Evaluation of Shallow Ground Improvement Methods for Liquefaction Mitigation

EQC
EARTHQUAKE COMMISSION
Kōmihana Rūwhenua

NEES@UTexas
The world is our equipment site;
Have mobile shakers, will travel.

NEES

NSF

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Presentation Outline

- **Overview**
  - Liquefaction Damage: 2010-2011 Canterbury Earthquakes and the Effects on Residential Housing
  - Purpose of Ground Improvements
- **Shallow (< 4m) Ground Improvement Trials**
  - Objective: Rebuild with Affordable Resilience
  - Goal: Thicken Non-Liquefying Surface Layer/Crust
  - Evaluate Performance of Various Ground Improvement Methods
- **Evaluating Effectiveness of Creating Non-liquefying Crust**
  - CPT and Shear Wave (Vs) and Compression Wave (Vp) Velocity
  - Full Scale Shaking Tests with T-Rex & Dynamic 2D Numeric Simulations
- **Evaluating Deformation Performance of Non-liquefying Crust**
  - Blast Liquefaction Testing & Static 3D Deformation Based Numeric Simulations
- **Conclusions**

Overview

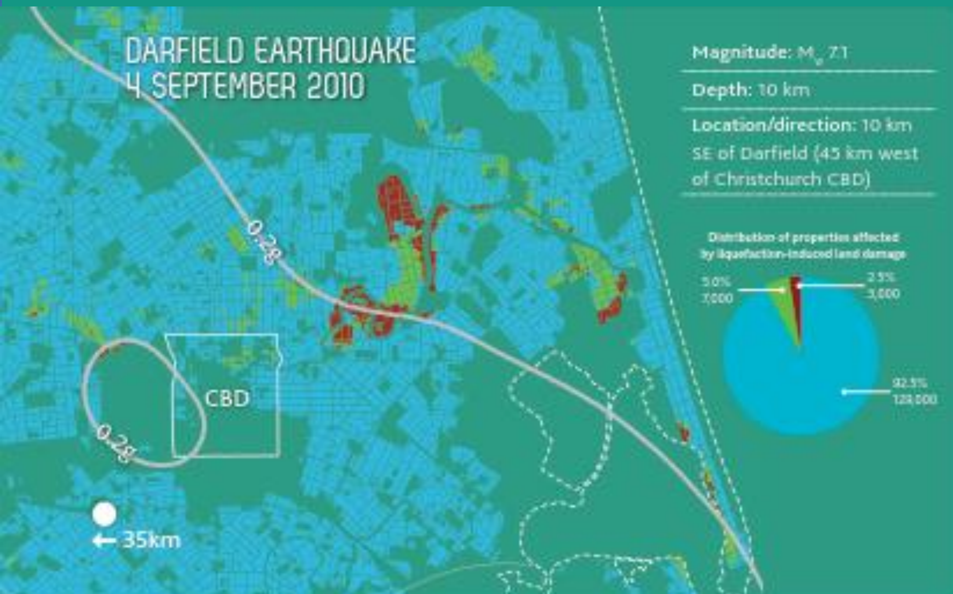
Liquefaction Damage: 2010-2011 Canterbury Earthquakes - Effects on Residential Housing

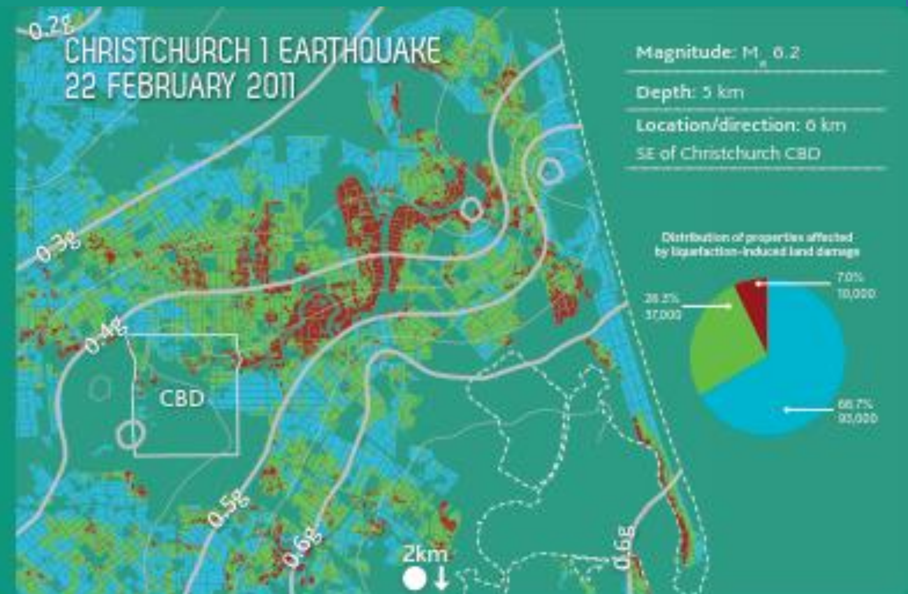
Was the Performance of the Residential Housing Portfolio Acceptable?

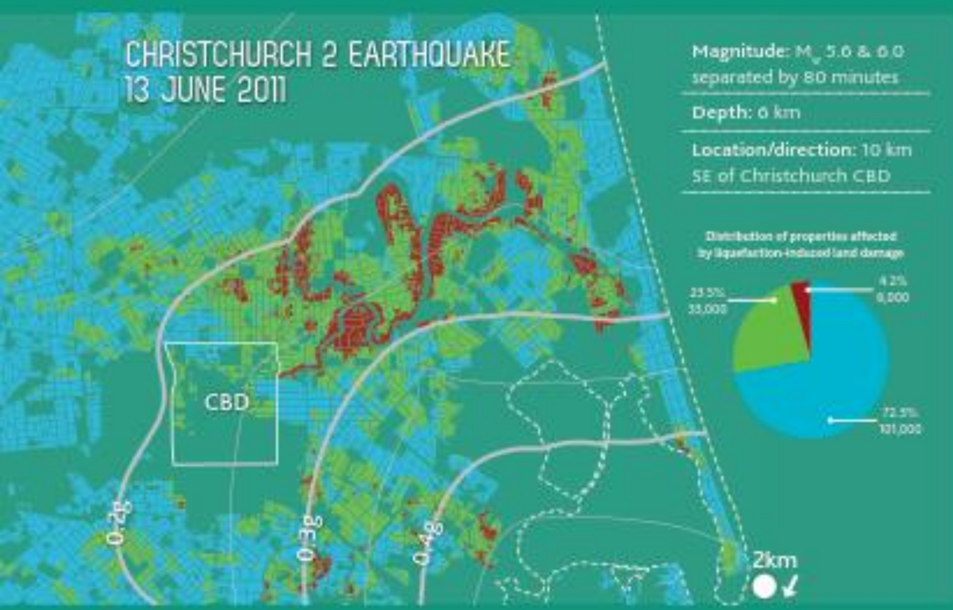
Why Ground Improvement?

