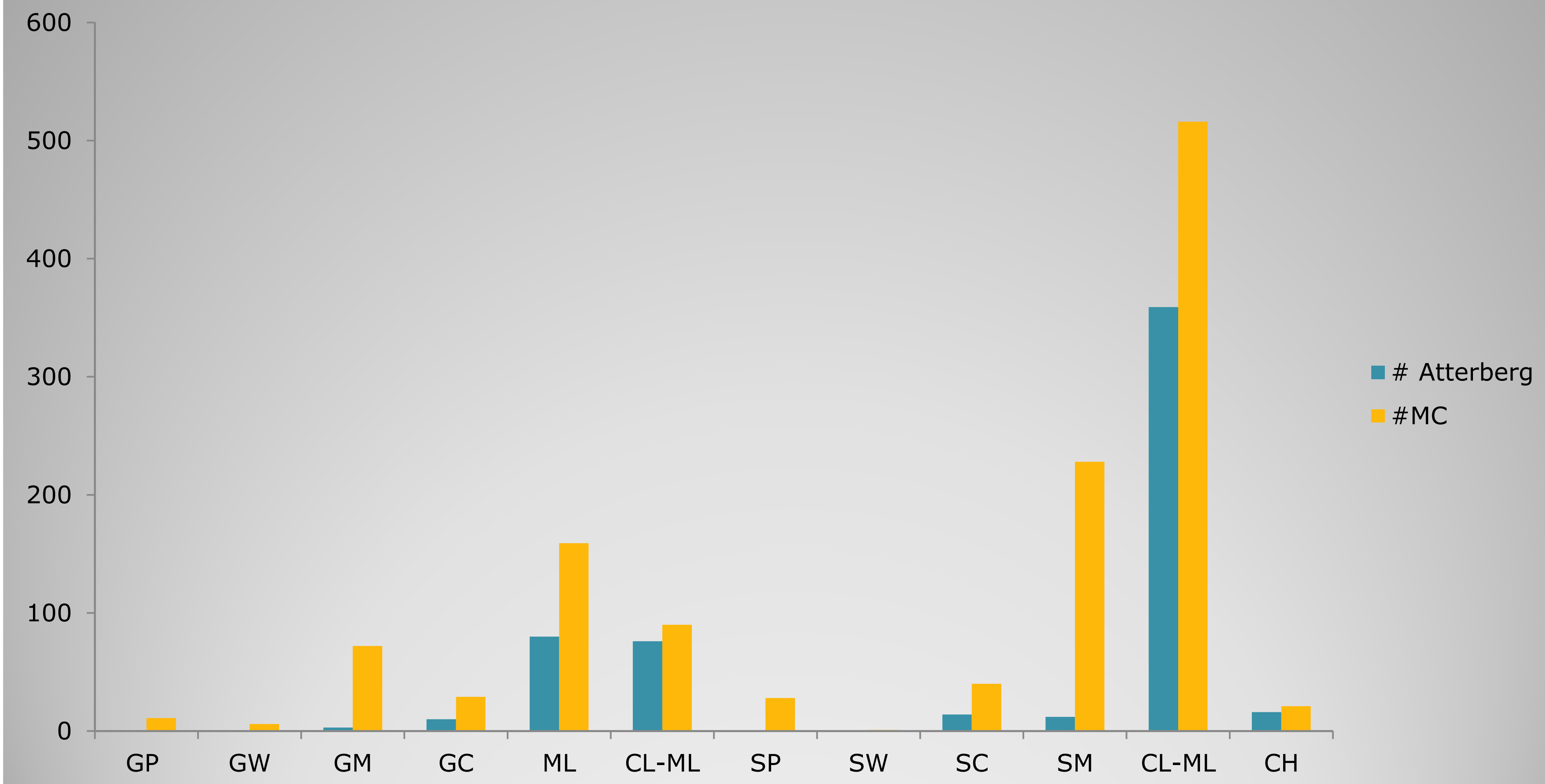
- Data collection
  - UDOT, UGS, City Governments, private companies
- Standard Penetration Testing (SPT)
  - 795 data points
- Cone Penetrometer Testing (CPT)
  - 39 data points

Subsurface Database

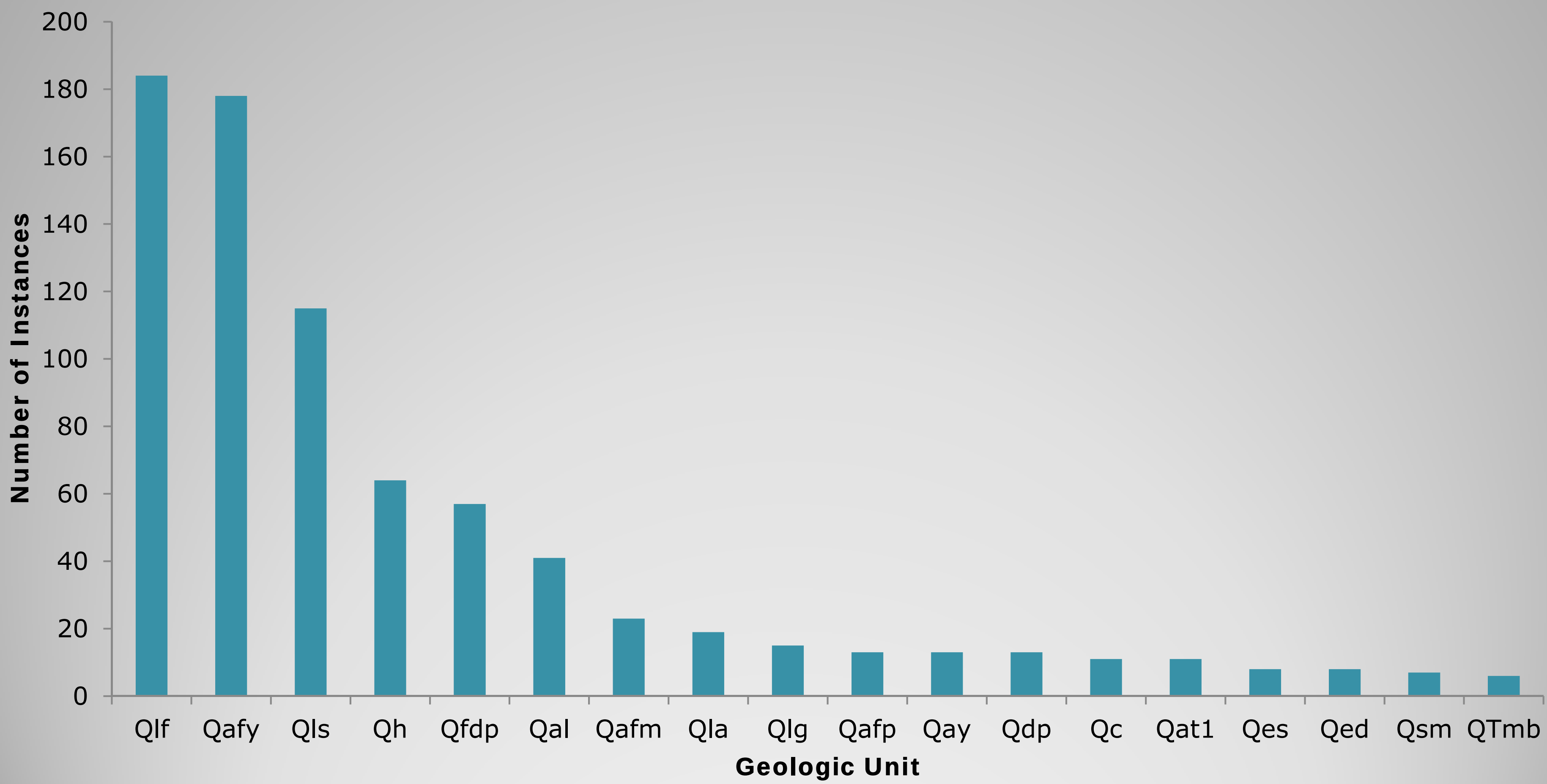


ID1	ID	SITEIDNO	BOREELEV	BORING	BoreDiam	BoreDiamEs	DATE_	DEPTHGW	DRILLER	DRILLMET
1	1	1	4566	1	3.9	1	9/22/1999	7.1	UDOT	RB
2	2	2	4545	2	3.9	1	9/24/1999	6.7	UDOT	RB
3	3	3	4580	3	3.9	1	10/8/1999	6.1	UDOT	RB
4	10	10	4588	1	4	1	1/14/2009	18.3	UDOT	RB
5	11	11	4589	2	4	1	1/29/2009	20	UDOT	RB
6	12	12	4497	1	3	1	10/19/1993	6.2	UDOT	RB
7	13	13	4500	3	3	1	10/30/1993	8.7	UDOT	RB
8	14	14	7200	2	4	1	10/30/2003	2.8	UDOT	RB
9	15	15	7193	4	4	1	11/14/2003	2.8	UDOT	RB
10	16	16	4817	1	3	1	5/2/1984	5.2	UDOT	RB
11	17	17	4809	2	3	1	5/7/1984	6.1	UDOT	RB
12	18	18	4781	TH-2	6	3	9/23/2002	16.5	Earthcore	Hollow Ste
13	19	19	4774	TH-3	6	3	9/23/2002	21	Earthcore	Hollow Ste
14	20	20	4766	TH-4	6	3	9/23/2002	16.5	Earthcore	Hollow Ste
15	21	21	4958	TH-1	6	3	12/6/2004	10.5	Earthtech	Hollow Ste
16	22	22	4959	TH-2	6	3	12/6/2004	16.5	Earthtech	Hollow Ste
17	23	23	4958	TH-3	6	3	12/6/2004	6	Earthtech	Hollow Ste
18	24	24	4970	TH-4	6	3	12/6/2004	8.5	Earthtech	Hollow Ste
19	25	25	4979	TH-5	6	3	12/6/2004	20	Earthtech	Hollow Ste
20	26	26	4976	TH-6	6	3	12/6/2004	12.3	Earthtech	Hollow Ste
21	27	27	4981	TH-7	6	3	12/6/2004	12	Earthtech	Hollow Ste
22	28	28	4991	TH-8	6	3	12/6/2004	16.5	Earthtech	Hollow Ste
23	29	29	4979	TH-9	6	3	12/6/2004	21.5	Earthtech	Hollow Ste
24	30	30	4520	TH-1	6	3	2/1/2005	3.5	Racon	Hollow Ste
25	31	31	4519	TH-2	6	3	2/1/2005	5.3	Racon	Hollow Ste
26	32	32	4518	TH-3	6	3	2/1/2005	5.6	Racon	Hollow Ste
27	33	33	4516	TH-4	6	3	2/1/2005	4	Racon	Hollow Ste
28	34	34	4516	TH-5	6	3	2/1/2005	3.3	Racon	Hollow Ste
29	35	35	4518	TH-6	6	3	2/1/2005	4.5	Racon	Hollow Ste
30	36	36	4520	TH-8	6	3	2/1/2005	3.8	Racon	Hollow Ste
31	37	37	4821	TH-1	6	3	1/7/2008	16.5	Racon	Hollow Ste

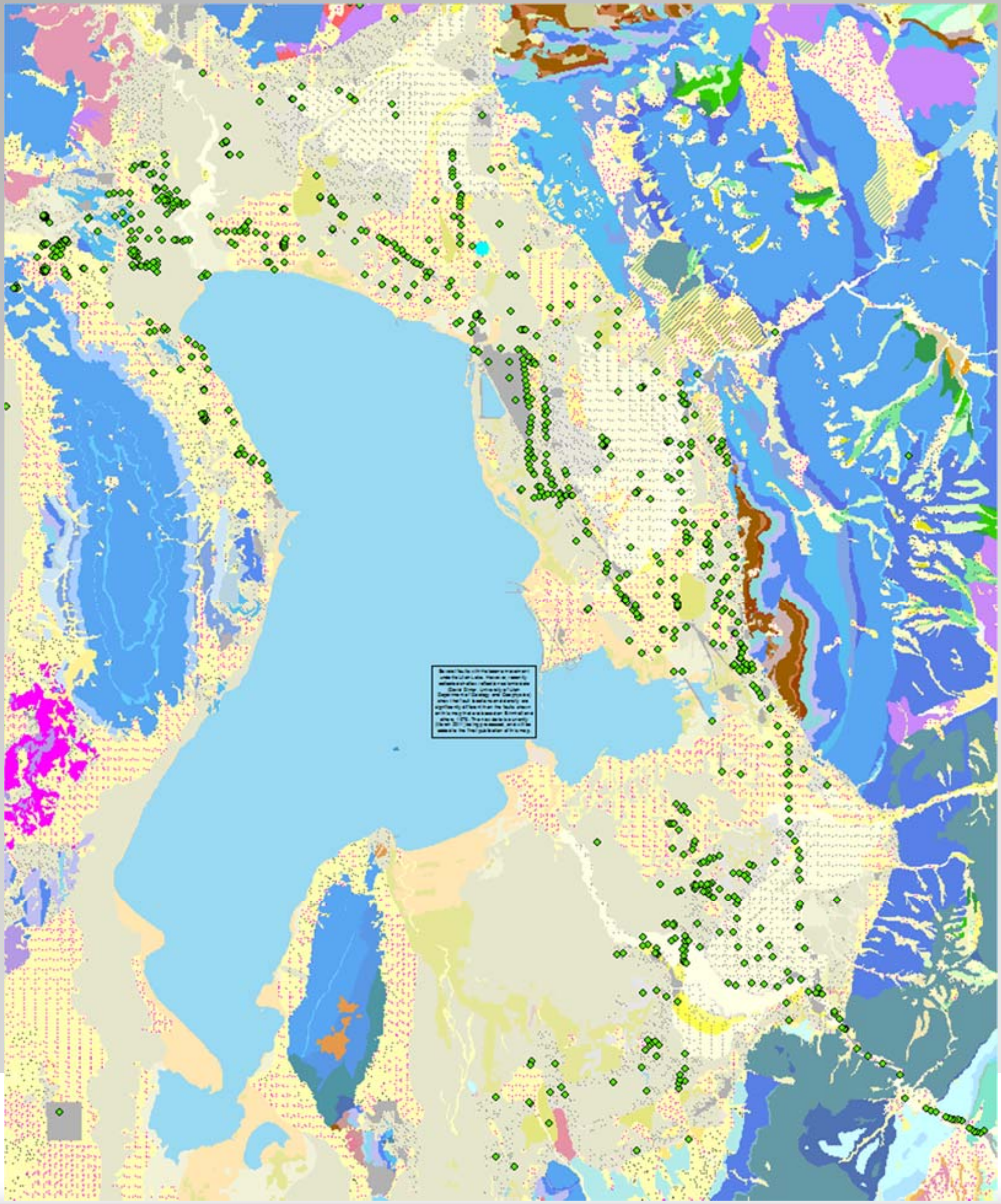
Subsurface Database



Subsurface database



Subsurface Database



- 834 total points

Mapping

- Types of maps
  - Liquefaction Triggering Maps
  - Lateral Spread Displacement Hazard Maps
    - Thresholds at 1 cm, 3 cm, and 10 cm

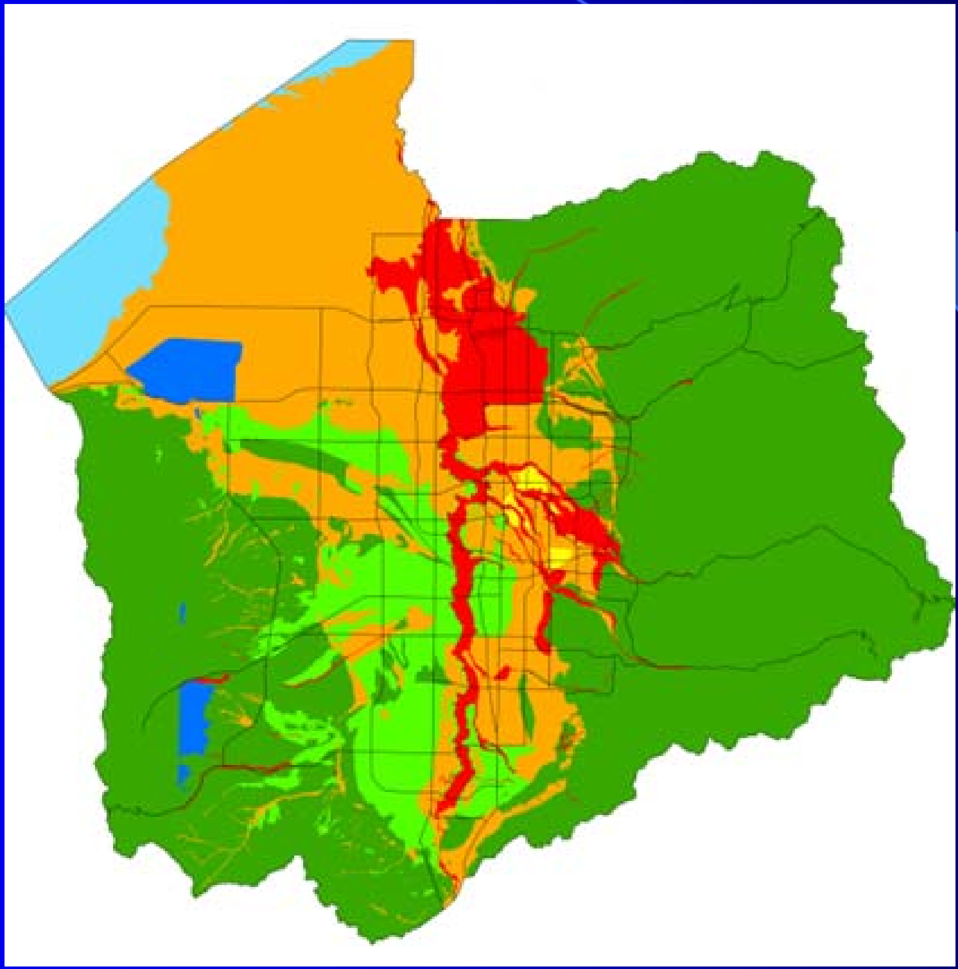
Mapping

- Boulanger and Idriss (2012) liquefaction triggering models
- Aerial lidar data for lateral spread mapping, better topographic models
- Performance-based approach

Timeline

- Subsurface database completed December 2014
- Liquefaction and Lateral Spread maps by July 2015