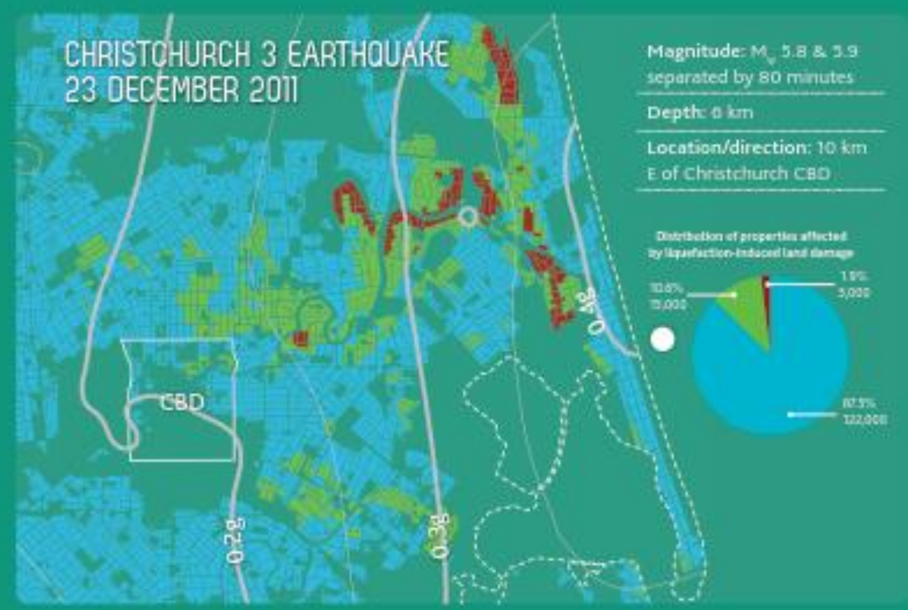
What do Ground Improvements Need to Achieve?

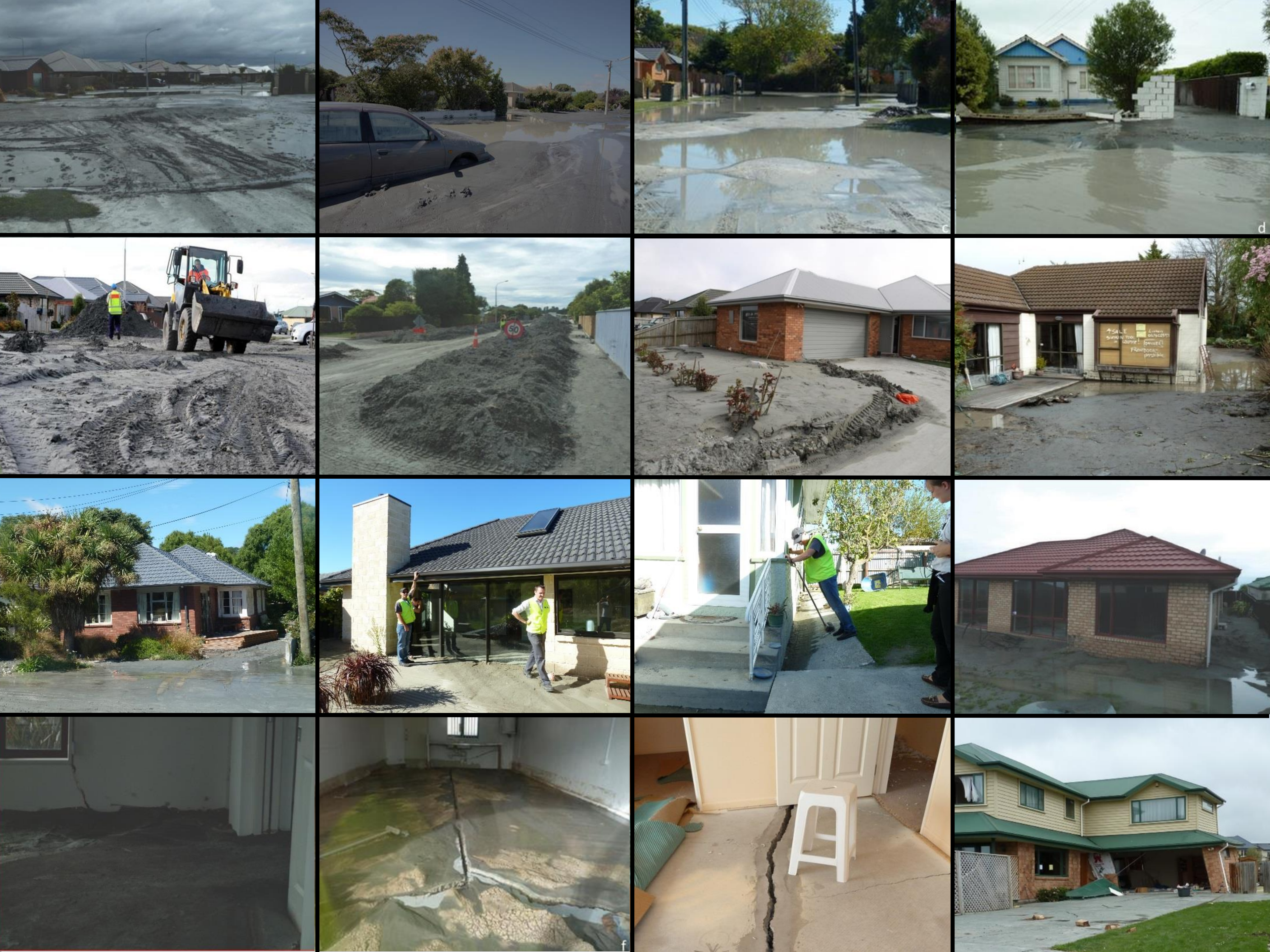
LIQUEFACTION LABORATORY





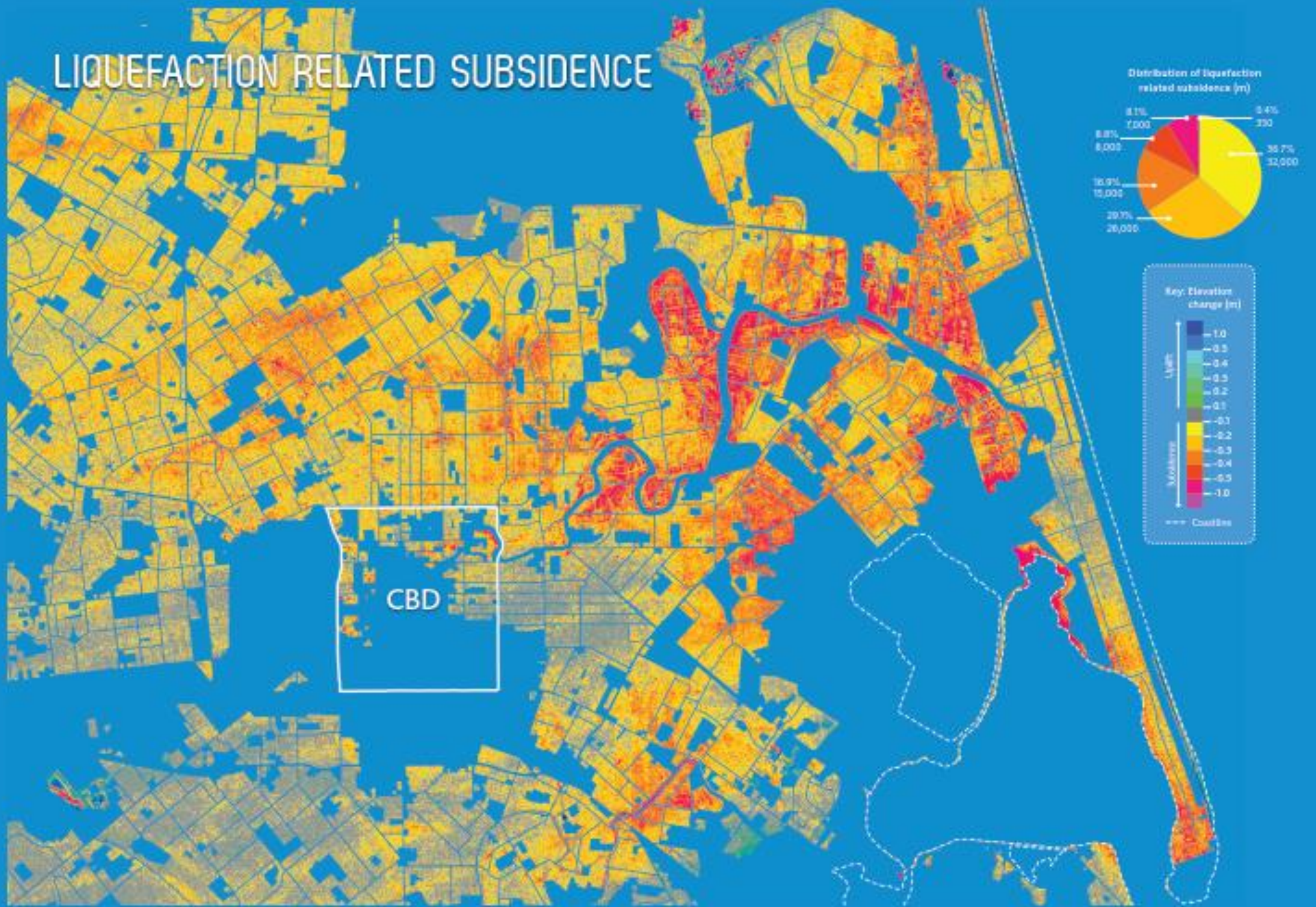





c
d
50
f

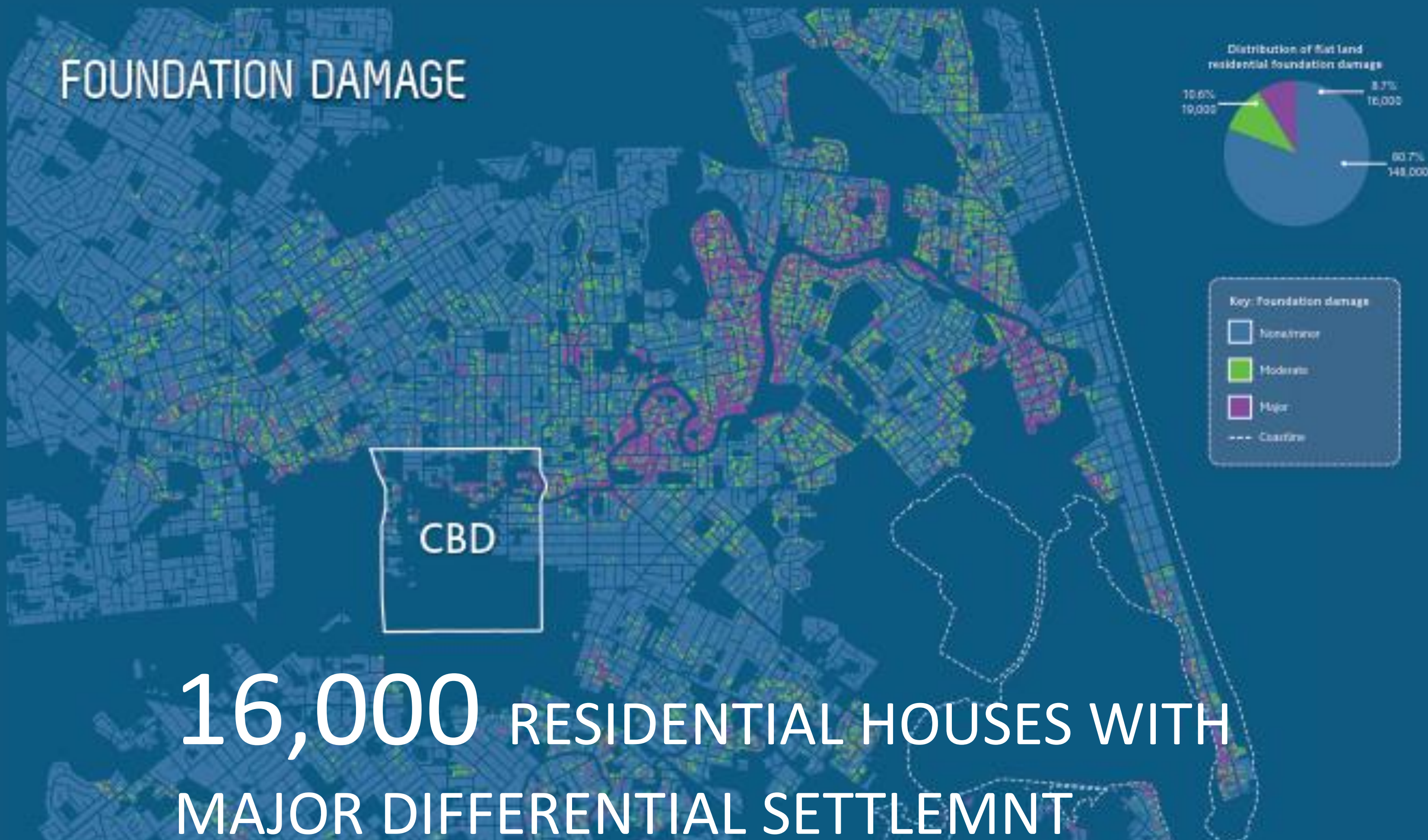

140,000
PROPERTIES
AFFECTED BY SHAKING
GREATER THAN 0.2G
51,000
PROPERTIES WITH
LIQUEFACTION-INDUCED