Liquefaction Hazards – From Mapping to Implementation



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David Simon, SBI

Grant Gummow, UDOT

Jim Higbee, UDOT

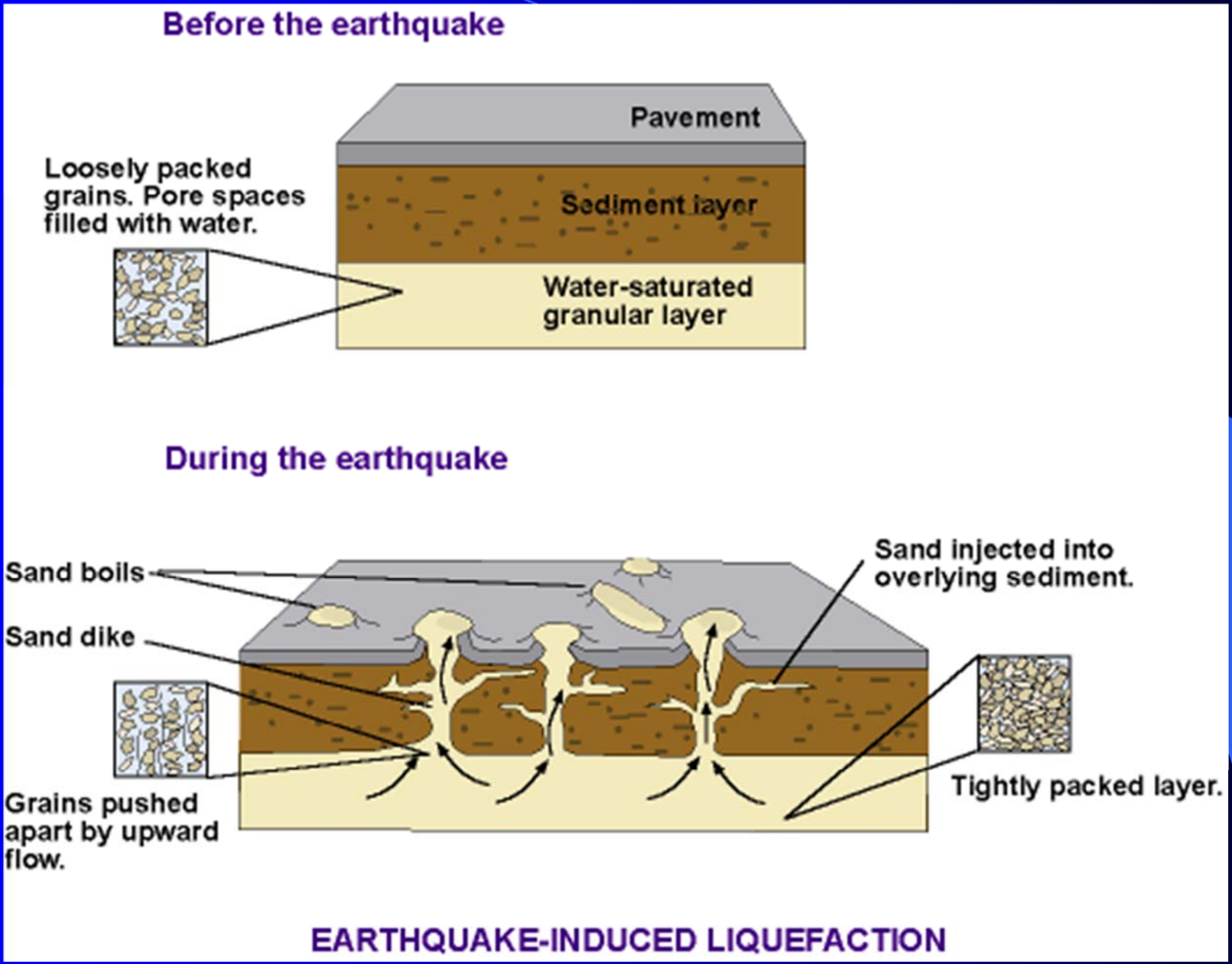
Bill Turner, Earthtec

Ryan Cole, Gerhart-Cole

Topics

- Liquefaction Damage
- Types of Liquefaction Maps
- Estimation of Frequency
- Estimation of Liquefaction Potential
- Estimation of Ground Displacement
- Estimation of Settlement
- Performance-Based Hazard Ordinances

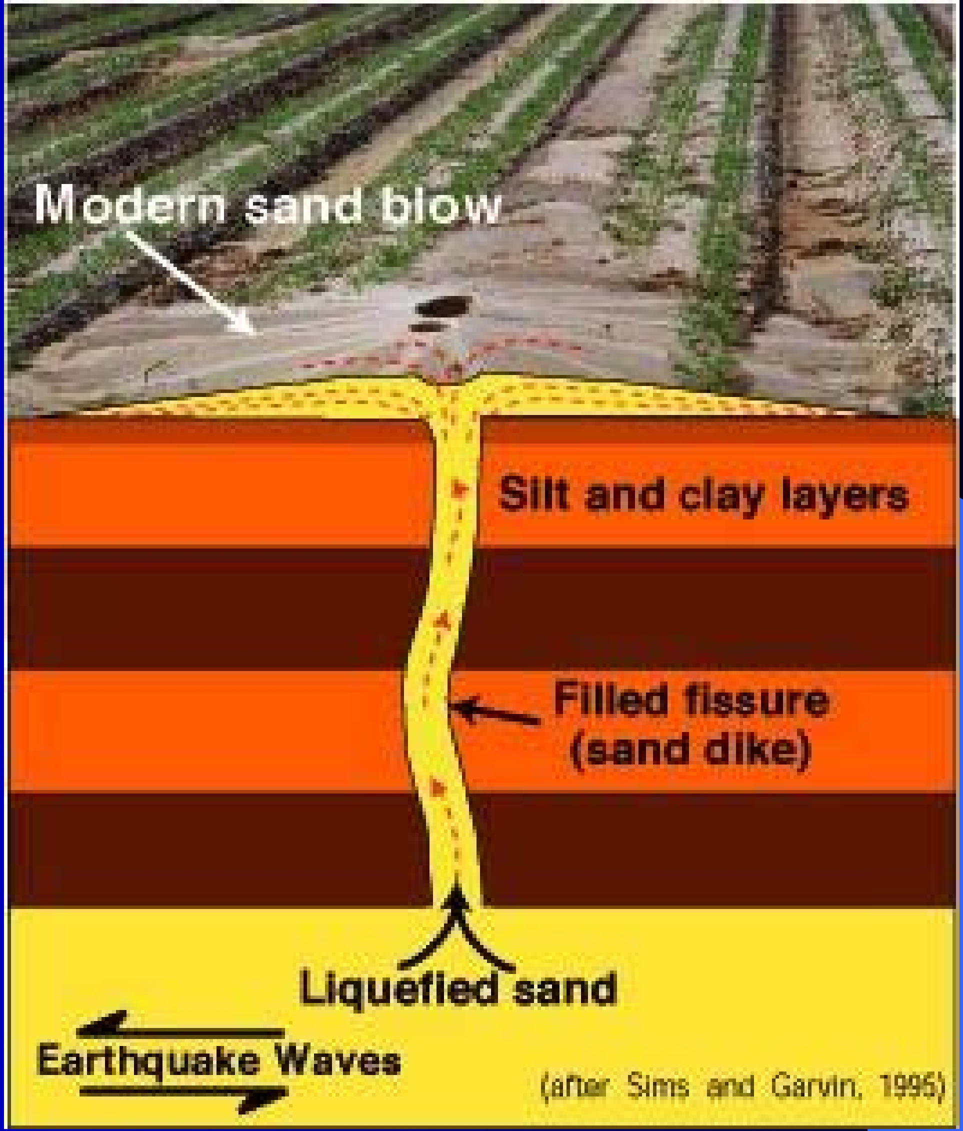
Liquefaction



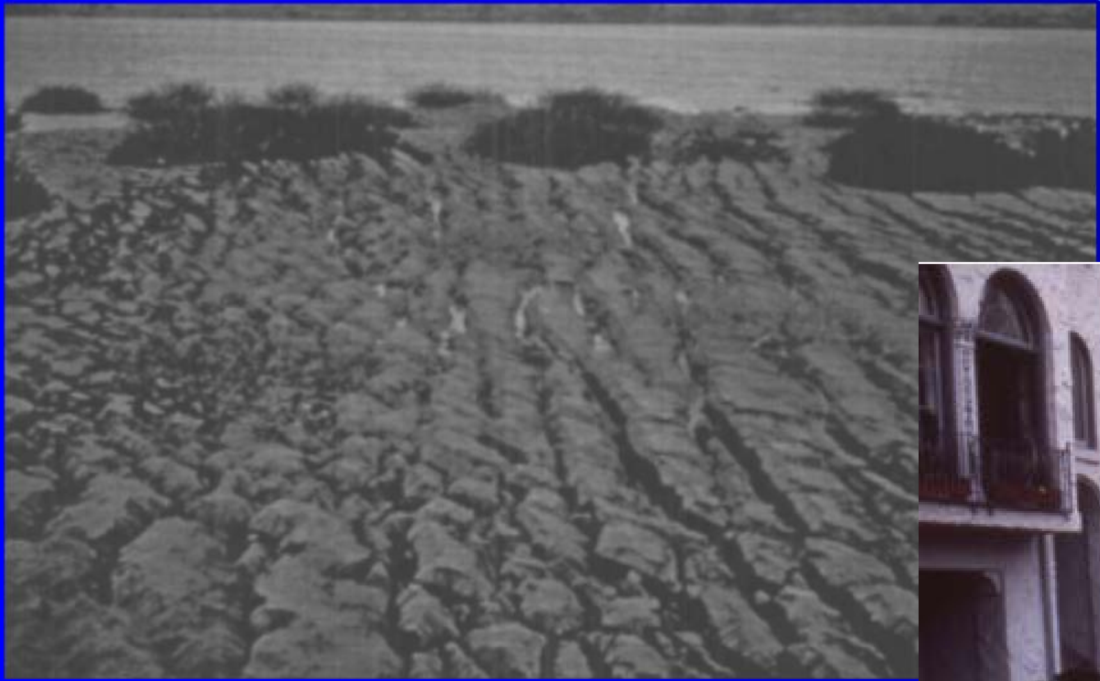
What is liquefaction?