LAND DAMAGE

SUBSIDENCE IN THE CITY



SUBSIDENCE IN THE CITY

FOUNDATION DAMAGE



16,000 RESIDENTIAL HOUSES WITH MAJOR DIFFERENTIAL SETTLEMNT

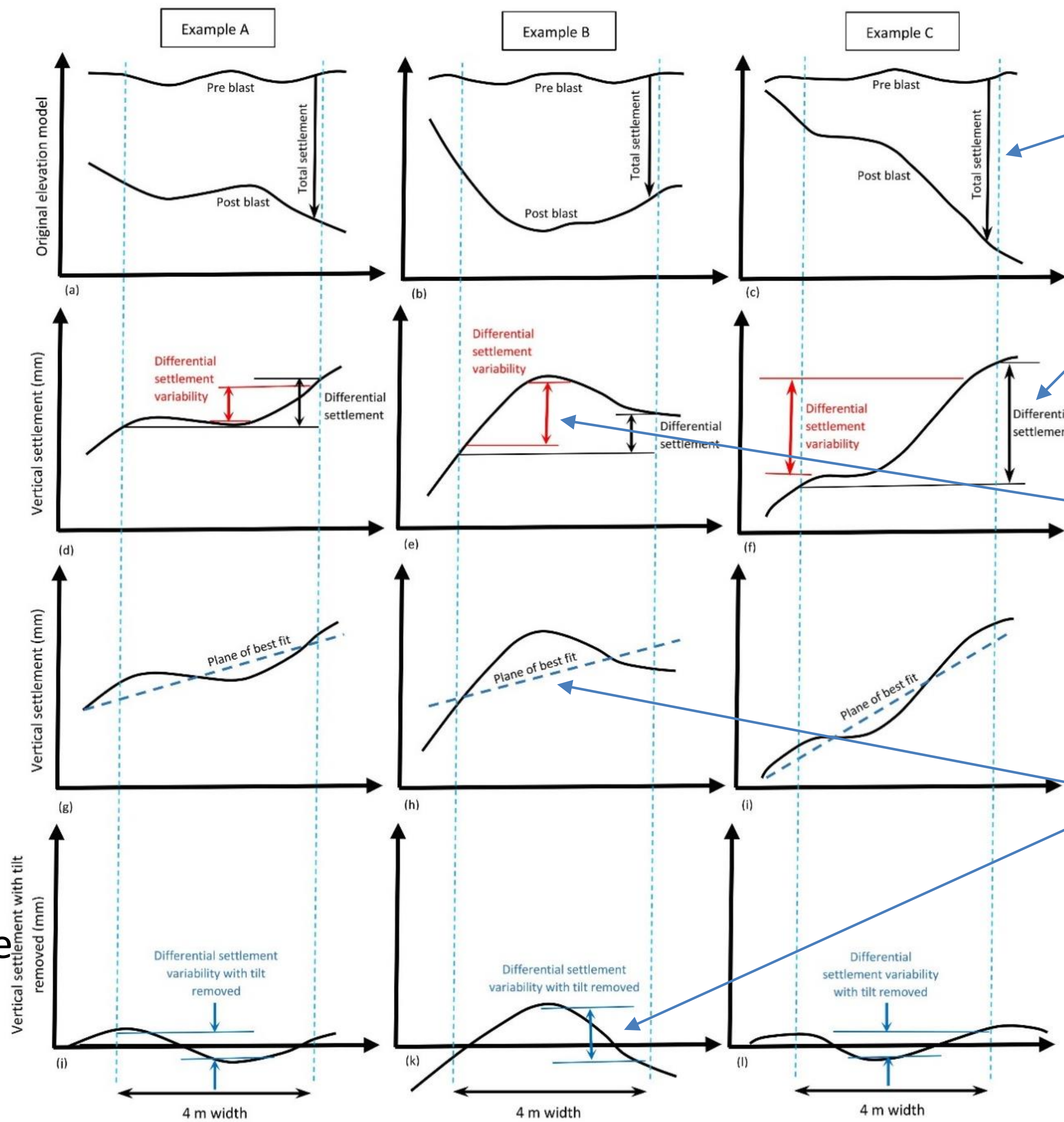
Total Settlement, Differential Settlement and Flexural Distortion