Types of Liquefaction Damage

Sand Blow or Sand Volcano



Types of Liquefaction Damage



Ground Oscillation

Marina District, San Francisco,
1989 Loma Prieta Earthquake

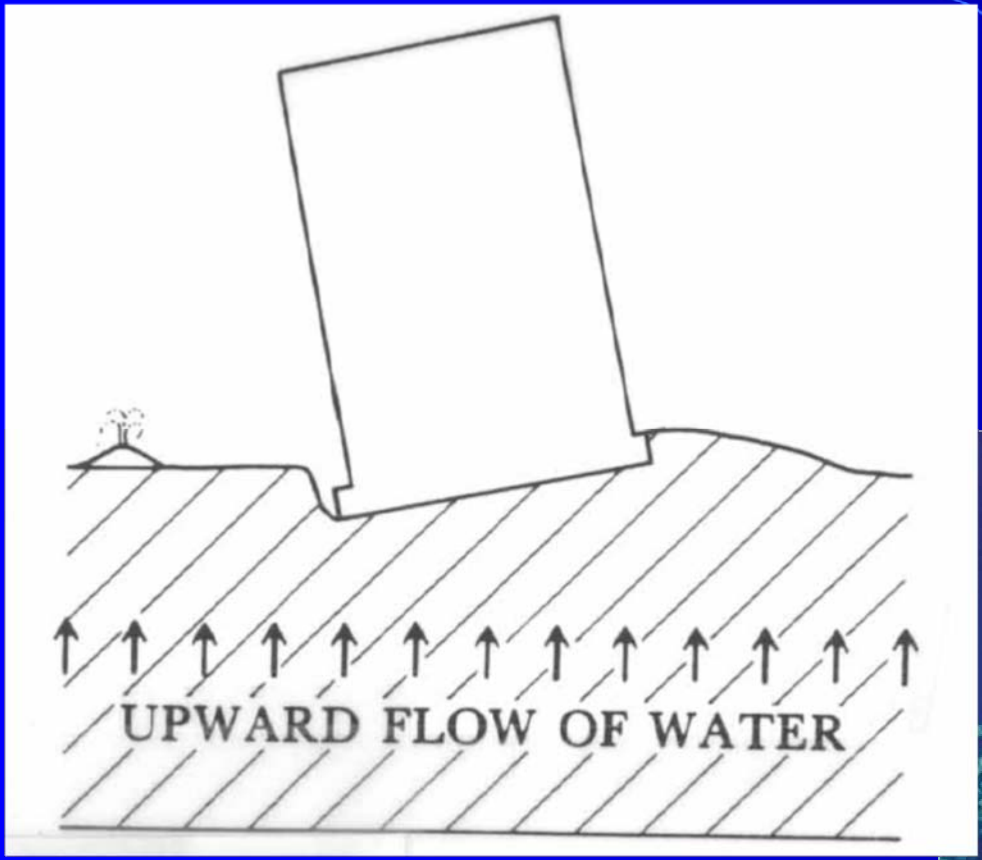
Types of Liquefaction Damage

2011 Tohoku Earthquake

Ground Settlement

2010 Christchurch Earthquake

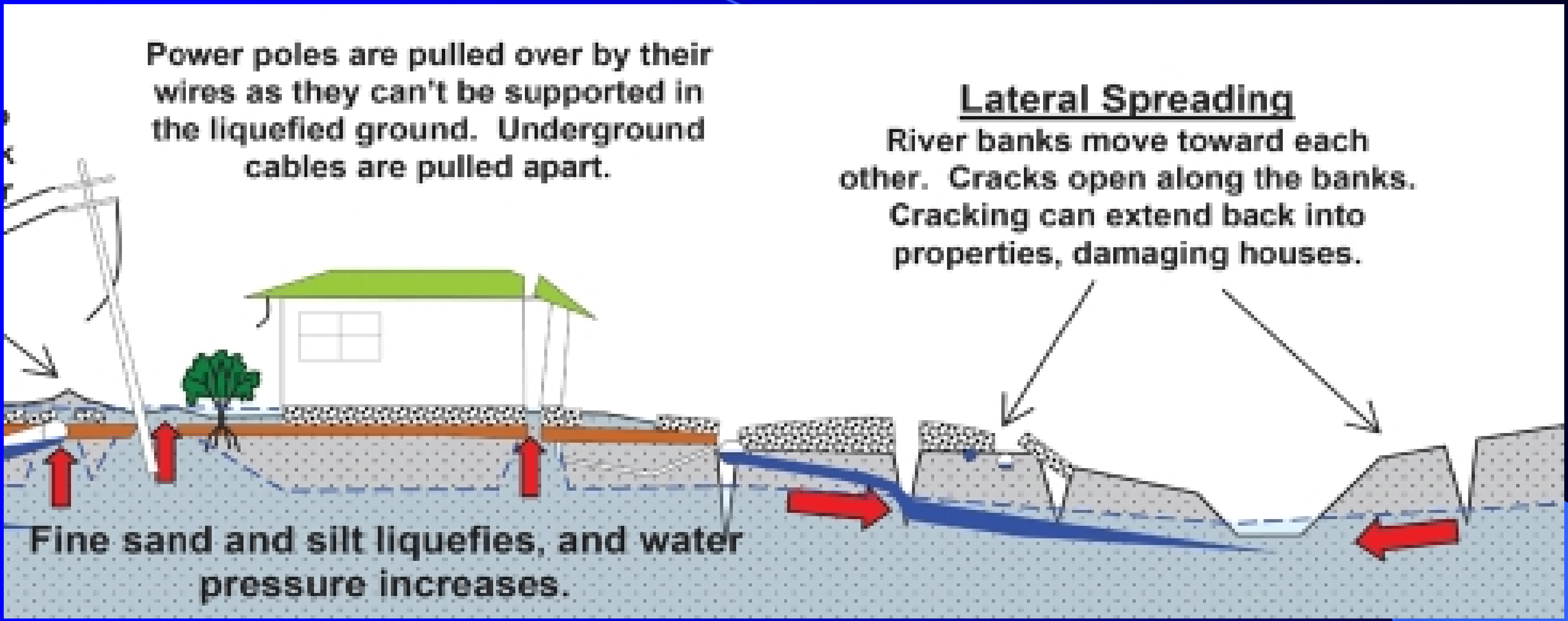
Types of Liquefaction Damage



Bearing Capacity Failure

1964 Niigata, Japan Earthquake

Types of Liquefaction Damage

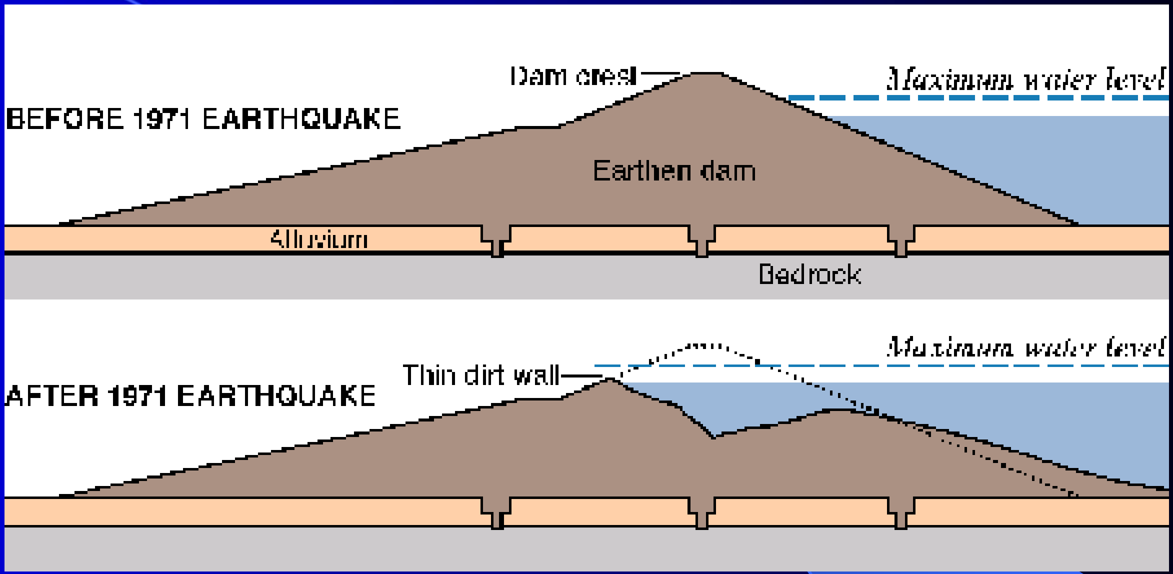


Lateral Spread

1964 Niigata, Japan Earthquake

Types of Liquefaction Damage

Flow Failure



Lower San Fernando Dam
1971 San Fernando
Earthquake

Valdez, 1964 Alaska
Earthquake

Topics

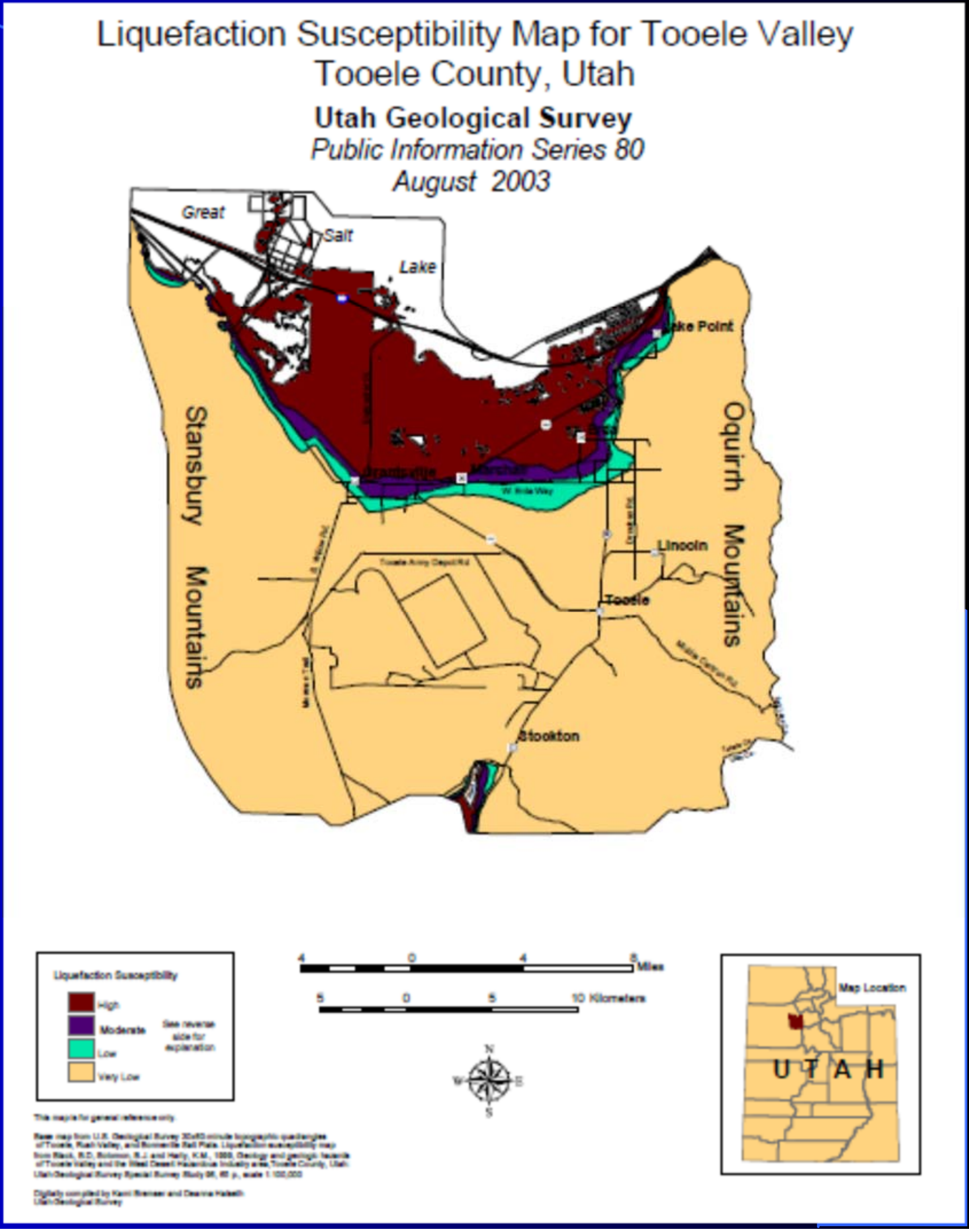
- Liquefaction Damage
- **Types of Liquefaction Maps**
- Estimation of Frequency
- Estimation of Liquefaction Potential
- Estimation of Ground Displacement
- Estimation of Settlement
- Performance-Based Hazard Ordinances

Types of Liquefaction Maps

- Liquefaction Susceptibility Maps
- Liquefaction Potential Maps
  - Scenario Maps
  - Probabilistic-Based Maps
- Ground Failure Maps
  - Lateral Spread
  - Ground Settlement

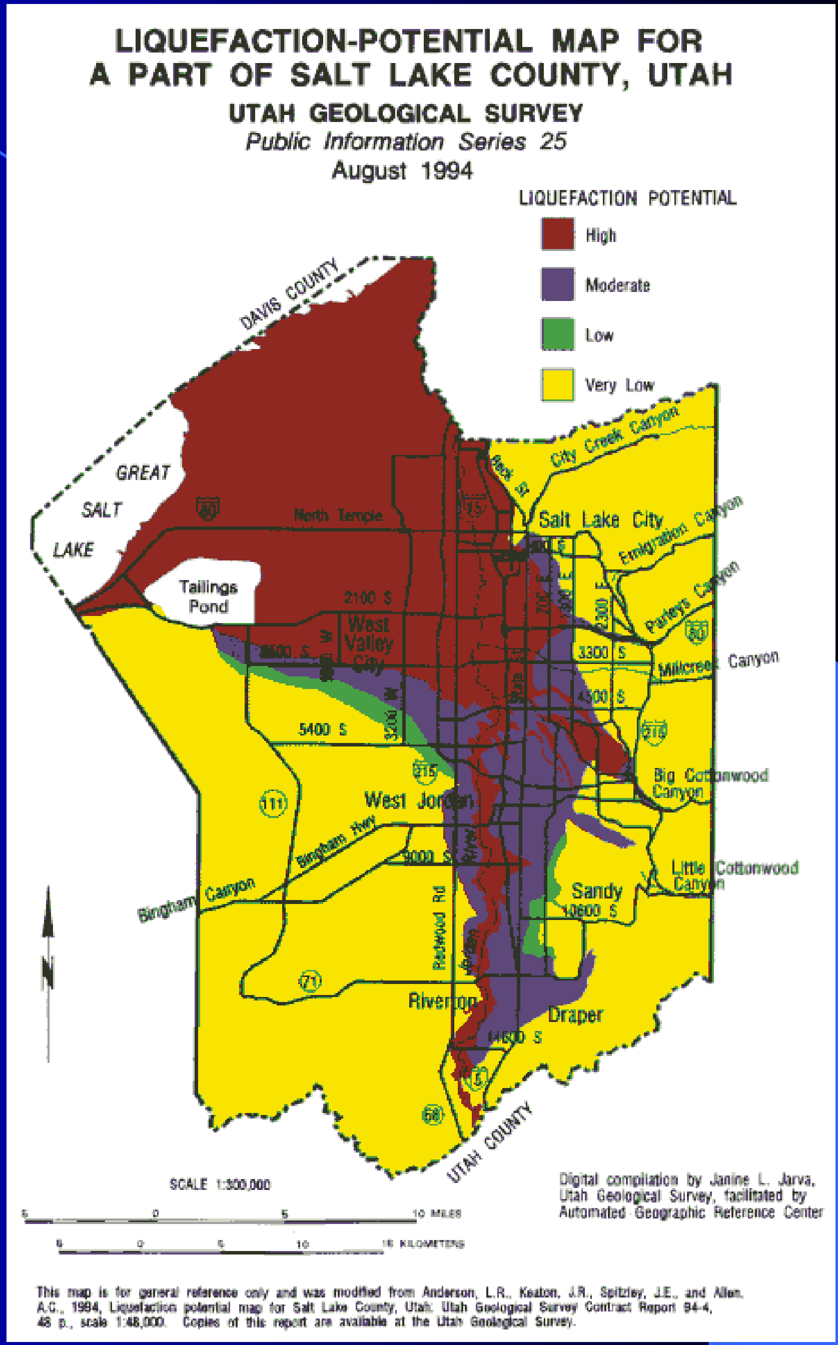
Types of Liquefaction Maps

- Liquefaction Susceptibility Maps
  - Show liquefaction hazard based on susceptibility (soil capacity), but do not consider demand (size of amplitude of strong ground motion)



Types of Liquefaction Maps

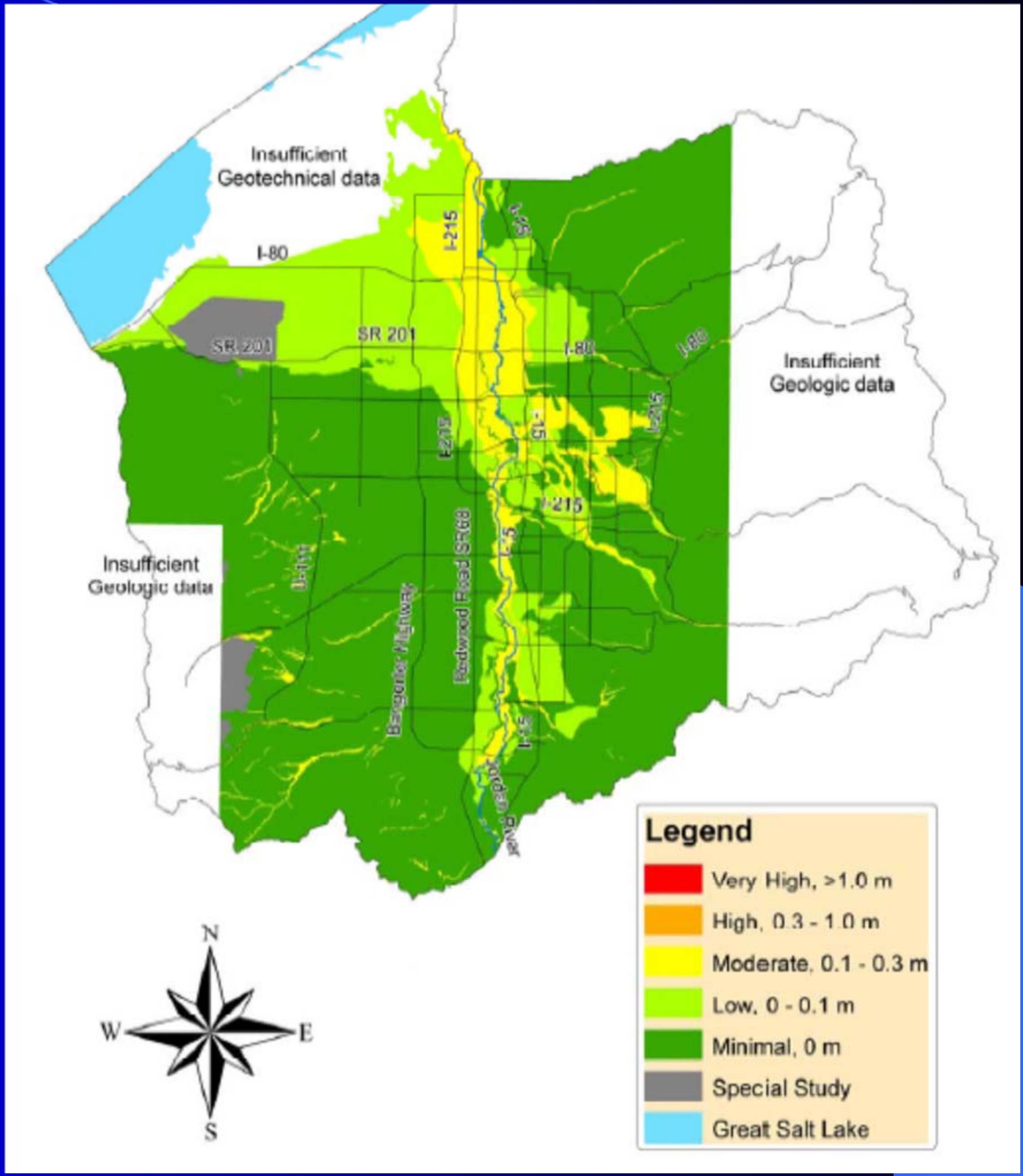
- Liquefaction Potential Maps
  - Combine liquefaction susceptibility (capacity) with seismic input (demand).
  - Demand can be expressed as a deterministic scenario event or a probabilistic-based estimate obtained from the national seismic hazard maps



Liquefaction potential for approximate 0.2g pga (Anderson and Keaton)

Types of Liquefaction Maps

- Ground Failure Maps
  - Consider liquefaction potential
  - Consider consequences of liquefaction (i.e., displacement)
    - Median probabilities of lateral spread displacement for 2,500-year return period seismic event



Types of Liquefaction Maps
(ULAG Maps funded by NEHRP)

- Liquefaction Potential and Ground Displacement Maps
- Seismic Strong Motion (SM) Inputs for Liquefaction Potential Maps
    - M7.0 Earthquake
    - SM with 10% probability of exceedance in 50 years
    - SM with 2% probability of exceedance in 50 years
- Lateral Spread maps (using above scenarios)
- Ground settlement maps (using above scenarios)
- Fully aggregated liquefaction map with PSHA input
    - – (see next two slides)

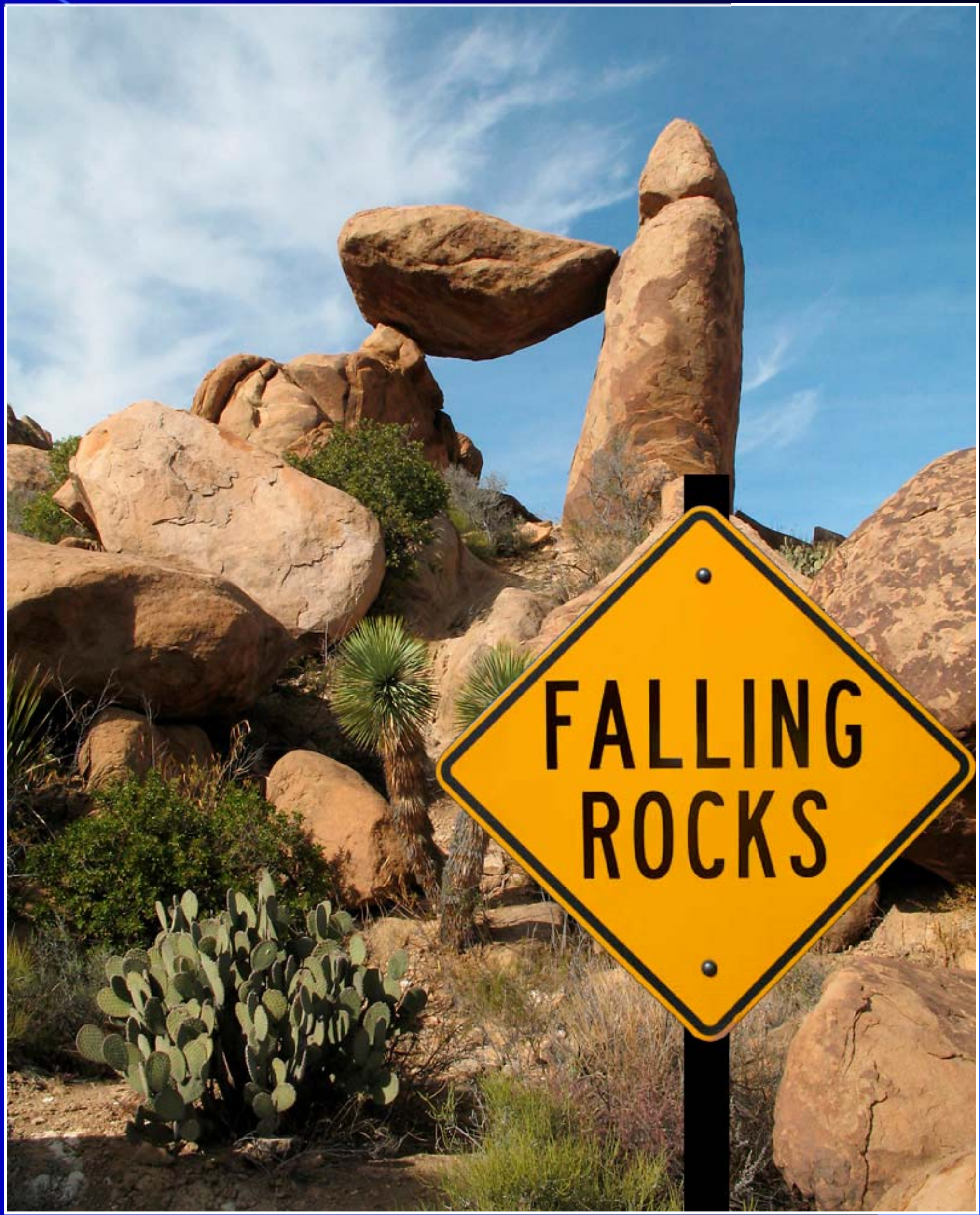
Topics

- Liquefaction Damage
- Types of Liquefaction Maps
- **Estimation of Frequency**
- Estimation of Liquefaction Potential
- Estimation of Ground Displacement
- Estimation of Settlement
- Performance-Based Hazard Ordinances

Estimation of Frequency

How often do bad things happen?

Average return period of event (yrs.)?



Estimation of Frequency

Relative Frequency	Frequent	Moderately Frequent	Infrequent	Rare
Frequency of Event[1]	0 to 500 yrs.	500 to 1000 yrs.	1000 to 2500 yrs.	> 2500 yrs.

1 Frequency of event means that the average return period occurs within that time range. For example if a frequency range is between 0 to 500 years, this implies that the event has an average repeat time that falls between 0 and 500 years. The frequency of the event must be established by geological/geotechnical evaluations.

Topics

- Liquefaction Damage
- Types of Liquefaction Maps
- Estimation of Frequency
- **Estimation of Liquefaction Potential**
- Estimation of Ground Displacement
- Estimation of Settlement
- Performance-Based Hazard Ordinances

Estimation of Frequency Liquefaction Potential

$$P(L) = \sum P[L \mid A,M] \; P[A, M]$$

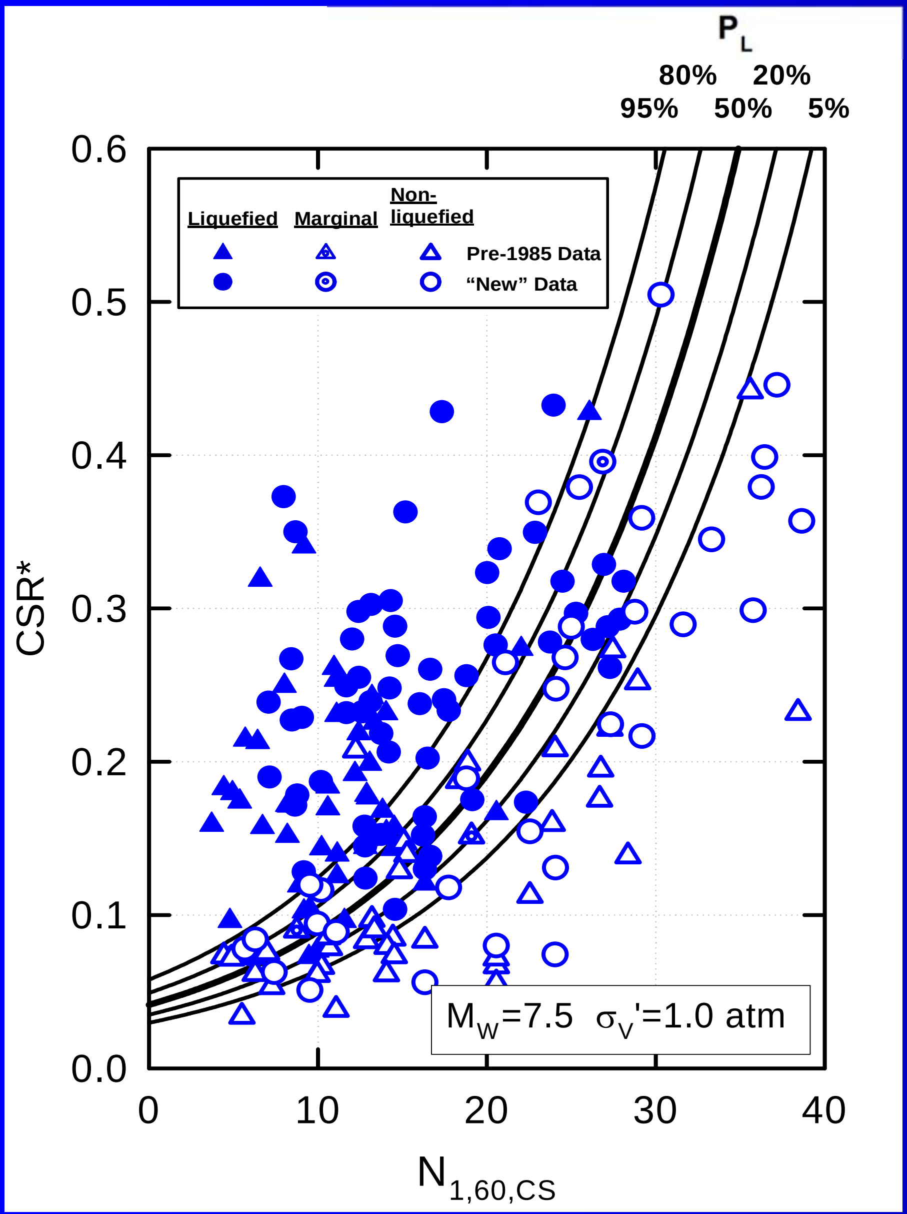
where:

P(L) = annual probability of liquefaction

P [L | A,M] = conditional probability of liquefaction given the peak ground acceleration and the earthquake magnitude,

P [A, M] = joint probability density function of peak ground acceleration and earthquake magnitude.

Estimation of Frequency Liquefaction Potential



Recommended "Probabilistic" SPT-Based Liquefaction Triggering Correlation

(For MW=7.5 and σv'=1.0 atm)

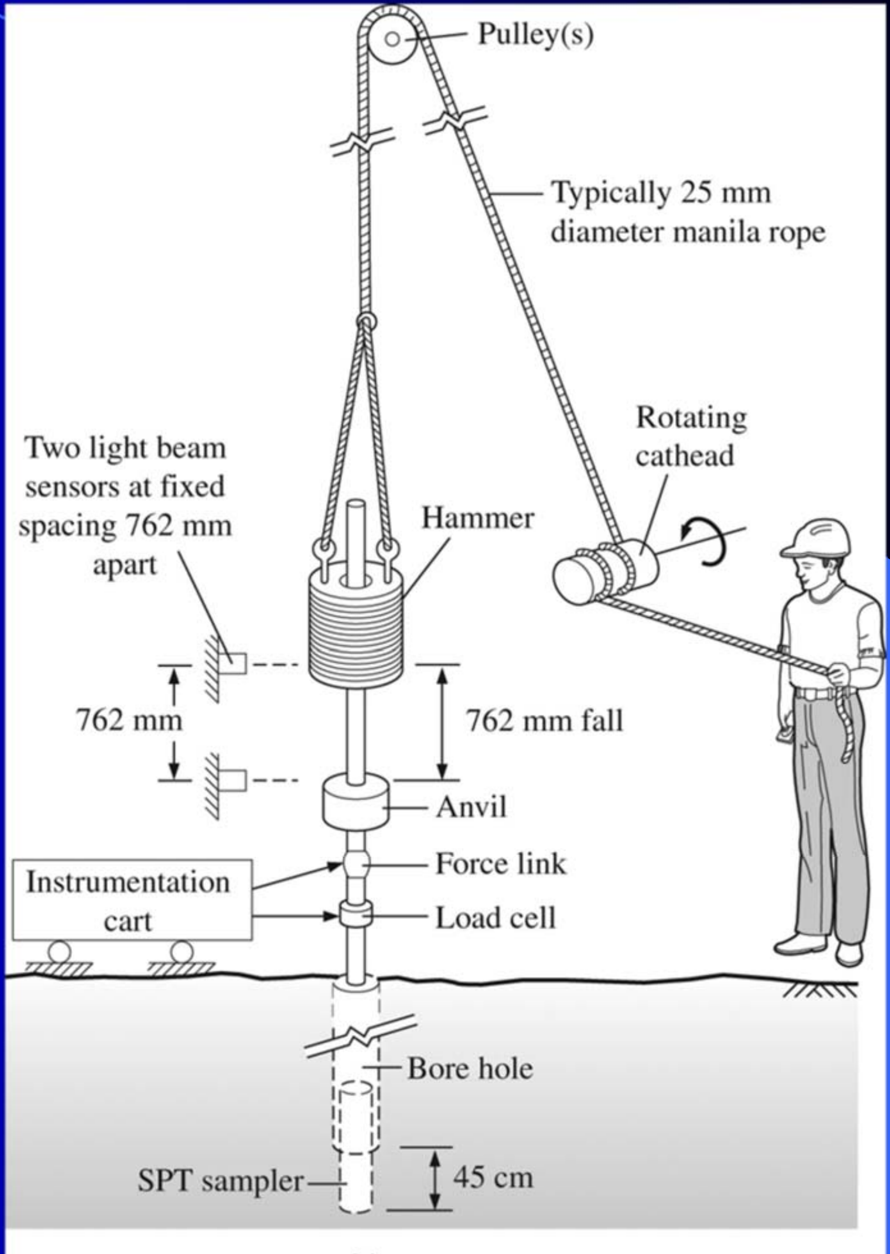
(Seed et al. 2003)

Estimation of Frequency Liquefaction Potential

- Subsurface data collection
  - Standard Penetration Testing (SPT)
  - Cone Penetrometer Testing (CPT)

Estimation of Frequency Liquefaction Potential

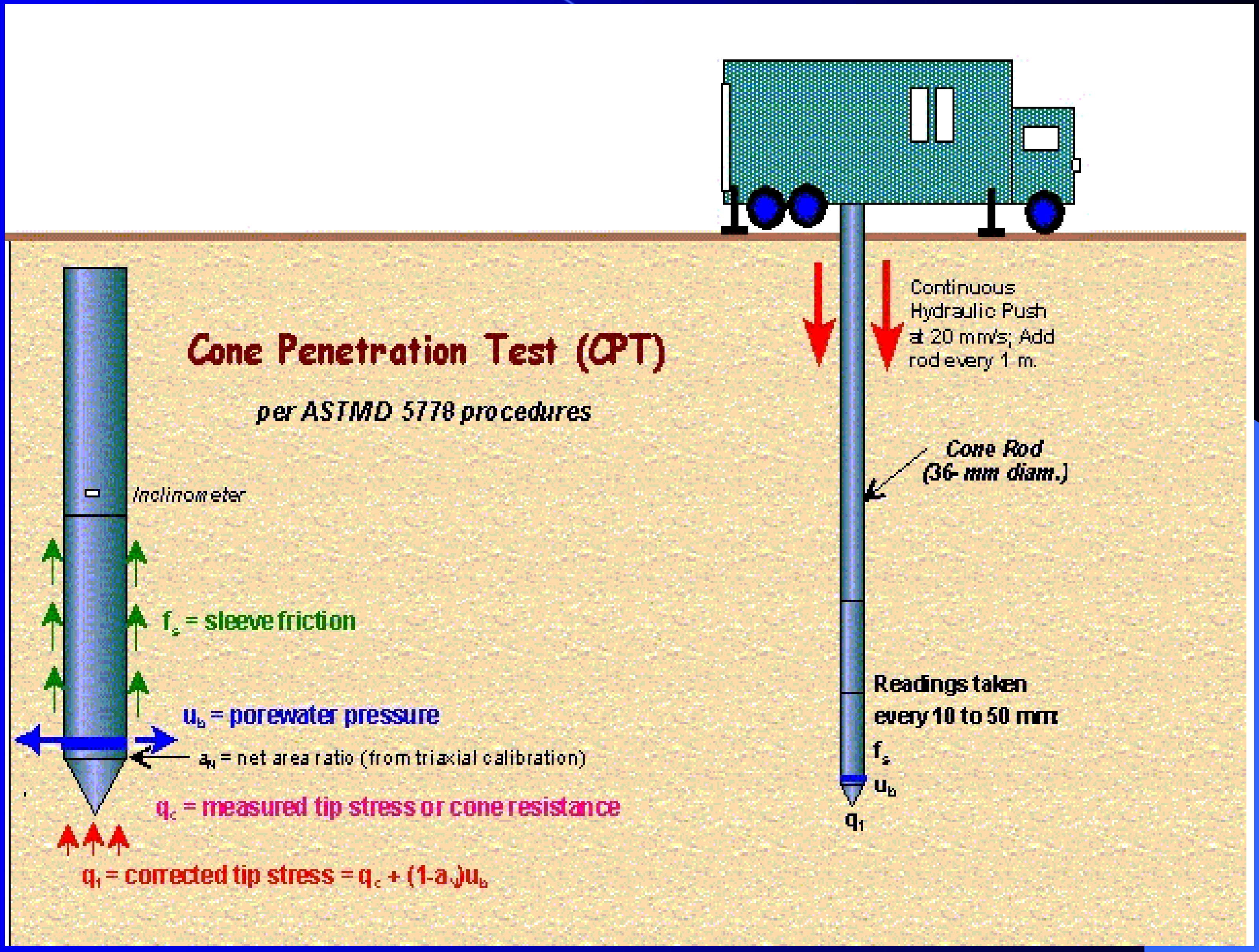
- Subsurface data collection
  - Standard Penetration Testing (SPT)



(a)

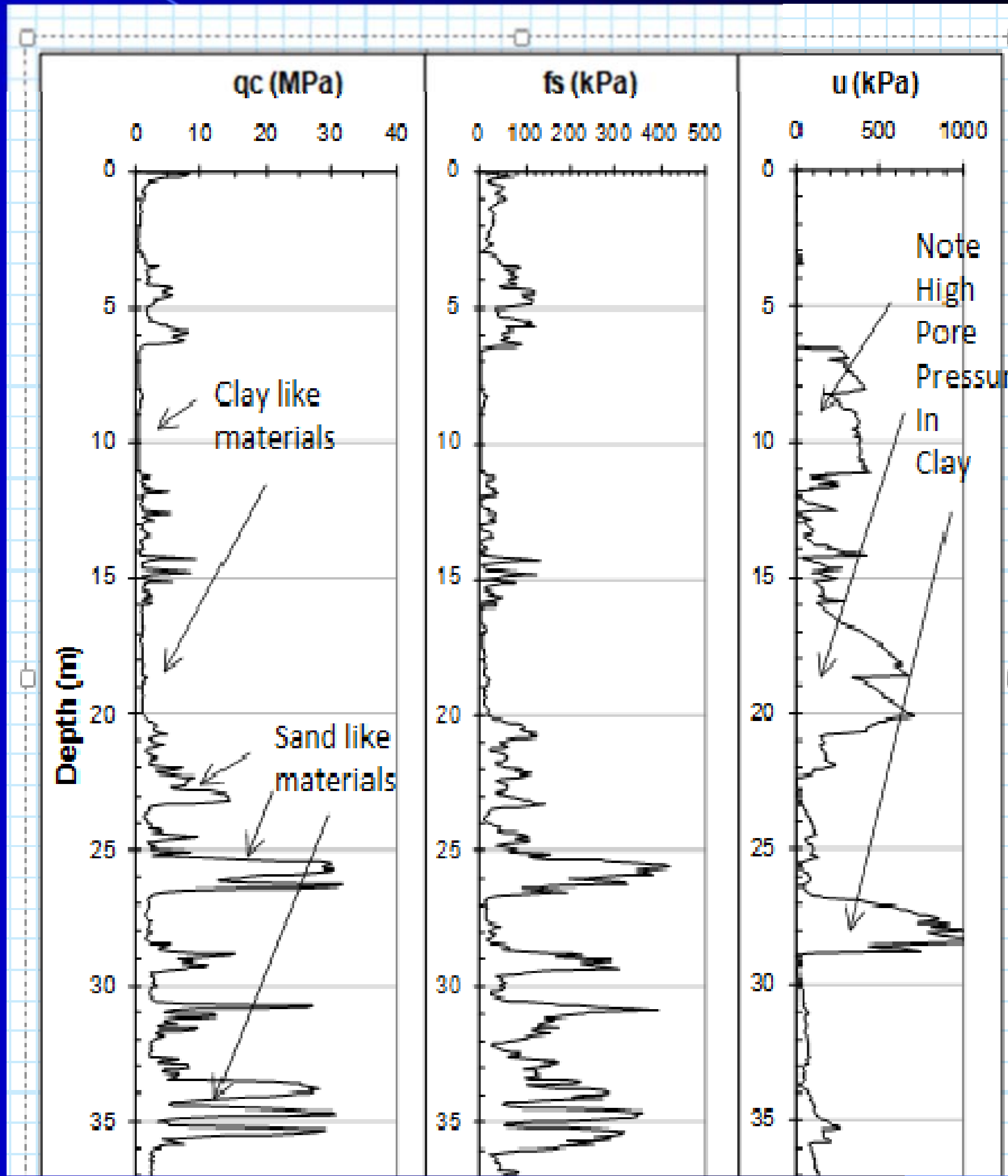
Estimation of Frequency Liquefaction Potential

- Subsurface data collection
  - Cone Penetro-meter Testing (CPT)