Pre and post surfaces

Total Settlement

Total Settlement with a fitted plane

Settlement Deviation from the Fitted Plane



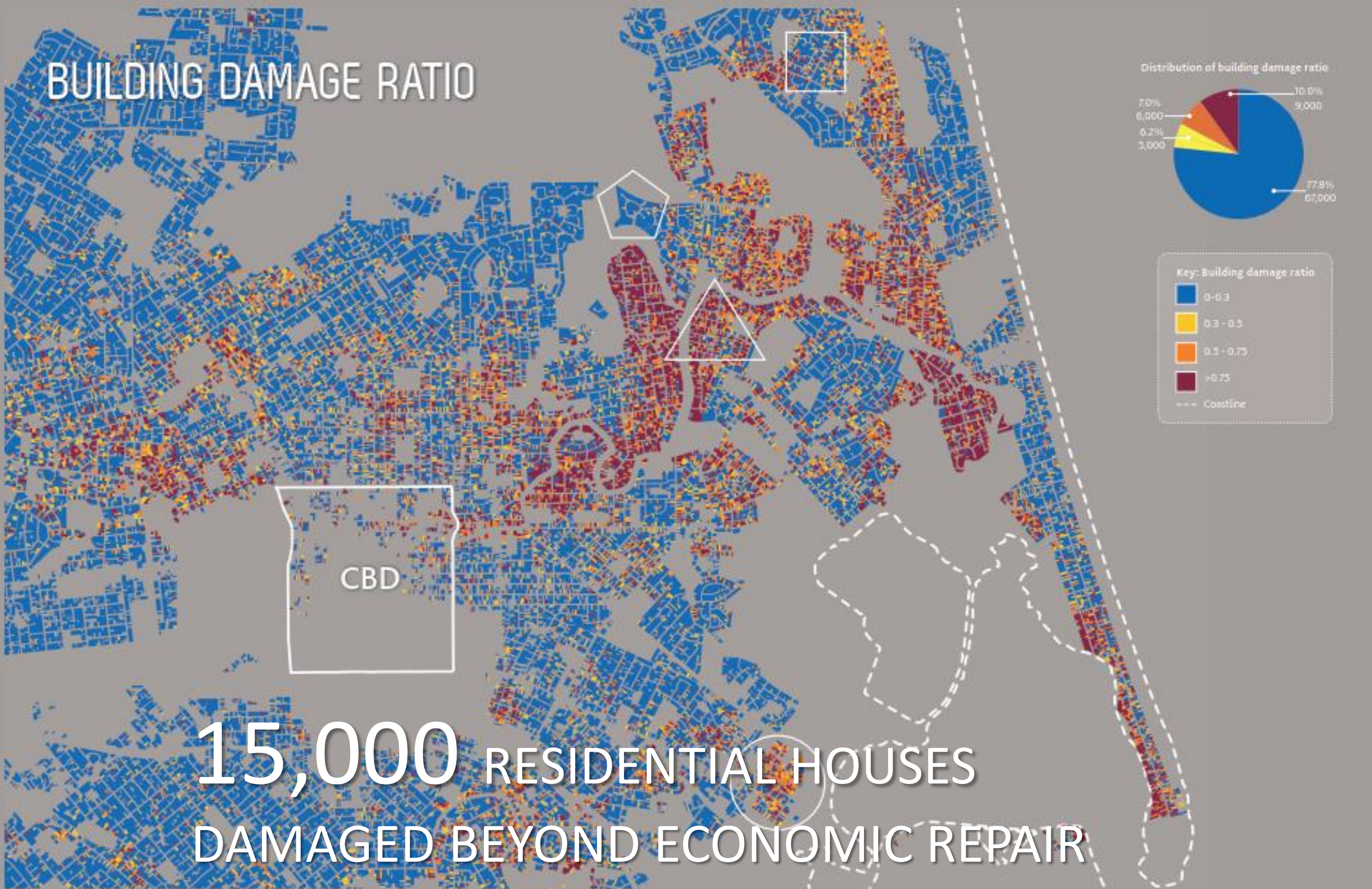
Total Settlement

Differential Settlement

Differential Settlement Variability

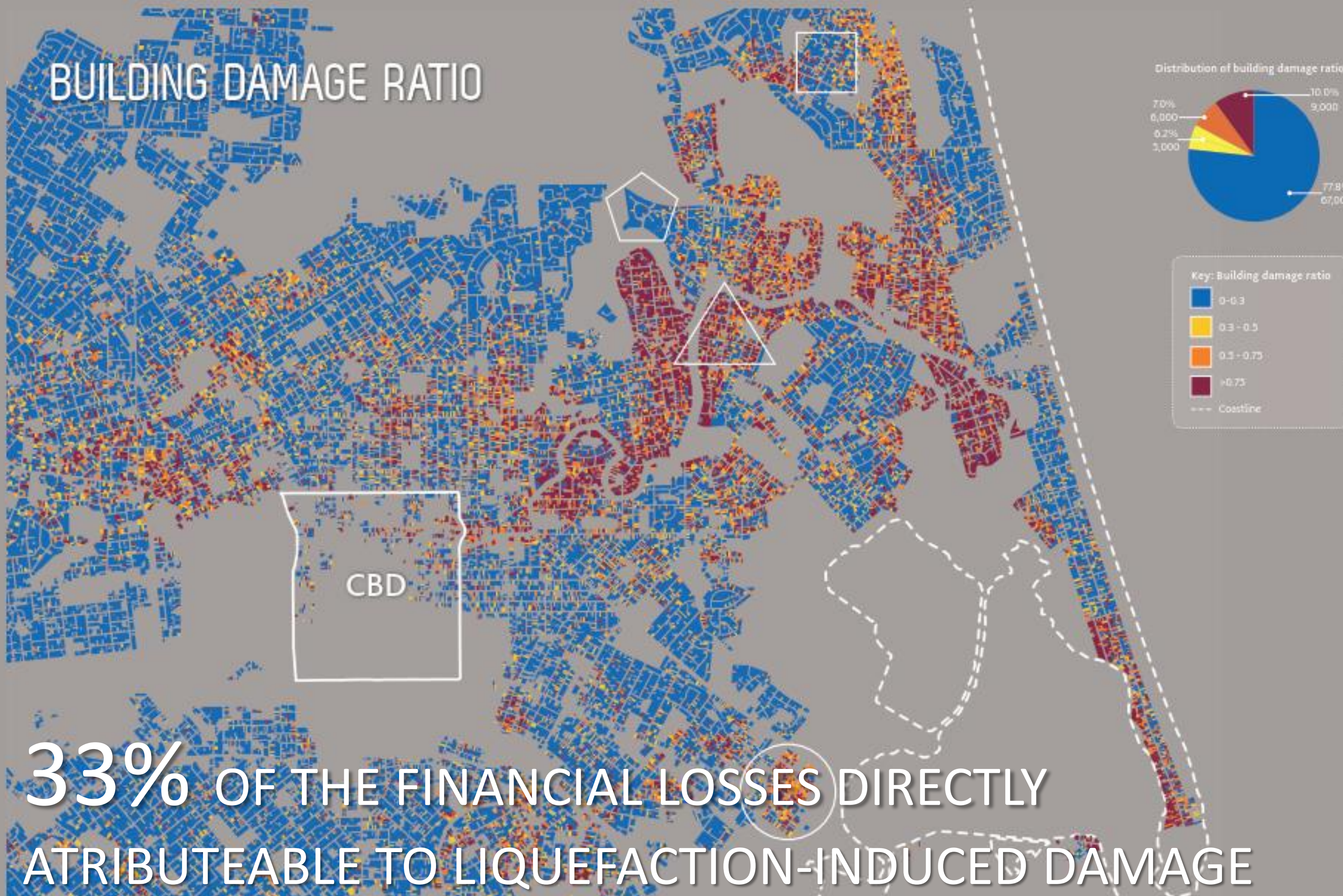
Flexural Distortion

NZ$40B ECONOMIC IMPACT



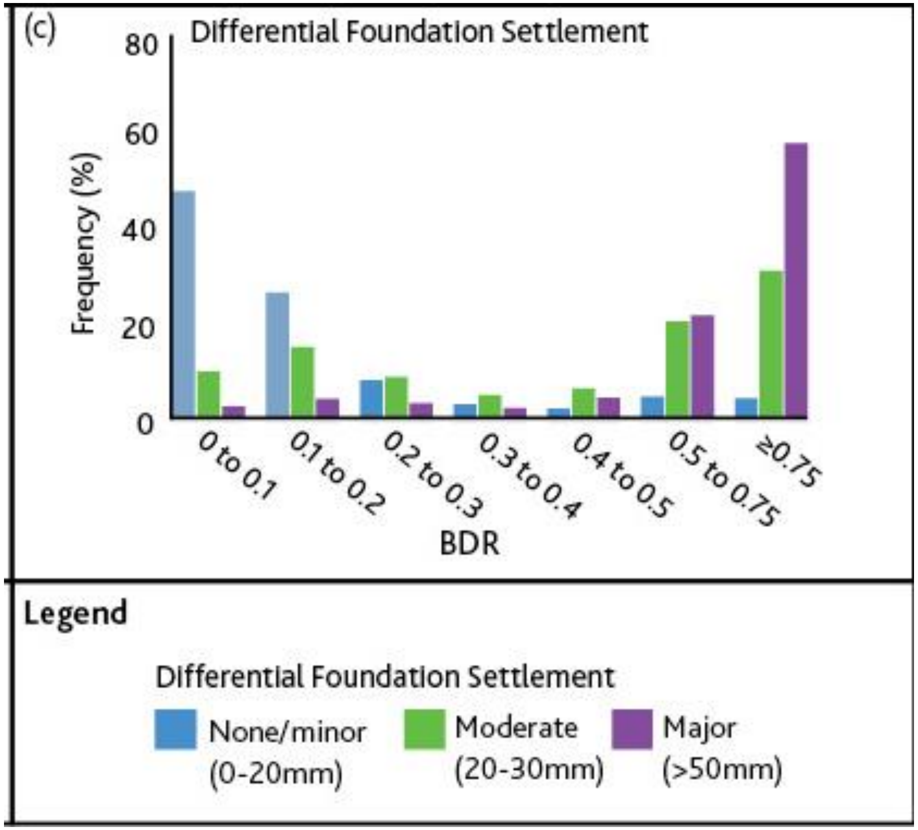
15,000 RESIDENTIAL HOUSES
DAMAGED BEYOND ECONOMIC REPAIR

NZ$40B ECONOMIC IMPACT



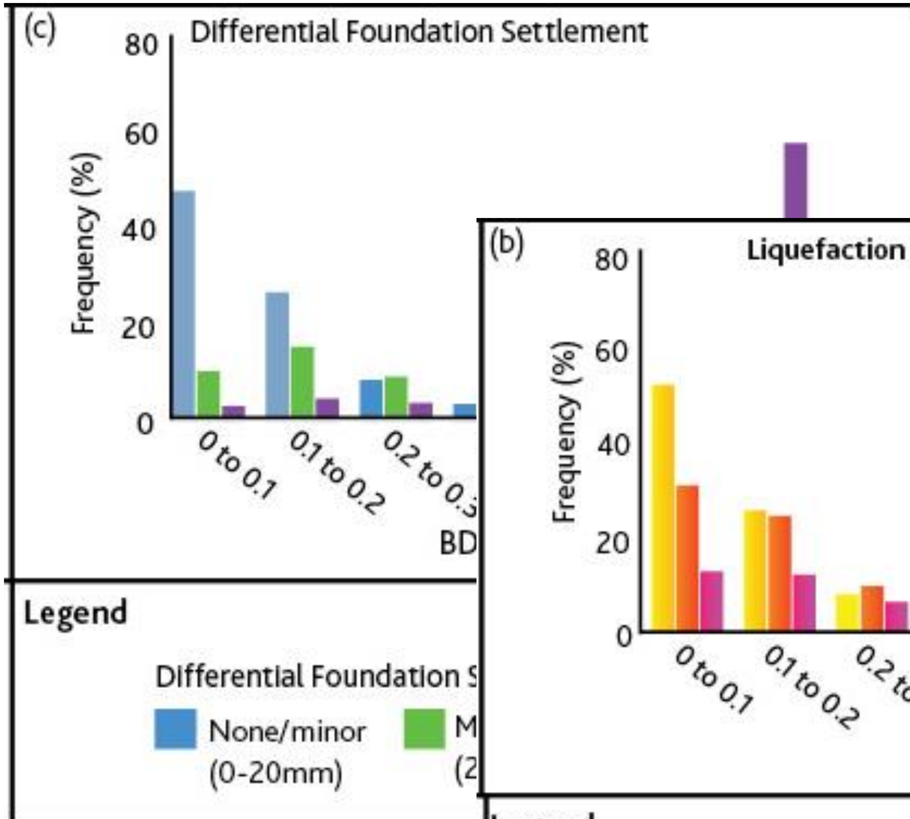
33% OF THE FINANCIAL LOSSES DIRECTLY ATRIBUTEABLE TO LIQUEFACTION-INDUCED DAMAGE

Correlation of Building Damage Ratio with…

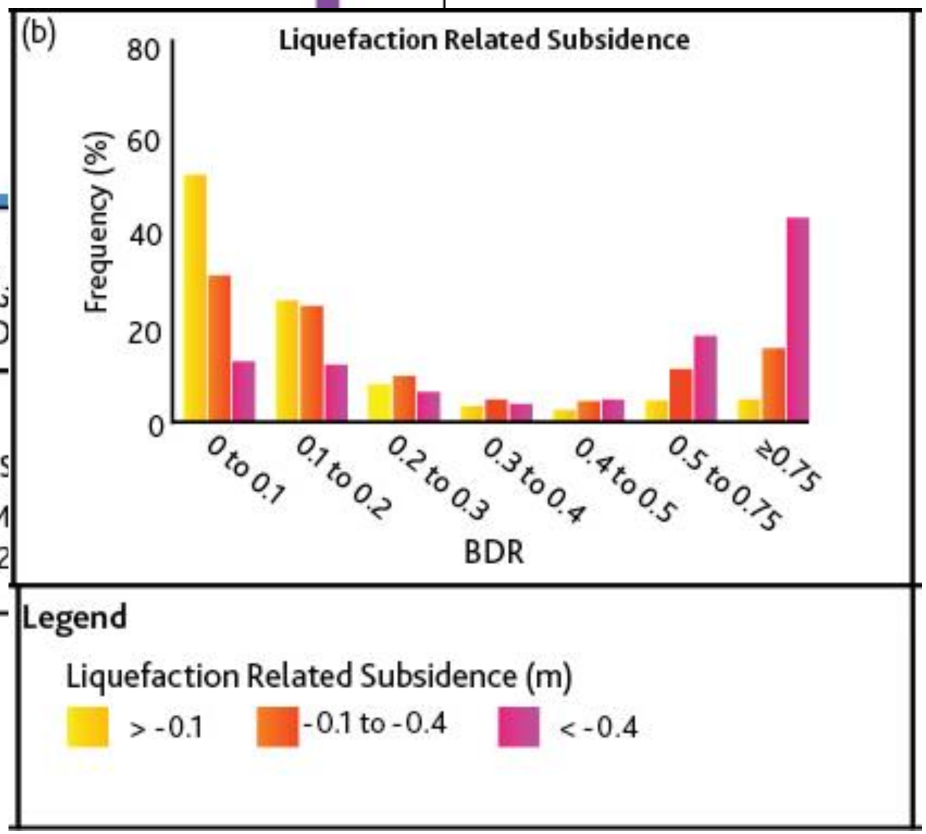


Foundation Differential Settlement

Correlation of Building Damage Ratio with…

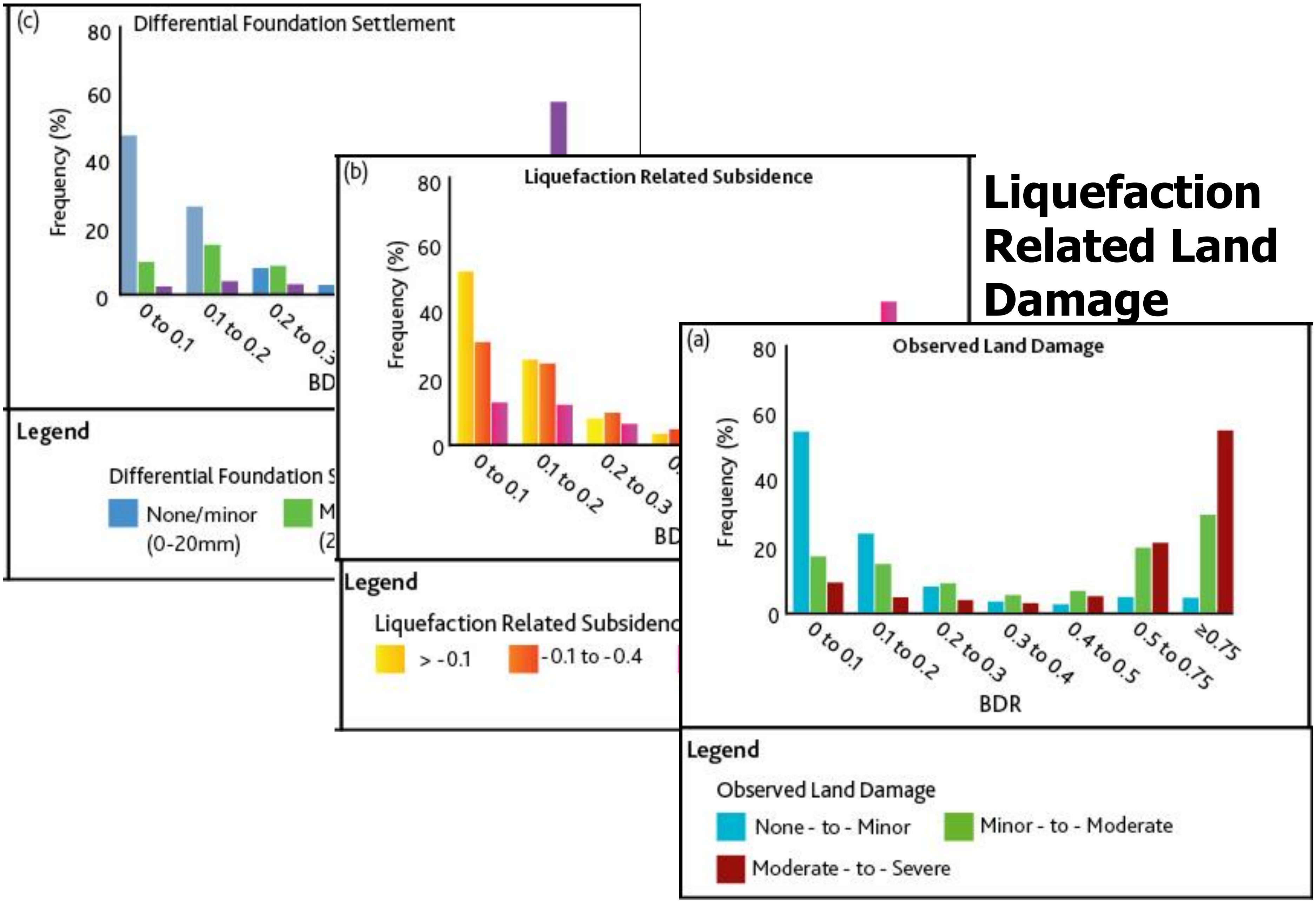


Liquefaction Related Subsidence



Correlation of Building Damage Ratio with…

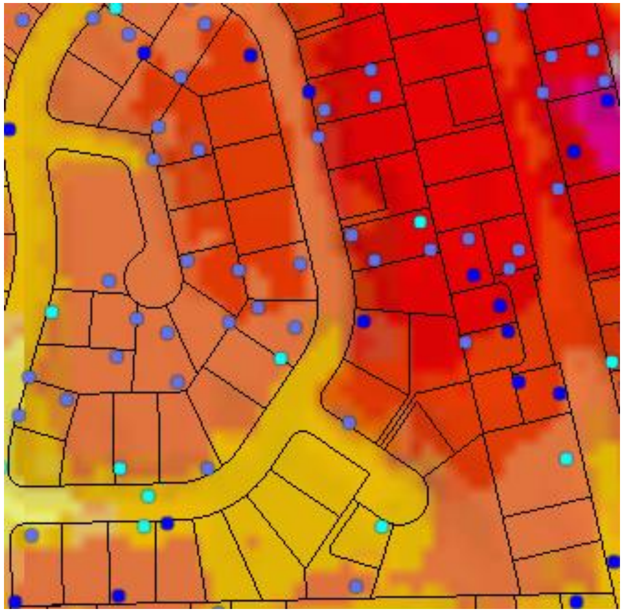
Liquefaction Related Land Damage



Liquefaction Related Building Damage

- Liquefaction related foundation differential settlement caused the large economic loses including the total loss of 15,000 houses
- Caused predominantly by liquefaction related ground surface subsidence
- The larger the measured liquefaction related ground surface subsidence the higher the likelihood of differential settlement
- Liquefaction ground surface subsidence caused by:
  - Volumetric densification – Calculated Settlement (S_{V1D})
  - Soil ejecta at the ground surface – LSN
  - Lateral spreading – Near waterways
  - Topographic re-levelling – **Often overlooked!**