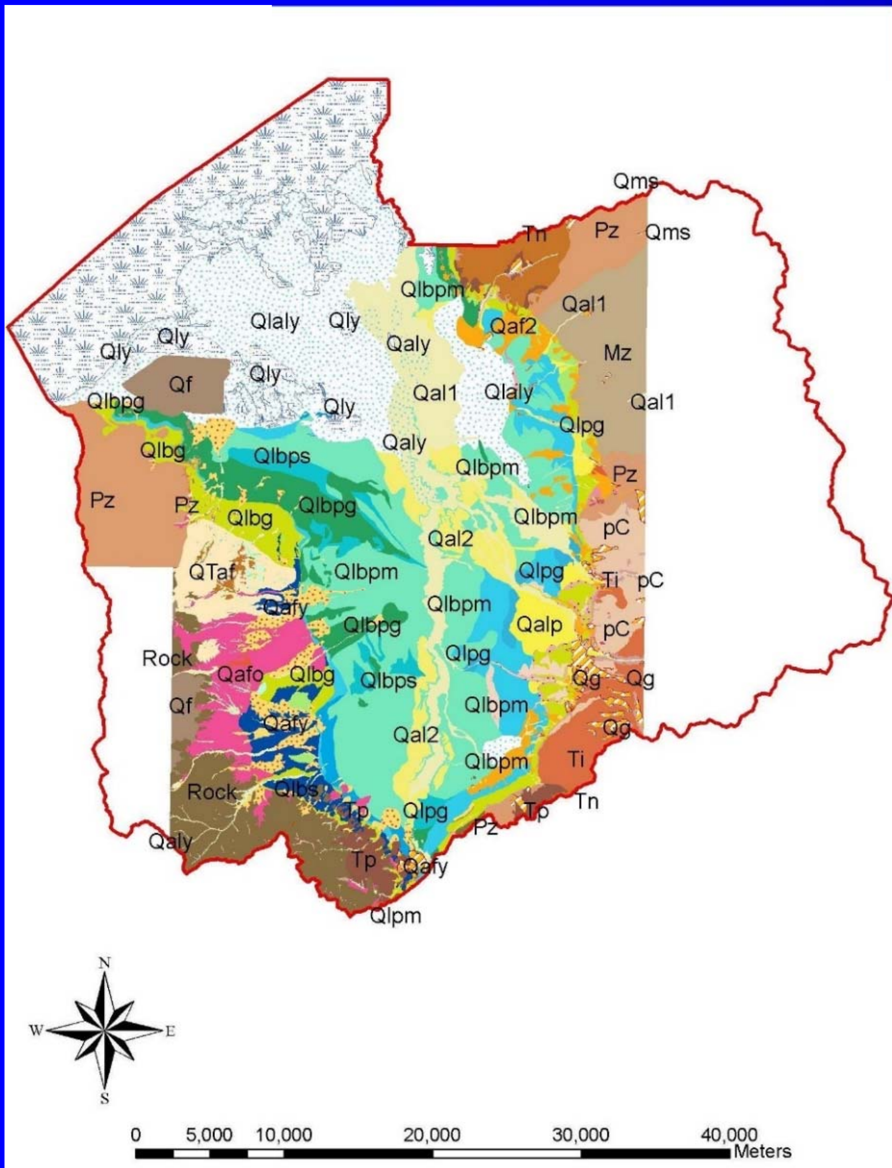


Estimation of Frequency Liquefaction Potential

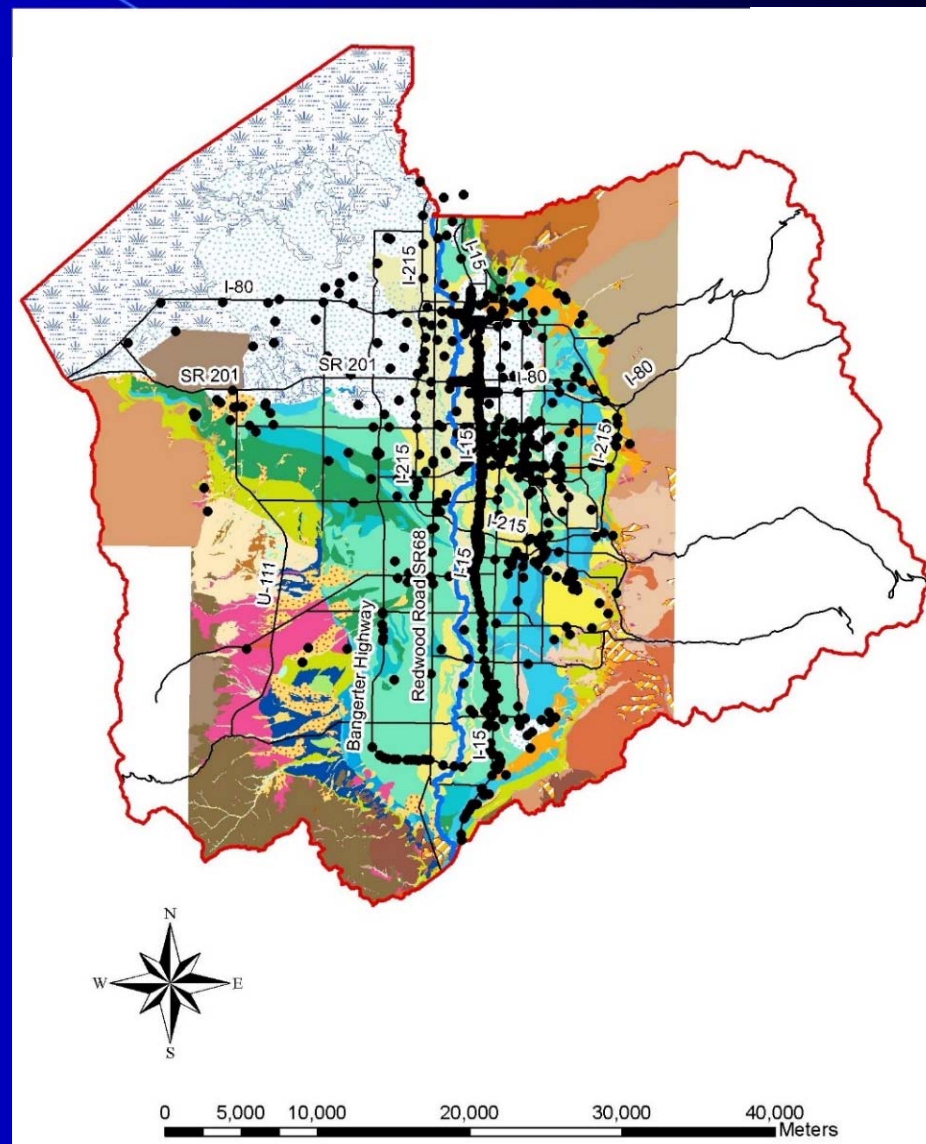
- Subsurface data collection
  - Cone Penetrometer Testing (CPT)



Estimation of Frequency Liquefaction Potential

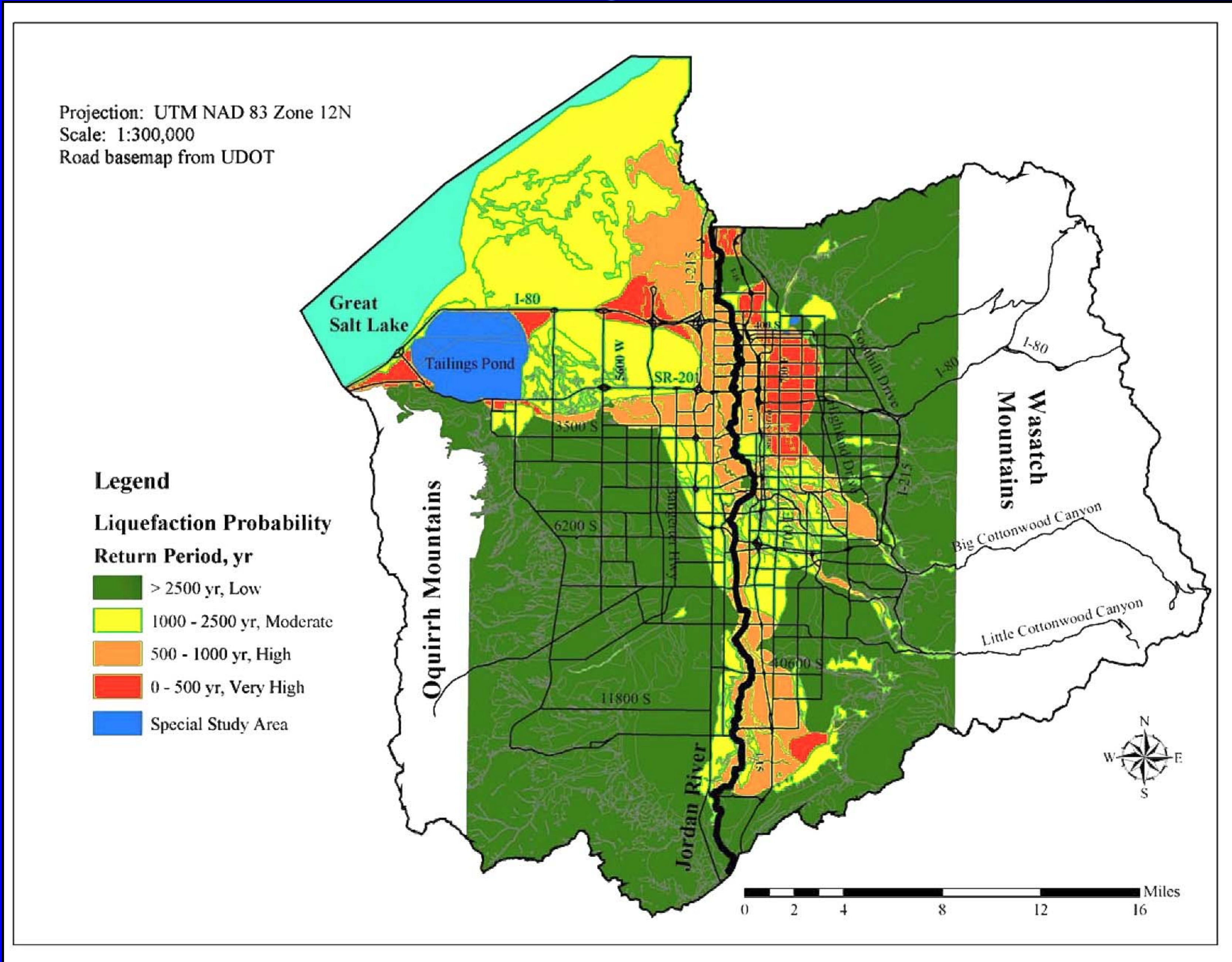


Geology Map

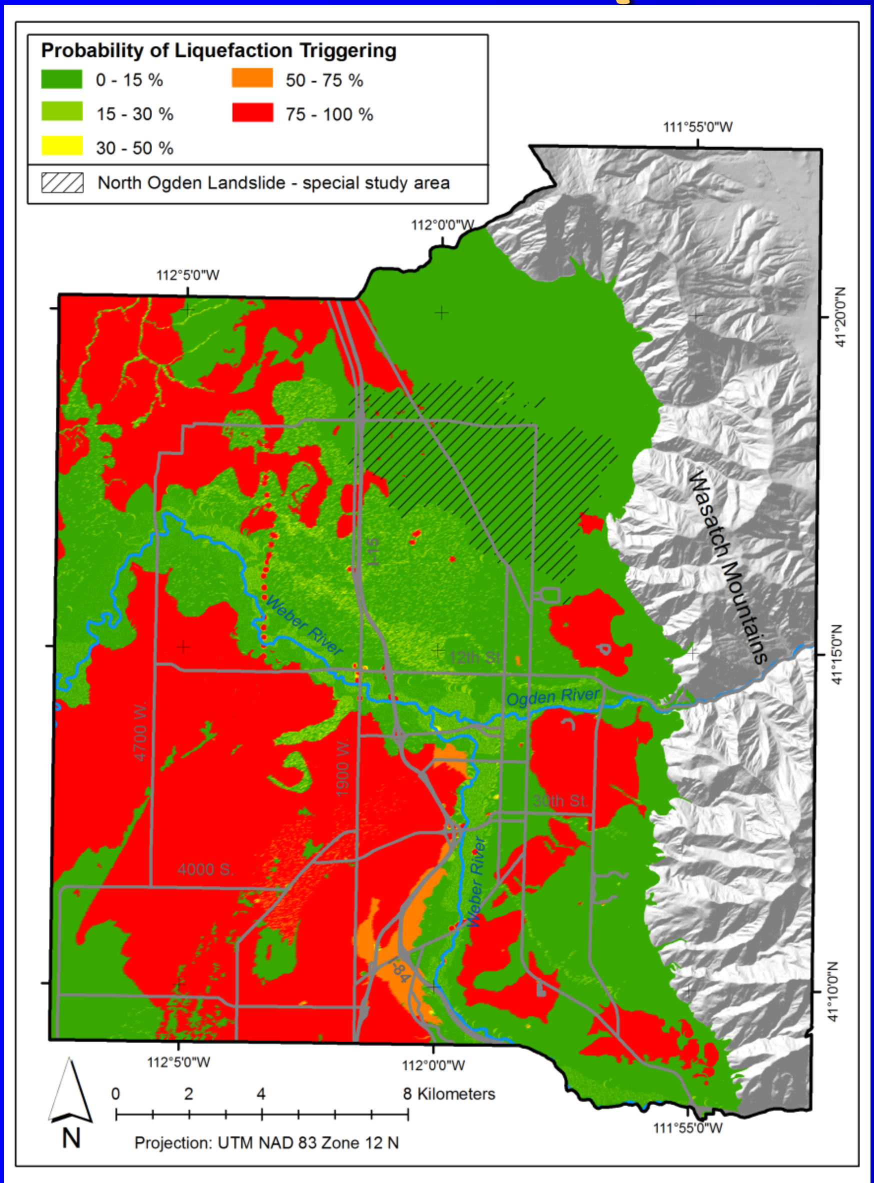


Borehole Map

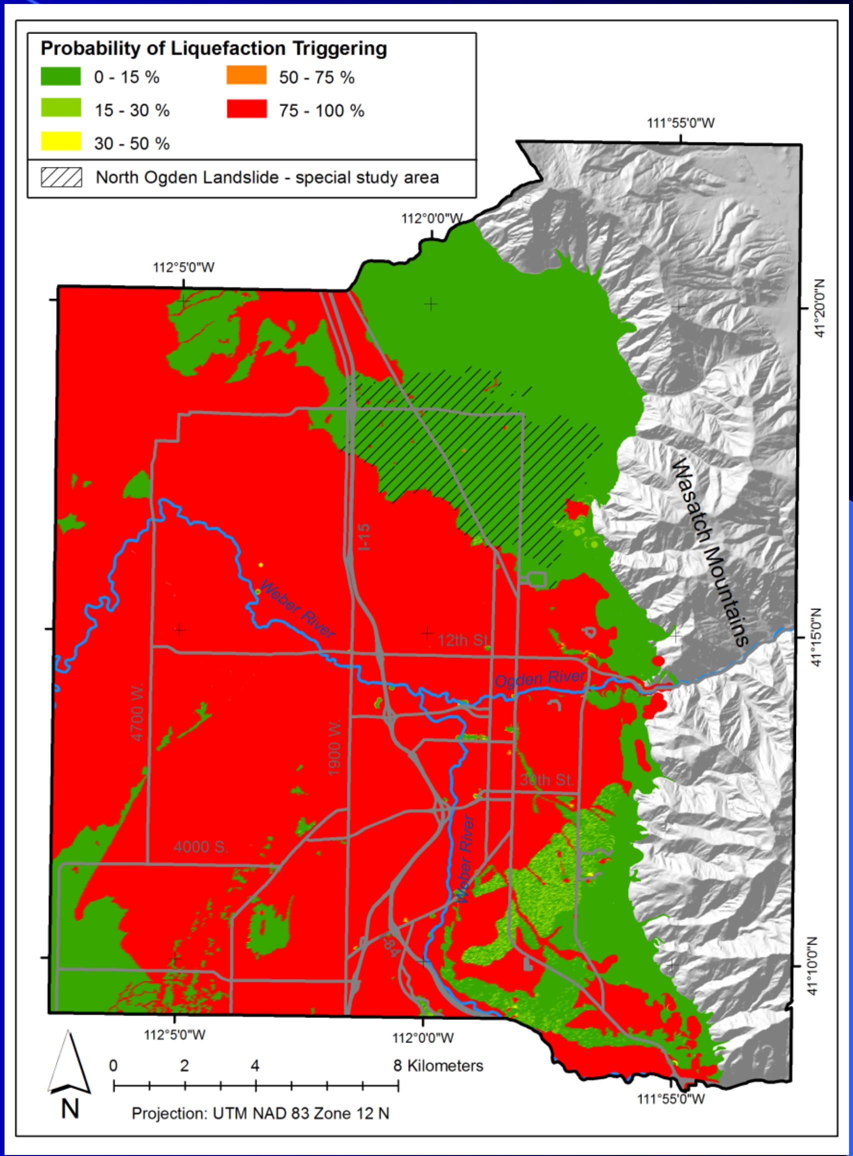
Estimation of Frequency (Liquefaction Return Period)



Liquefaction Potential Maps (Weber County)



Median probabilities of P_L, 500-year seismic event



Median probabilities of P_L, 2,500-year seismic event

Topics

- Liquefaction Damage
- Types of Liquefaction Maps
- Estimation of Frequency
- Estimation of Liquefaction Potential
- **Estimation of Ground Displacement**
- Estimation of Settlement
- Performance-Based Hazard Ordinances

Estimation of Ground Displacement

- $P(DH > x) = \Sigma\, P[\,(DH > x) \mid L]\; P[\,L \mid A, M, R\,]\; P[A, M, R]$

  Where:

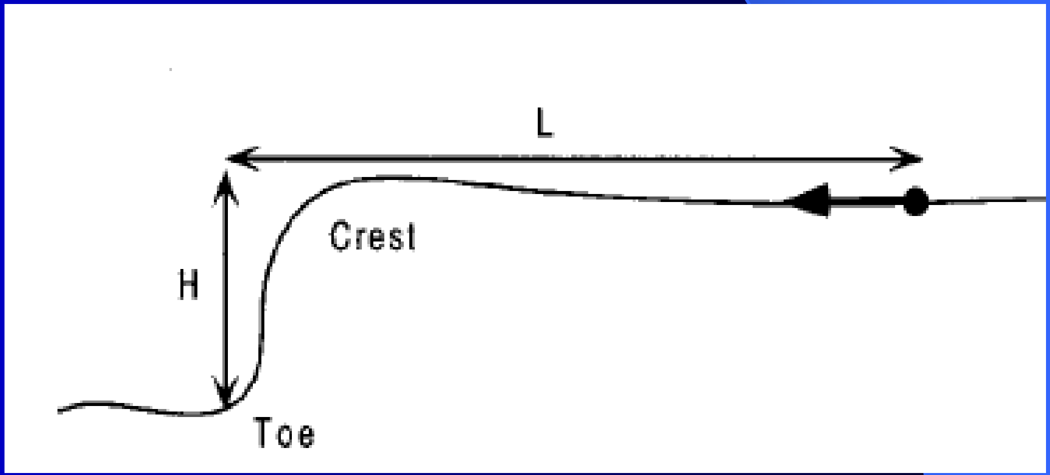
  - P(DH>x) = The probability of lateral spread exceeding a threshold value (e.g., x= 0.1 m and 0.3 m)
  - P[L| A,M,R] = the probability of liquefaction given an acceleration, magnitude, and source distance.
  - P[A,M,R] = joint probability density function of peak ground acceleration, magnitude and source distance.