Topographic Re-levelling and Calculated Settlement

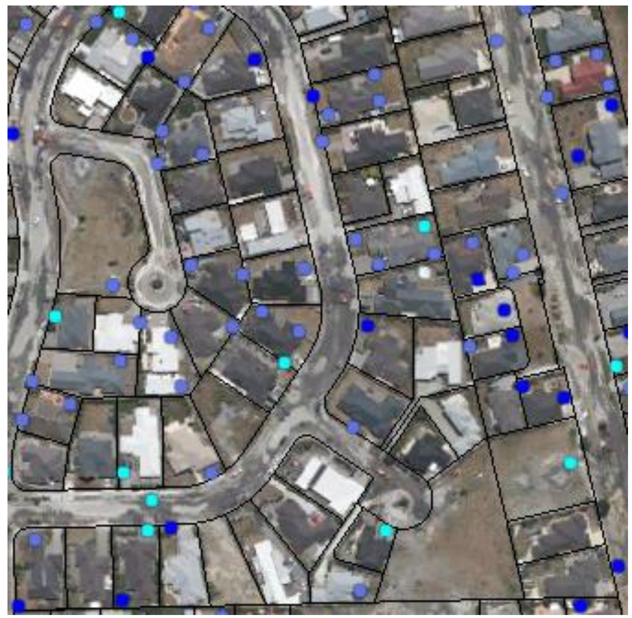


▲ Ground Surface Elevation

Lyttelton Datum	Christchurch City Datum
5.5 to 6.0 m	14.5 to 15.0 m
5.0 to 5.5 m	14.0 to 14.5 m
4.5 to 5.0 m	13.5 to 14.0 m
4.0 to 4.5 m	13.0 to 13.5 m
3.5 to 4.0 m	12.5 to 13.0 m
3.0 to 3.5 m	12.0 to 12.5 m

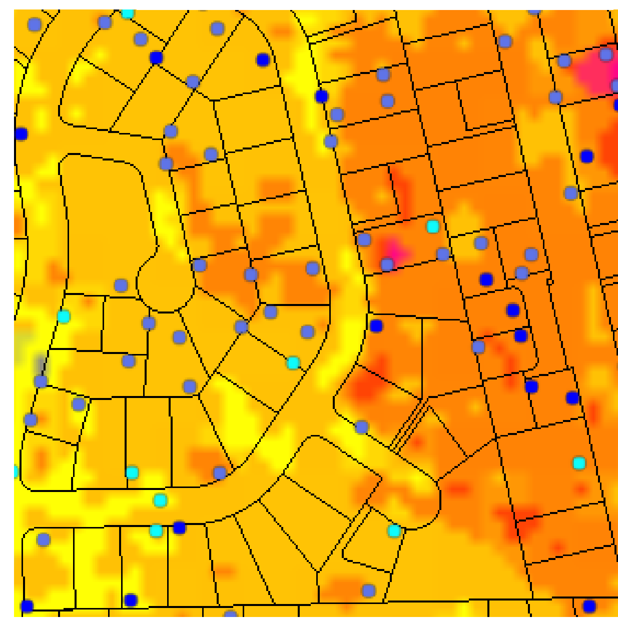
Calculated Settlement, S_{V1D} (mm)

- 0 - 60
- 60 - 120
- 120 - 180
- 180 - 240



▼ Vertical Elevation Change without Tectonic Component

- -0.2 to -0.1 m
- -0.3 to -0.2 m
- -0.4 to -0.3 m
- -0.5 to -0.4 m



Elevation differences can caused properties to settle (and differentially settle) considerably more than the predicted CPT-based calculated settlement.

Rebuilding with Resilience

1. Reduce differential settlement by reducing the liquefaction related settlement – i.e. deep ground improvements

2. Partially reduce differential settlement and also reduce flexural distortion by intermediate ground improvement (4m deep) in conjunction with structural TC2 foundation systems

3. Reduce flexural distortion by using shallow stiff ground improvement (1.2m deep) in conjunction with structural TC2 foundation systems

4. Reduce flexural distortion by using a robust re-levellable structural shallow TC3 foundation system

While all the above options would be compliant with the building code, they do not have the same performance.

Rebuilding with Resilience

1. Reduce differential settlement by reducing the liquefaction related settlement – i.e. deep ground improvements - Low likelihood of minor re-levelling in a future ULS event
2. Partially reduce differential settlement and also reduce flexural distortion by intermediate ground improvement (4m deep) in conjunction with structural TC2 foundation systems – Moderate likelihood of minor-to-moderate re-levelling in a future ULS event
3. Reduce flexural distortion by using shallow stiff ground improvement (1.2m deep) in conjunction with structural TC2 foundation systems – Higher likelihood moderate re-levelling in a future ULS event
4. Reduce flexural distortion by using a robust re-levellable structural shallow TC3 foundation system – Higher likelihood moderate re-levelling in a future ULS event

While all the above options would be compliant with the building code, they do not have the same performance.

Rebuilding with Affordable Resilience

1. ~~Reduce differential settlement by reducing the liquefaction related settlement – i.e. deep ground improvements - Low likelihood of minor re-levelling in a future ULS event~~
2. Partially reduce differential settlement and also reduce flexural distortion by intermediate ground improvement (4m deep) in conjunction with structural TC2 foundation systems – Moderate likelihood of minor-to-moderate re-levelling in a future ULS event
3. Reduce flexural distortion by using shallow stiff ground improvement (1.2m deep) in conjunction with structural TC2 foundation systems – Higher likelihood moderate re-levelling in a future ULS event
4. Reduce flexural distortion by using a robust re-levellable structural shallow TC3 foundation system – Higher likelihood moderate re-levelling in a future ULS event

While all the above options would be compliant with the building code, they do not have the same performance.

Objective: Rebuild with Affordable Resilience

Shallow (< 4m) Ground Improvement Trials

Goal: Thicken Non-Liquefying Surface Layer/Crust

Evaluate Performance of Various Ground Improvement Methods

Purpose of Ground Improvement Trials

"One good test is worth a thousand expert opinions"

--Werner Von Braun
Designer of Saturn V Moon Rocket

What is a good test?