Estimation of Ground Displacement (Salt Lake Valley)

Youd, Hansen, Bartlett (2002) Empirical Model

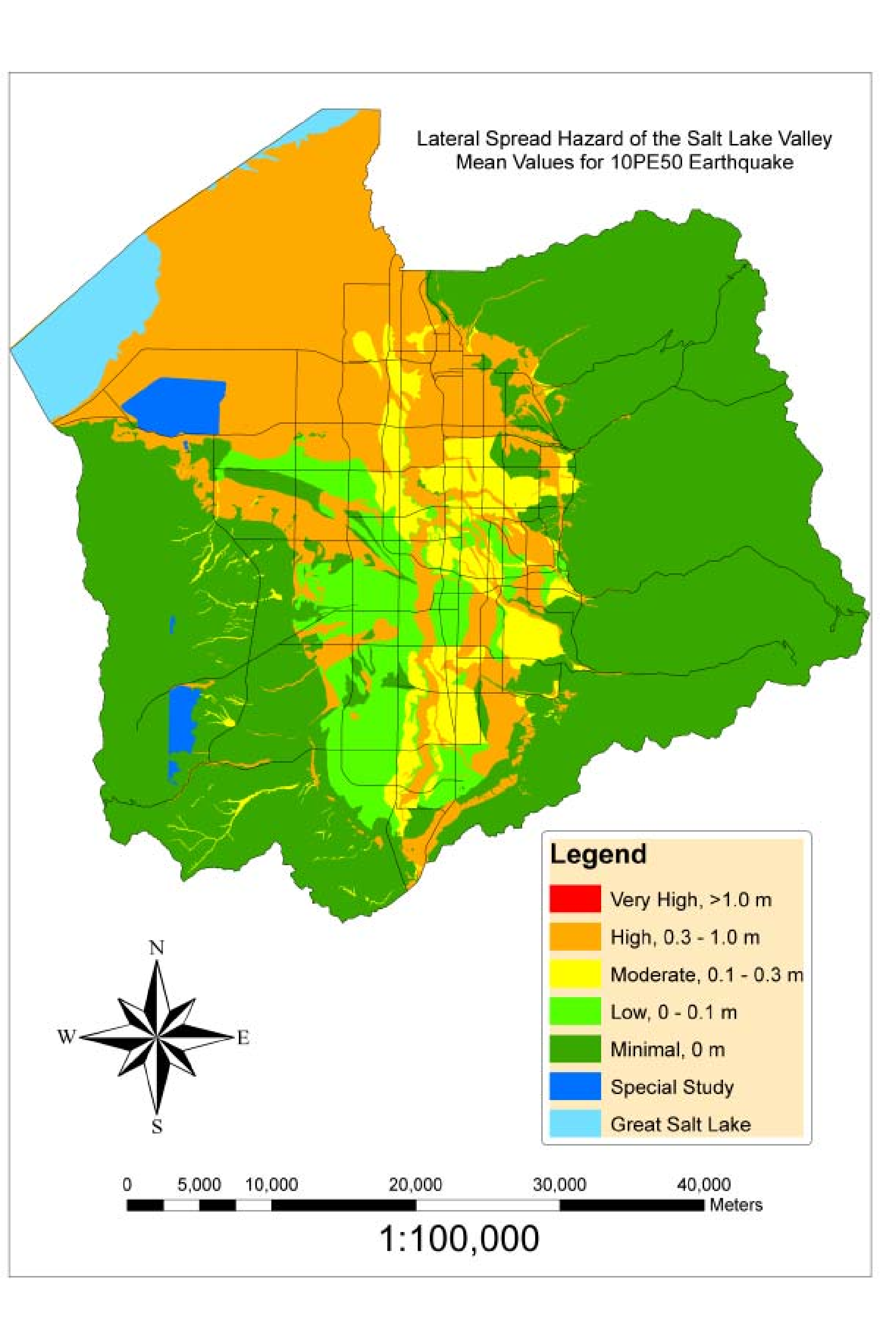
$$LogD_H = \begin{array}{c} b_o + b_{off}\alpha + b_1 M + b_2 LogR^* + b_3 R + b_4 LogW + b_5 LogS + b_6 LogT_{15} + \\ + b_7 Log(100 - F_{15}) + b_8 Log(D50_{15} + 0.1\text{ mm}) \end{array}$$

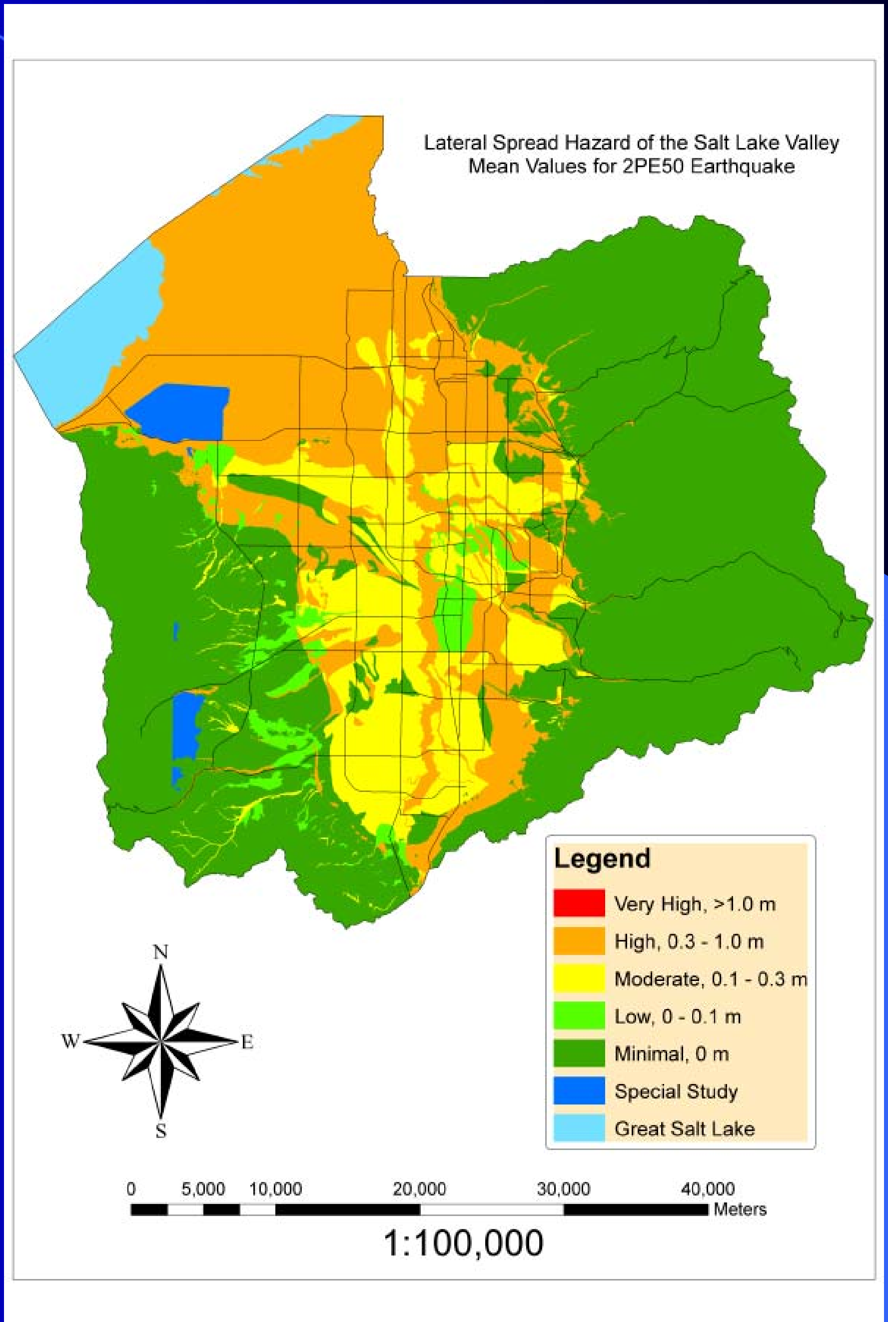
- Seismic Factors
  - *M, R*
- Topographic Factors
  - *W, S*
- Geotechnical Factors
  - T_{15}, F_{15}, $D50_{15}$



Free-face ratio: ***W (%) = H / L * 100***

Ground Displacement (Salt Lake Valley)
Lateral Spread or 500 and 2500-year scenarios

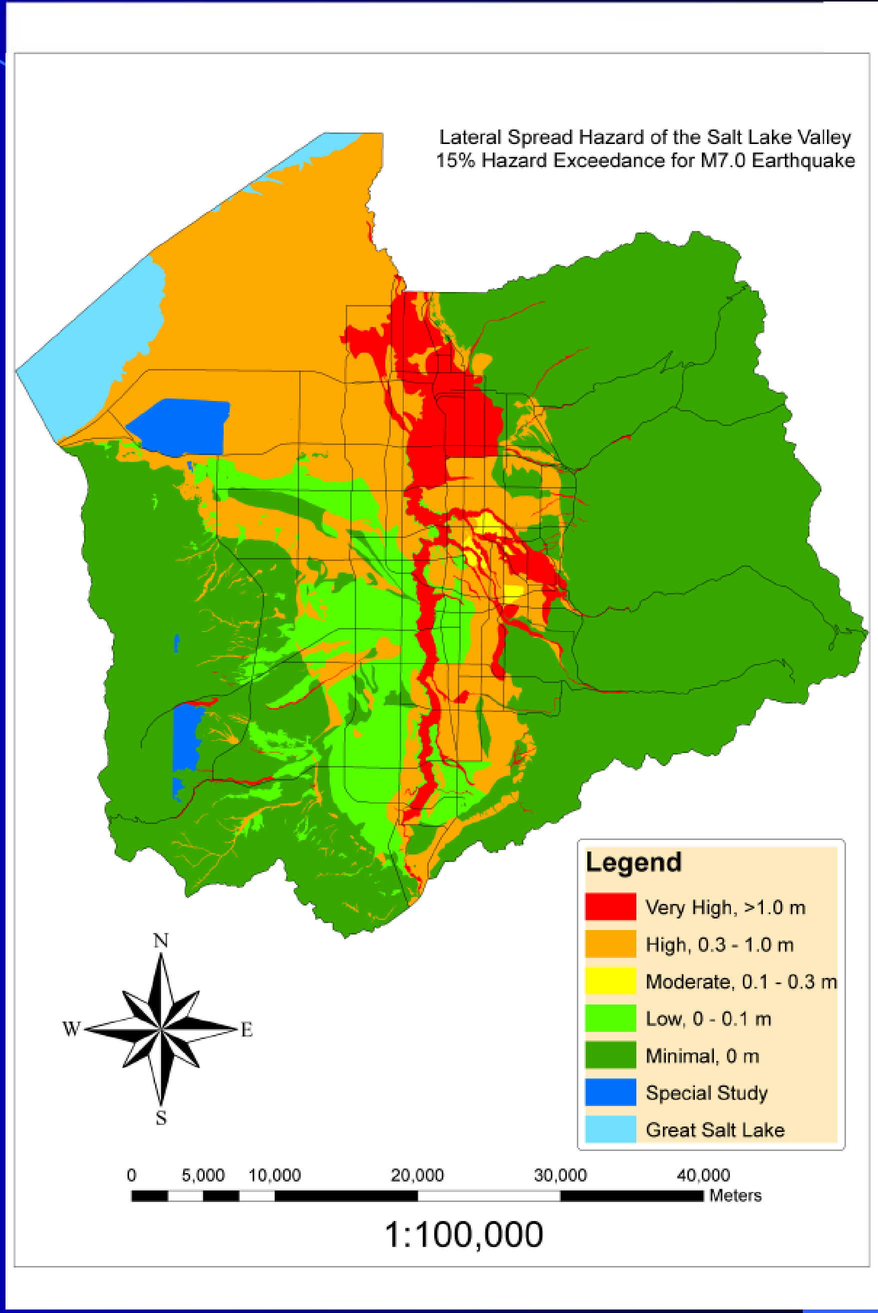




Ground Displacement (Salt Lake Valley)
Lateral Spread or 500 and 2500-year scenarios

M 7.0 Lateral spread displacement map

(85 percent chance of non-exceedance)



Estimation of Ground Displacement (Weber Co.)

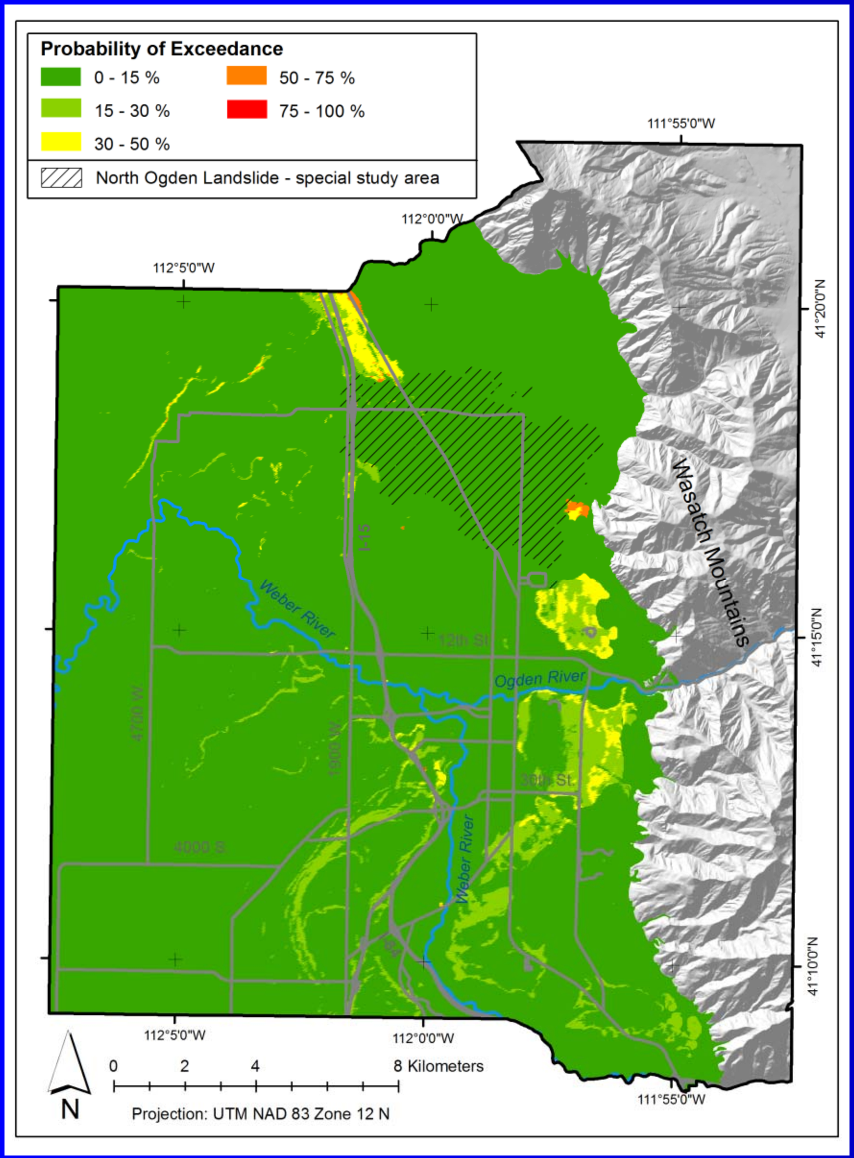
Gillins and Bartlett (2013) Empirical Model

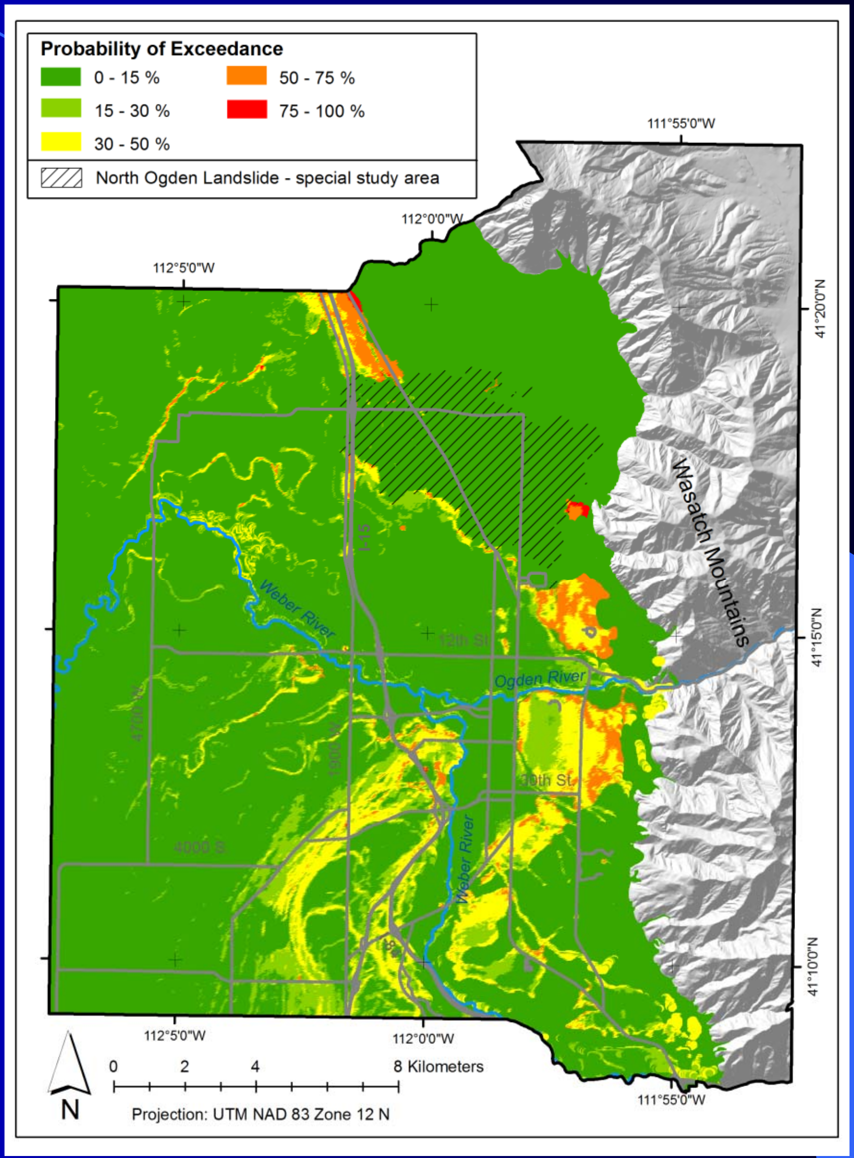
$$LogD_H = \begin{array}{l} b_o + b_{off}\alpha + b_1 M + b_2 LogR^* + b_3 R + b_4 LogW + b_5 LogS + \\ + b_6 LogT_{15} + a_1 x_1 + a_2 x_2 + a_3 x_3 + a_4 x_4 + a_5 x_5 \end{array}$$

x_i = the portion (decimal fraction) of T_{15} in a borehole that has a soil index corresponding to the table below

Soil Index *(SI)*	Typical Soil Description in Case History Database	General USCS Symbol
1	Silty gravel, fine gravel	GM
2	Coarse sand, sand and gravel	GM-SP
3	Medium to fine sand, sand with some silt	SP-SM
4	Fine to very fine sand, silty sand	SM
5	Low plasticity silt, sandy silt	ML
6	Clay (not liquefiable)	CL-CH

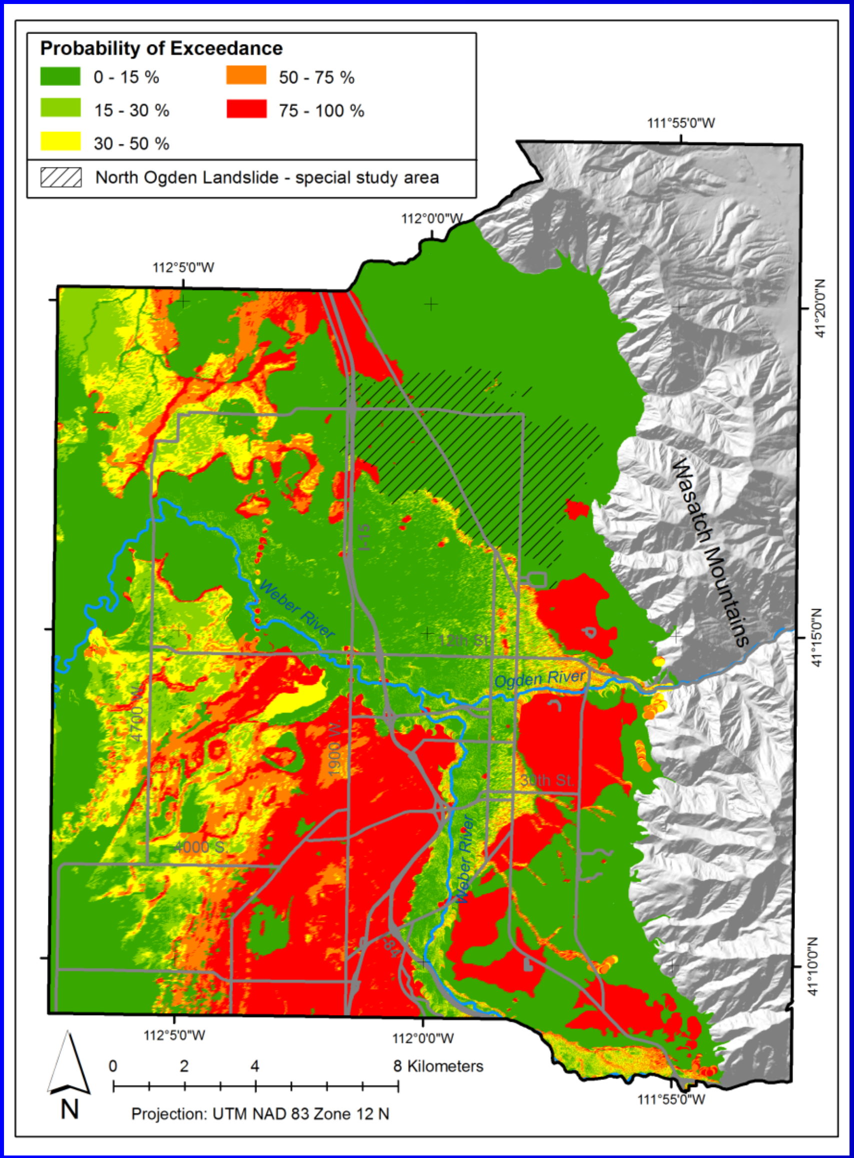
Ground Displacement (Weber Co.)
Lateral Spread or 500-year scenario



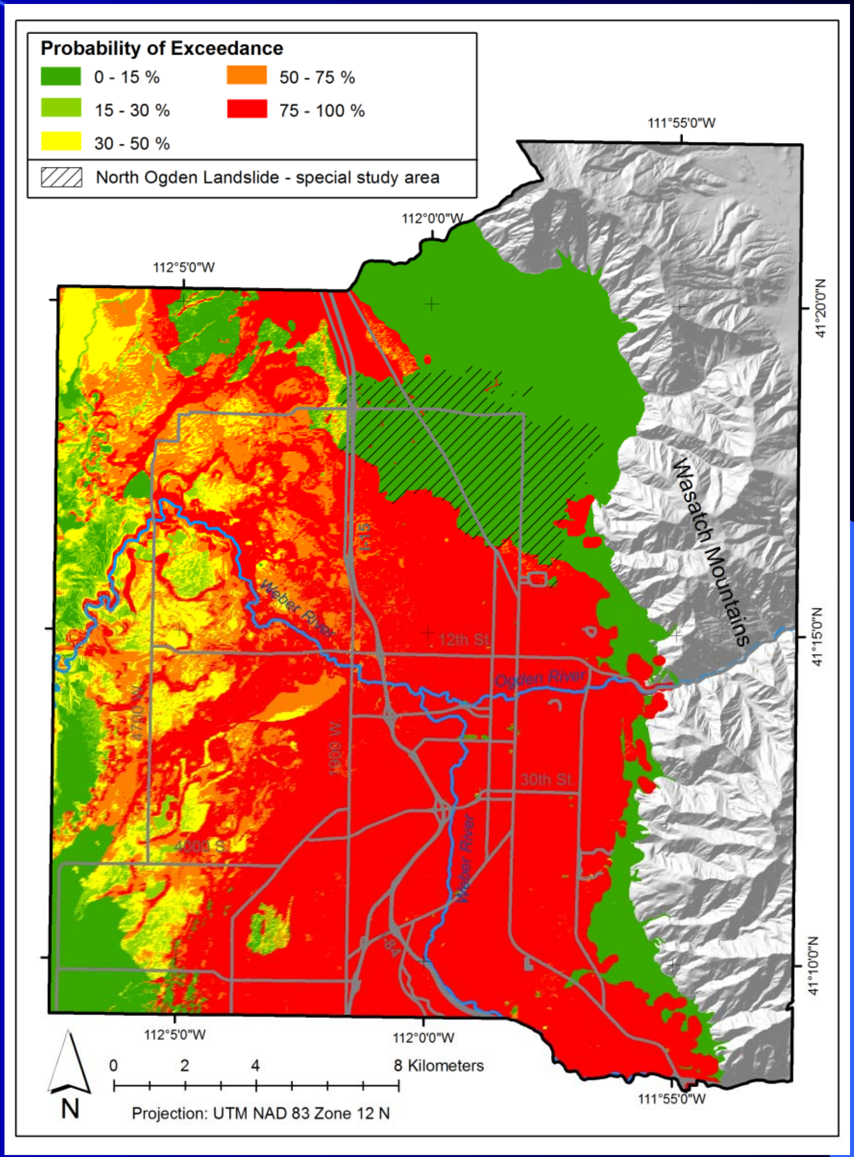


- Median probabilities of exceeding 0.3 m, 500-year event
- 84th percentile probabilities, of exceeding 0.3 m, 500-year event

Ground Displacement (Weber Co.)
Lateral Spread or 2500-year scenario



Median probabilities of exceeding 0.3 m, 2500-year event



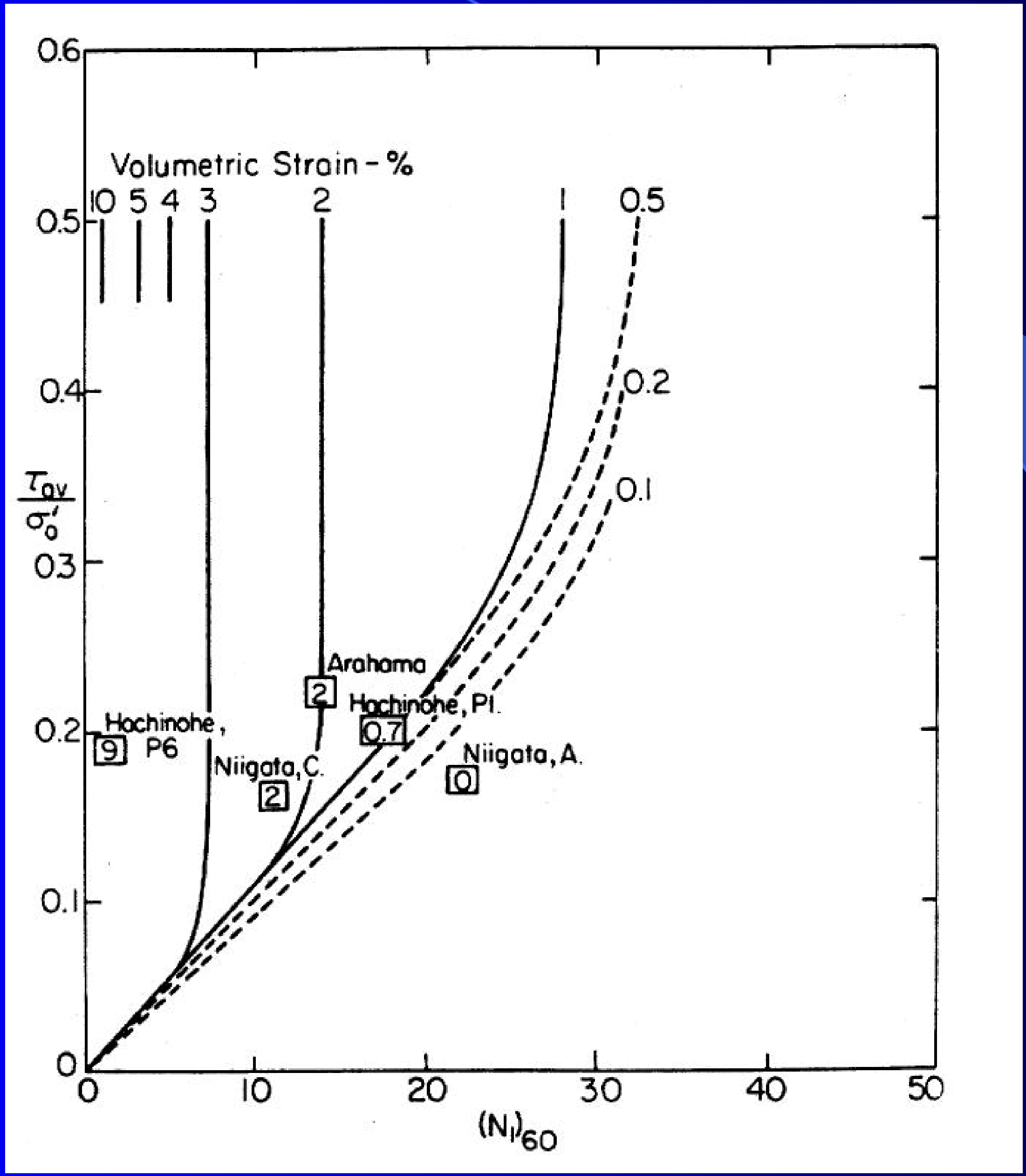
84th percentile probabilities, of exceeding 0.3 m, 2500-year event

Topics

- Liquefaction Damage
- Types of Liquefaction Maps
- Estimation of Frequency
- Estimation of Liquefaction Potential
- Estimation of Ground Displacement
- **Estimation of Settlement**
- Performance-Based Hazard Ordinances

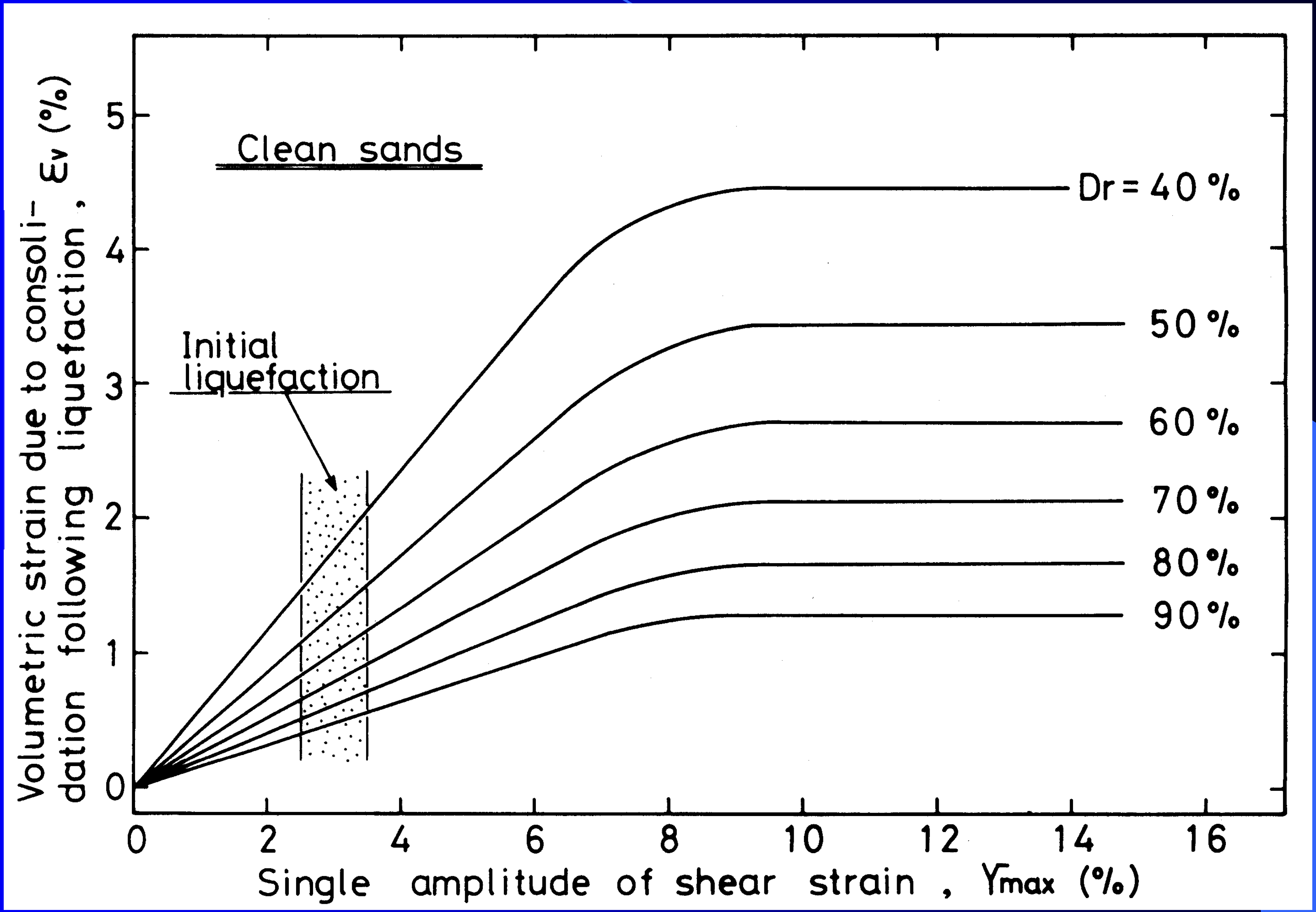
Estimation of Settlement

(Tokimatsu And Seed, 1987)

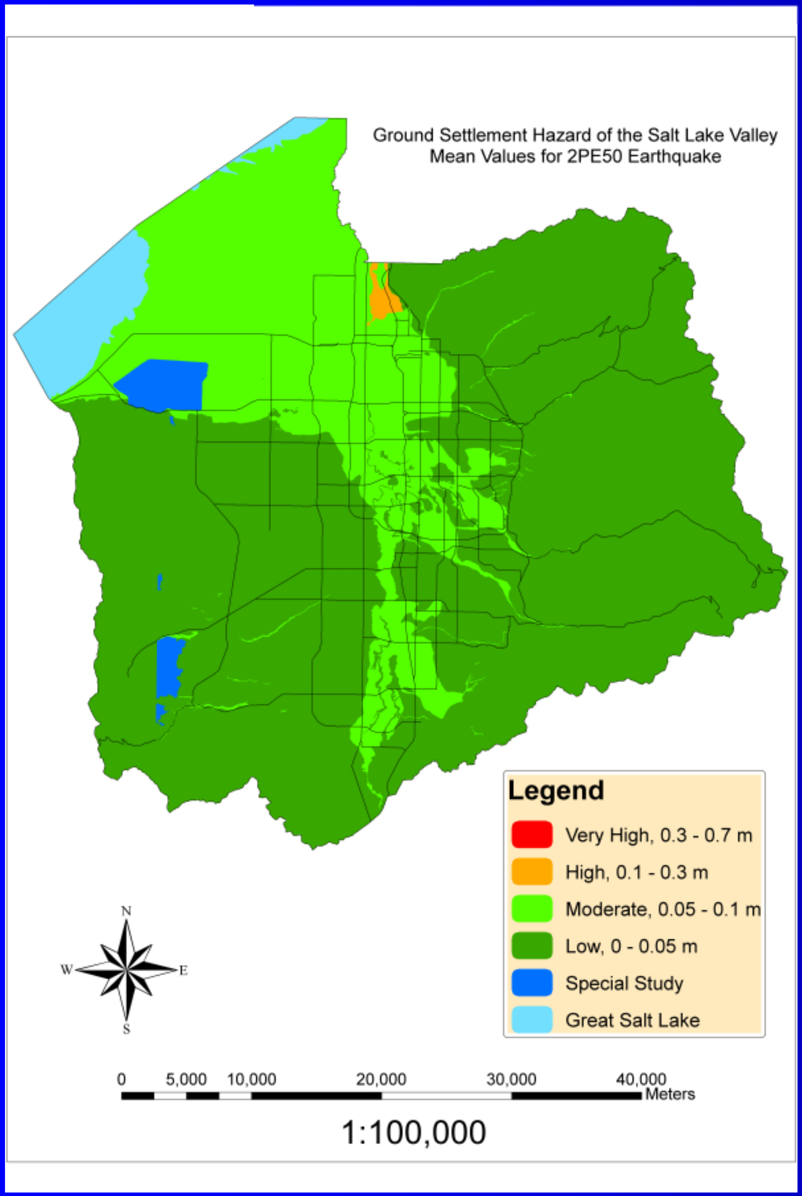


Estimation of Settlement

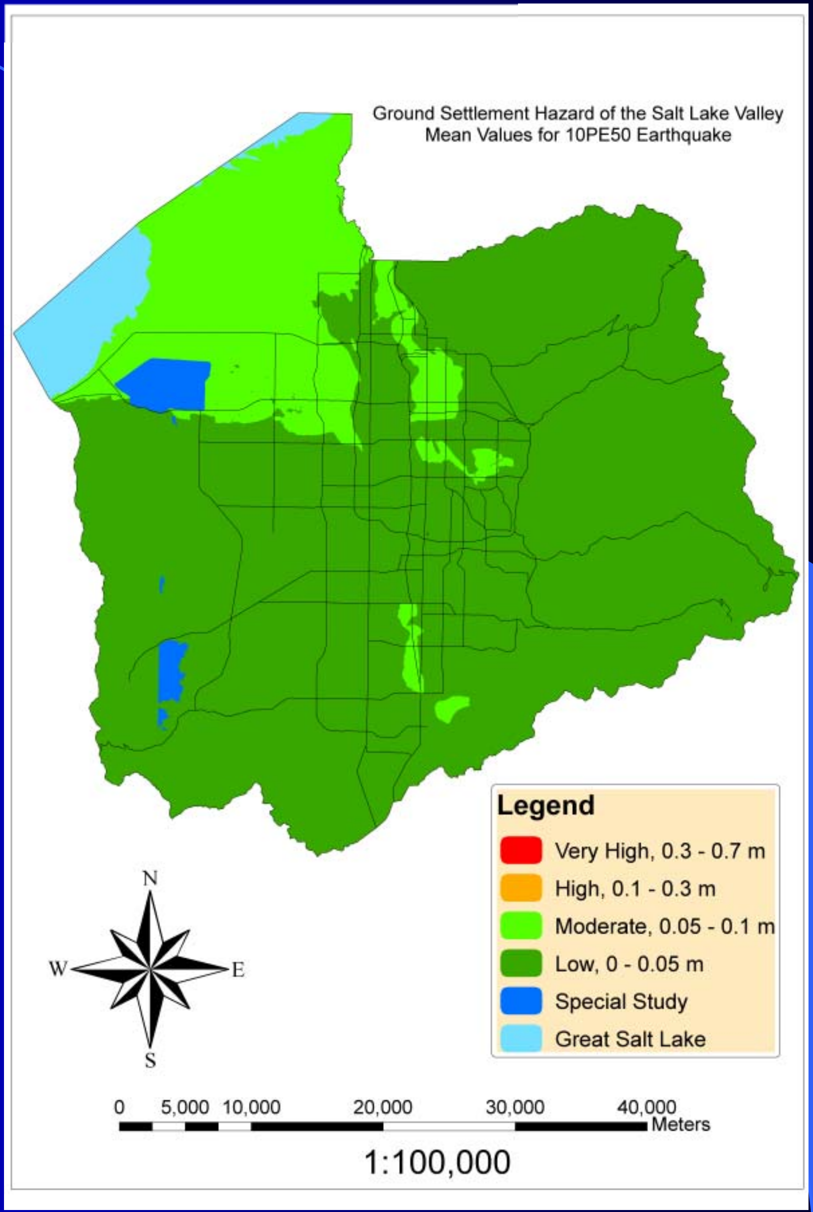
(Ishihara and Yoshimine 1992).



Settlement (Salt Lake Valley) for 500 and 2500-year scenarios



500-yr event



2500-yr event

Topics

- Liquefaction Damage
- Types of Liquefaction Maps
- Estimation of Frequency
- Estimation of Liquefaction Potential
- Estimation of Ground Displacement
- Estimation of Settlement
- **Performance-Based Hazard Ordinances**

Performance-Based Hazard Ordinances

- **What constitutes "acceptable risk?"**
- **Need a graded, risk-based approach based on performance goals.**

- Level of seismic hazard quantified by frequency or return period of event.
- Facilities/structures/systems classified according to importance.
- Performance goals defined for each class
  - Input owners/stakeholders/public
- Performance goal(s) evaluated in design process.

Classification of Systems

Functional Classification	Examples
Critical (Seismic Use Group III)	Hospitals, fire and police stations, emergency response command and control centers, vital utilities and services.
Essential (Seismic Use Group II)	Essential government and commercial facilities. Multi-unit housing. Important cultural and religious facilities. Facilities containing hazardous or toxic substances. Important bridges and major transportation corridors.
Important (Seismic Use Group I)	Single unit residential housing. Non-essential commercial facilities and utilities. Secondary streets and transportation arteries.
Routine	Non-habitable structures (e.g., garages, sheds, storage facilities, etc.) and private roads.

Safety/Environmental Performance Goals

	Performance Goal
Level 1	No loss of life or injury to occupants. No release of hazardous or toxic substances.
Level 2	No significant loss of life or major injury to occupants or significant release of hazardous or toxic substances.
Level 3	Safety goals are not applicable because these facilities or structures are not used for occupancy.

Systems Performance Goals

	Goal
Level 1 (Operational)	Facility or structure is *<u>functional and operational immediately following the event</u>* without interruption or repair.
Level 2 (Immediate Occupancy)	Facility, structure or system is functional and safe for occupancy soon after the geohazard event without significant loss of function or interruption. Structures should be *<u>safe for occupancy and use within days to a few weeks of the event</u>* with only minor interruption or repair.
Level 3 (Damaged/Repairable)	Facility, structure or system is damaged but repairable following the geohazard event with some interruption. *<u>Structures should be safe for occupancy or use within several months</u>* after the event with major interruption and repair.
Level 4 (Damaged/Irreparable)	Facility, structure or system is severely damaged and is not repairable. *<u>Structures are not safe for occupancy and not repairable; but have not collapsed</u>*.

Performance Goals vs. Event Frequency

Functional Classification	Frequency of Geohazard	Safety Performance Goal	System Performance Goal
Critical	Frequent Moderately Frequent Infrequent Rare	Level 1 Level 1 Level 1 Level 1	Level 1 Level 1 Level 1 Level 1
Essential	Frequent Moderately Frequent Infrequent Rare	Level 1 Level 1 Level 2 Level 2	Level 1 Level 1 Level 2 Level 3
Important	Frequent Moderately Frequent Infrequent Rare	Level 1 Level 1 Level 2 Level 2	Level 1 Level 1 Level 3 Level 4
Routine	Frequent Moderately Frequent Infrequent Rare	NA NA NA NA	NA NA NA NA

2015 UTAH LIQUEFACTION ADVISORY GROUP (ULAG) MEETING

David B. Simon
Simon Associates LLC

Alan Taylor
Taylor Geotechnical

SA Simon Associates LLC

Purpose

1. Current issues and problems in addressing liquefaction related to geologic hazard ordinances.

2. Development of geologic hazards ordinances.

3. Data collaboration.

PURPOSE – continued

Having been involved in the drafting of two municipal geologic hazardous ordinances, the primary issue appears to be municipalities reluctance/refusal to establish a geologic hazard ordinance ... not necessarily issues and problems in addressing liquefaction in a geologic hazard ordinance.

In regards to issues and problems in addressing liquefaction in a geologic hazard ordinance ... DATA.

PURPOSE – continued

History of geologic ordinances at Draper City and Morgan County would be appropriate and effective examples

LIQUEFACTION REFERENCES

Initial Anderson Studies

- Anderson, L.R., Keaton, J.R., and Bay, J.A., 1994, Liquefaction potential map for the **northern Wasatch front**, Utah, complete technical report: Utah Geological Survey Contract Report 94-6, 148 p., 6 plates, scale 1:48,000. (west Cache County, east Box Elder County, and west and central Weber County).
- Anderson, L.R., 1994, Liquefaction potential map for **Utah County**, Utah: Non-Technical Summary, Utah Geological Survey Contract Report 94-3, 6 p. and 3 Plates, scale 1:48,000.
- Anderson, L.R., Keaton, J.R., Spitzley, J.E., and Allen, Andrew C., 1994, Liquefaction potential map for the **Salt Lake County, Utah**, complete technical report: Utah Geological Survey Contract Report 94-9, 68 p., 6 plates, scale 1:48,000.
- Anderson, L.R., Keaton, J.R., Aubrey, K., and Ellis, S., 1994, Liquefaction potential map for **Davis County, Utah**, complete technical report: Utah Geological Survey Contract Report 94-7, 50 p., 3 plates, scale 1:48,000.

LIQUEFACTION REFERENCES - continued

Subsequent Studies

- Black, B.D, Solomon, B.J. and Harty, K.M., 1999, Geology and geologic hazards of **Tooele Valley** and the **West Desert Hazardous Industry area**, Tooele County, Utah: Utah Geological Survey Special Survey Study 96, 65 p., scale 1:100,000.

- Harty, K.M., and Lowe, M., 2003, Geologic evaluation and hazard potential of **liquefaction-induced landslides** along the **Wasatch Front**, Utah: Utah Geological Survey Special Study 104, 40 p., 16 plates, scale 1:24,000.

- J.P. McCalpin, J.P., and Solomon, B.J., 2010, Seismic hazards mapping of the central **Cache Valley**, Utah—a Digital Pilot Project, step-by-step procedures for GIS mapping of earthquake hazards, and hazard maps at a scale of 1:24,000, UGS, in-progress.

- Olsen, M.J., Bartlett, S.F., and Solomon, B.J., 2007, Lateral spread hazard mapping of the **Northern Salt Lake Valley**, Utah, for a M7.0 scenario earthquake: Earthquake Spectra, v. 23, i. 1, p. 95-113.

LIQUEFACTION REFERENCES - continued

Southern Utah

- Lund, W.R., Knudsen, T.R., and Sharrow, D.L., 2010, Liquefaction susceptibility, **Zion National Park** geologic-hazard study area, Plate 5, Utah Geological Survey Special Study 133, Zion National Park Geologic-Hazard Study Area, Washington and Kane Counties.
- Lund, W.R., Knudsen, T.R., Vice, G.S. and Shaw, L.M., 2008, Geologic hazards and adverse construction conditions, **St. George – Hurricane metropolitan area, Washington County**, Utah: Utah Survey Special Study 148, 13 p. Geological Survey Special Study 127, 105 p, 14 plates, DVD.
- Knudsen, T.R. and Lund, W.R., 2013, Geologic hazards of the **State Route 9 corridor, La Verkin City to town of Springdale, Washington County**, Utah: Utah Geological

LIQUEFACTION REFERENCES - continued

Recent Folio Maps

- Castleton, J.J., Elliott, A.H., and McDonald, G.N., 2011, Geologic hazards of the **Magna quadrangle**, Salt Lake County, Utah: Utah Geological Survey Special Study 137, 73 p., 10 plates, scale 1:24,000, CD.

- Castleton, J.J., Elliott, A.H., and McDonald, G.N., 2014, Geologic hazards of the **Copperton quadrangle**, Salt Lake County, Utah: Utah Geological Survey Special Study 152, 24 p., 10 plates, scale 1:24,000, CD.

Compilation

- Christenson, G.E., and Shaw, L.M., 2008, Geographic Information System **database** geologic-hazard special study areas, **Wasatch Front**, Utah: Utah Geological Survey Circular 106, 7 p., GIS data, scale 1:24,000, compact disk.

Municipalities with Comprehensive Prescriptive Geologic Hazard Ordinances

1. Salt Lake County
2. Draper City
3. Morgan County
4. Iron County

SA Simon Associates LLC

DRAPER CITY'S INITIAL IMPRESSION OF GEOLOGISTS

Geologists are "scientists" with an unnatural obsession with rocks and alcohol. Often too intelligent to do monotonous sciences like biology, chemistry, or physics, geologists devote their time to mud-worrying, volcano spotting, fault poking, skiing, bouldering, dust-collecting, and high-risk coloring.

Anti-Regulatory Development Attitude When Draper City and Morgan County Entered into the Process

1. Utah is a "property rights" state.

2. Many state legislators are developers, builders, real estate agents.

3. Developers question a municipality's role/rights in reviewing a private developer's consultant's work.

Draper City Review Process

- Prior to 2003 Draper City “blindly” accepted reports from “professionals” without clear and concise prescriptive minimum standards and/or a formalized review process.

- In 2003, Draper City initiated a geologic review process via adoption of the Salt Lake County geologic hazards ordinance, which included inconsistent review by City consultants.

Draper City Review Process – continued

- Revised Geologic Hazard Ordinance in 2006 – resulted in the most comprehensive geologic hazard ordinance in Utah and was used as the model ordinance by the Governor's Geologic Hazards Working Group.
- In 2007, Draper City initiated thorough geologic reviews.

Morgan County Process

- In 2004, existing Ordnance in place – two issues, County not requiring geologic review as stipulated and ordinance allowed approval of subdivisions with restricted “R” lots.
- October 17, 2006 created a building moratorium in specific subdivisions in the Mountain Green area County Ordinance No Co-06-22.
- New ordinance adopted June 1, 2010, which effectively removed geologic review in lieu of “Professional Certification.”

MORGAN COUNTY CERTIFICATION

- A written, stamped certification from a professional geologist and engineer, licensed in the state of Utah, that:

- The geologic hazard reports have been prepared pursuant to the requirements of this article;

- Every proposed development lot or building pad does not present an **unreasonable or unacceptable risk to the health, safety, and welfare of persons or property** ... because of the presence of geologic hazards or because of modifications to the site due to the proposed land use;

- Every proposed development lot or building site demonstrates that, **consistent with the state of the practic**e, the identified geologic hazards can be mitigated to a level where the risk to human life and damage to property are reduced to an acceptable and reasonable level in a manner which will not violate applicable federal, state, or local statutes, ordinances or regulations.

MORGAN COUNTY CERTIFICATION - continued

- A **mitigation plan that demonstrates that the identified hazards or limitations will be addressed without impacting or adversely affecting off site are**as. Mitigation measures must be reasonable and practical to implement and shall not require ongoing maintenance by property owners; and

- Verification from the issuer of **professional errors and omissions liability insurance, in the amount of one million dollars ($1,000,000.00)**, which covers the preparer of the statements from the licensed geologist and engineer, and which are in effect on the date of preparation of all required reports and certifications.

- Morgan County may set other requirements as are necessary to mitigate any geologic hazards and to ensure that the purposes of this article are met. These requirements may include, but are not limited to ...

MORGAN COUNTY CERTIFICATION - continued

1. Additional or more detailed studies and professional certifications to understand or quantify the hazard or determine whether mitigation measures recommended in the report are adequate;

2. Specific mitigation requirements; establishing buildable and nonbuildable areas; limitations on slope grading and controls on grading, or revegetation;

3. Prior to receiving a grading, excavation, or building permit, final grading plans, when required, shall be prepared, signed and sealed by the licensed professional engineer and the engineering geologist and geotechnical engineer that prepared the geologic hazards and geotechnical report(s) to verify that their recommendations have been appropriately incorporated in the final grading plan and that building locations are approved;

MORGAN COUNTY CERTIFICATION - continued

4. As built grading plans, when required, shall be prepared, signed and sealed by the licensed professional engineer and the engineering geologist and geotechnical engineer that prepared the geologic hazards and geotechnical report(s) to verify that their recommendations have been appropriately incorporated and that building locations are approved, prior to the issuance of a building permit;

5. Grading plans, when required, shall include, at a minimum, the following:

   a. Maps of existing and proposed contours;
   b. Present and proposed slopes for each graded area;
   c. Existing and proposed drainage patterns;
   d. Location and depth of all proposed cuts and fills;
   e. Description of methods to be employed to achieve stabilization and compaction;
   f. Location and capacities of proposed drainage, structures, and erosion control measures based on maximum runoff for a 100-year storm;
   g. Location of existing buildings or structures on or within one hundred feet (100') of the site, or which may be affected by proposed grading and construction; and Plan for monitoring and documentation of testing, field inspections during grading, and reporting to Morgan County;

MORGAN COUNTY CERTIFICATION - continued

6. Installation of monitoring equipment and seasonal monitoring of surface and subsurface geologic conditions, including groundwater levels; and

7. Other requirements such as time schedules for completion of the mitigation and phasing of development.

C. Morgan County may also set requirements necessary to protect the health, safety, and welfare of the citizens of Morgan County, protect Morgan County's infrastructure and financial health, and minimize potential adverse effects of geologic hazards to public health, safety, and property as a condition of approval of any development which requires a geologic hazards report.

D. Morgan County may require the engineering geologist and geotechnical engineer that prepared the geologic hazards and geotechnical report(s) be on site, at the cost of the applicant, during certain phases of construction, particularly during grading phases and the construction of retaining walls.

ISSUES TO OVERCOME

- City leadership and willingness to leap into "regulation."
- Recognition that previous procedures were woefully inadequate.
- "Education" of City officials the general geologic review processes -using examples from surrounding communities where geologic issues were ignored is important.
- Commitment by City leadership to support staff and the regulatory review process.

SUMMARY

The Draper City ordinance *works and works well* because Draper City has established a clear and concise set of prescriptive minimum standards. Developers and their consultants now know the "rules."

The Morgan County ordinance works and works well when properly implemented and supported by County Council.

SUMMARY - CONTINUED

The success of a geologic hazard program has, and continues to be, directly proportional to City/County officials, administrators, and planners ability to understand geologic processes. Other factors include:

- review-consultants who understand City processes and can circumvent potential issues that could adversely impact the City;
- making the hard decisions in regards to development, even if it involves halting approved developments;
- advocating with the State legislature to assure a municipality's right to geologic and geotechnical review and the protection of public health, safety and welfare.

SUMMARY - CONTINUED

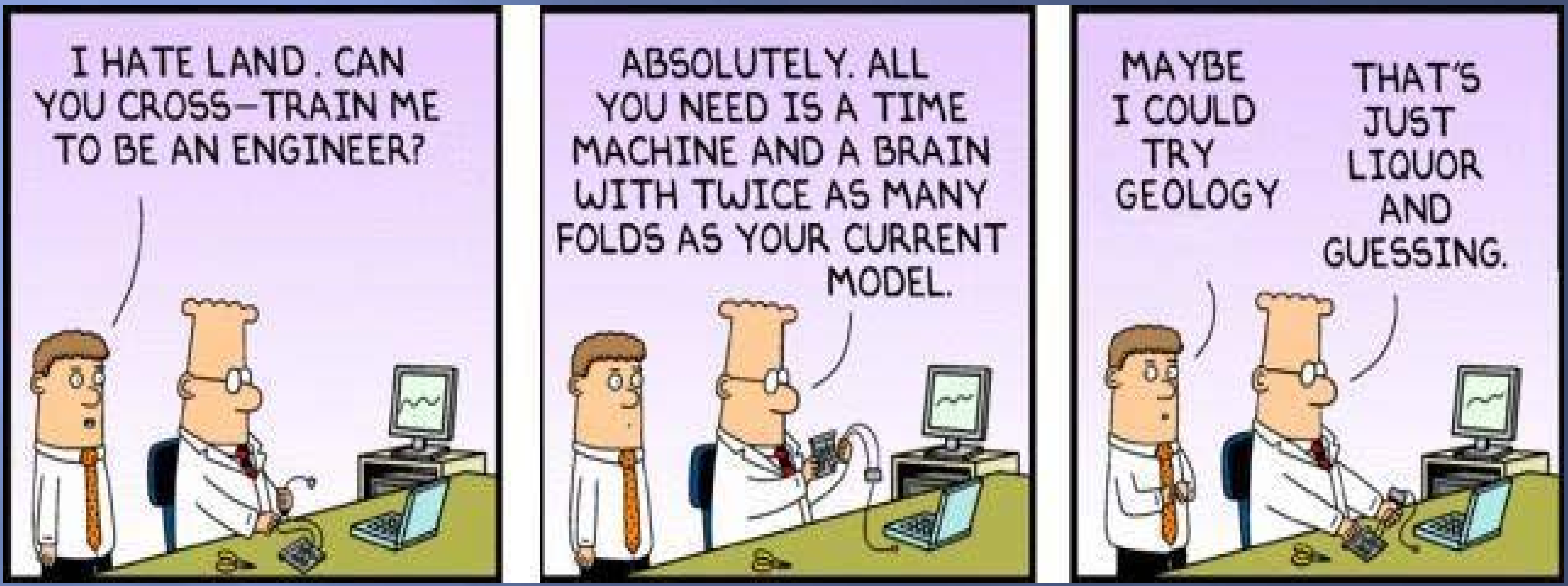
Challenges faced by the municipalities during successful implementation of a geologic hazard ordinance include the continued outrage by the development community (including likely litigation), resistance by Consultants, and continued attempts by the development community to take control of the development process.

Less resistance from the consulting community and implementation of a continuing education requirement would greatly contribute to achieving a municipality's mandate of protecting public health, safety, and welfare.

SUMMARY - CONTINUED

Work to be done includes educating cities without an ordinance of the need and benefits of a prescriptive geologic hazard ordinance.

Thank You



Questions?

Collaboration of Data

Alan Taylor
Taylor Geotechnical