CPT Test

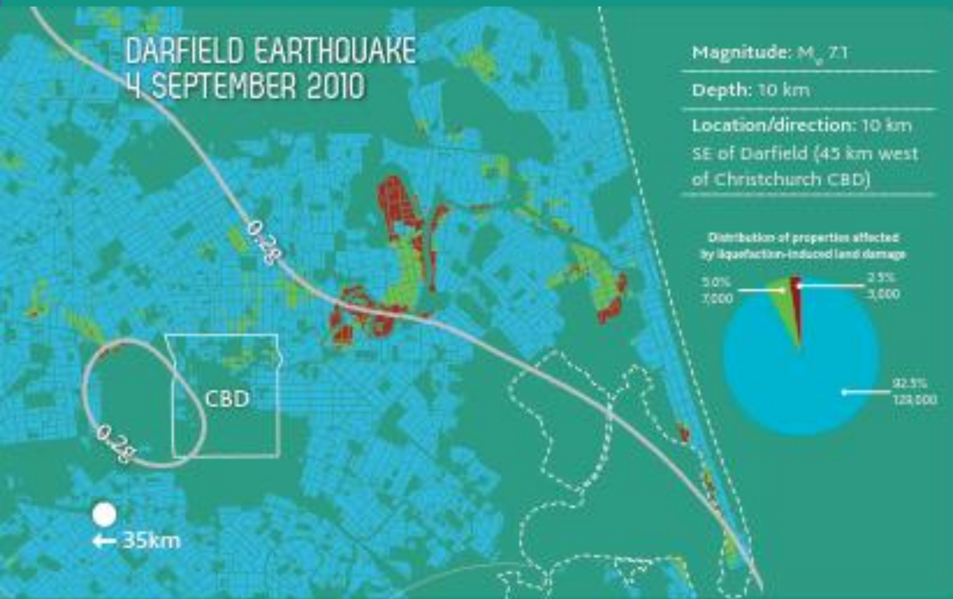
Crosshole V_s – V_p Test

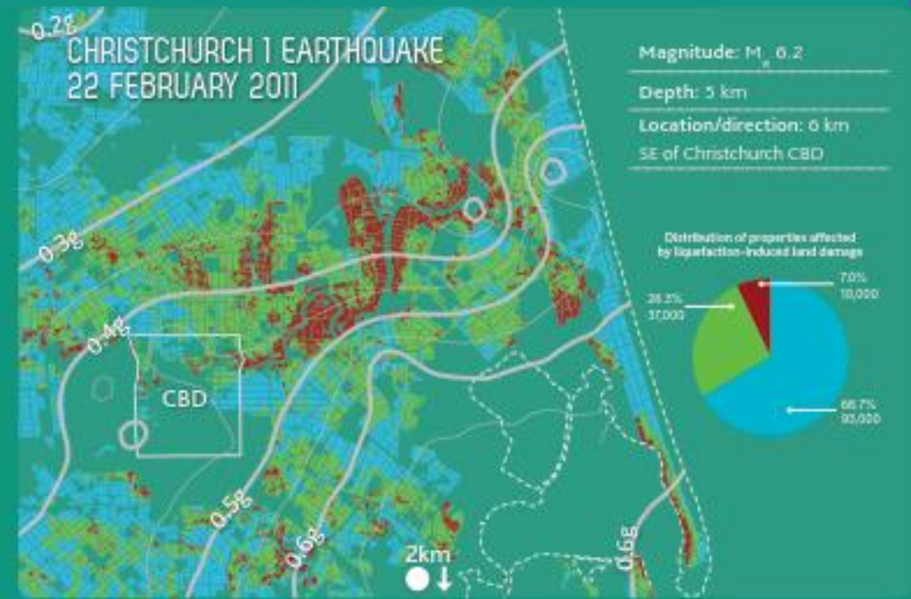
T-Rex Shake Test

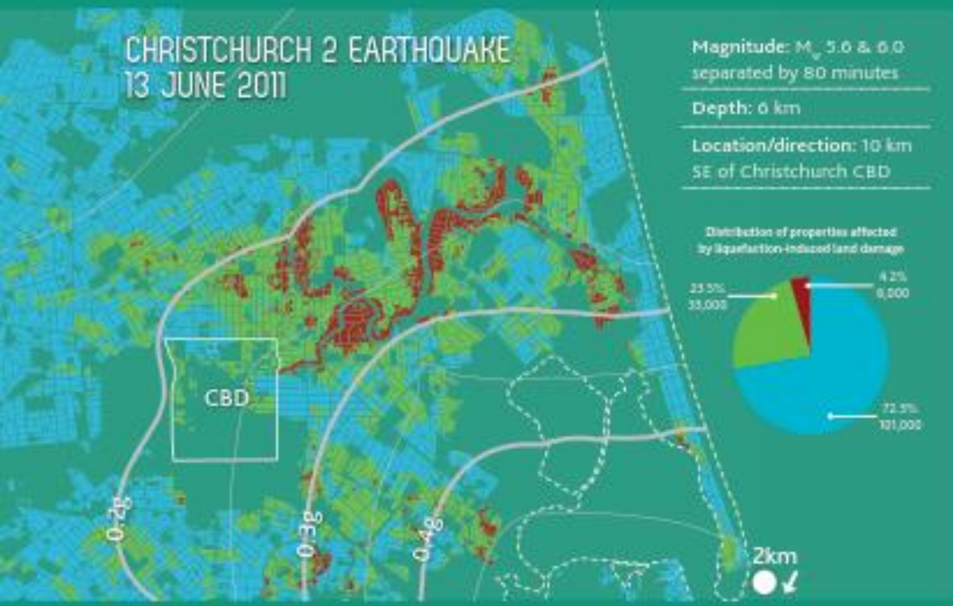
Dynamite (Blast Test)

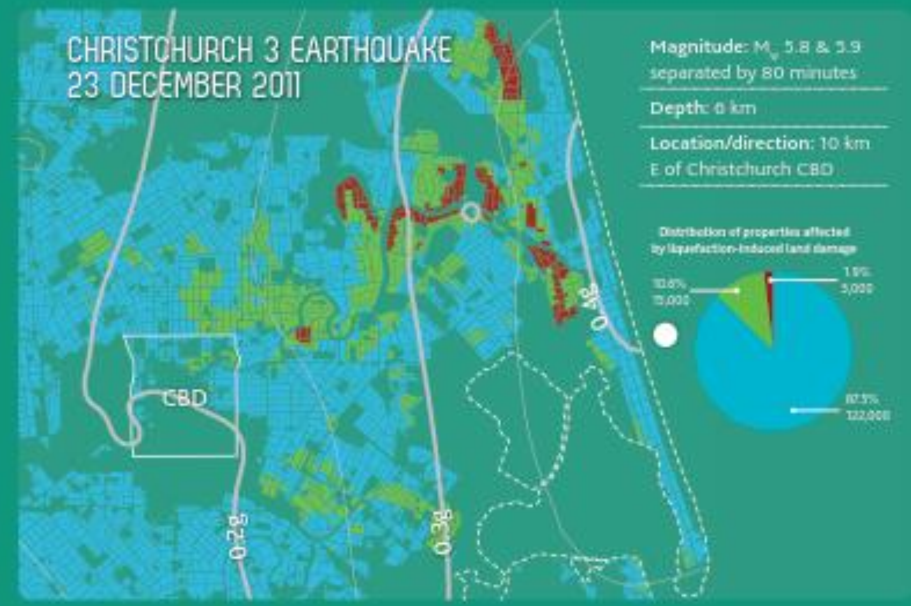
City Scale Liquefaction Laboratory

LIQUEFACTION LABORATORY









Assessment of Liquefaction-Induced Consequences

Site investigations

Geological model

Laboratory testing

Susceptibility

- Bray and Sancio (2006) criteria

Site specific correlation calibration

- FC-I_c relationship

Triggering methods

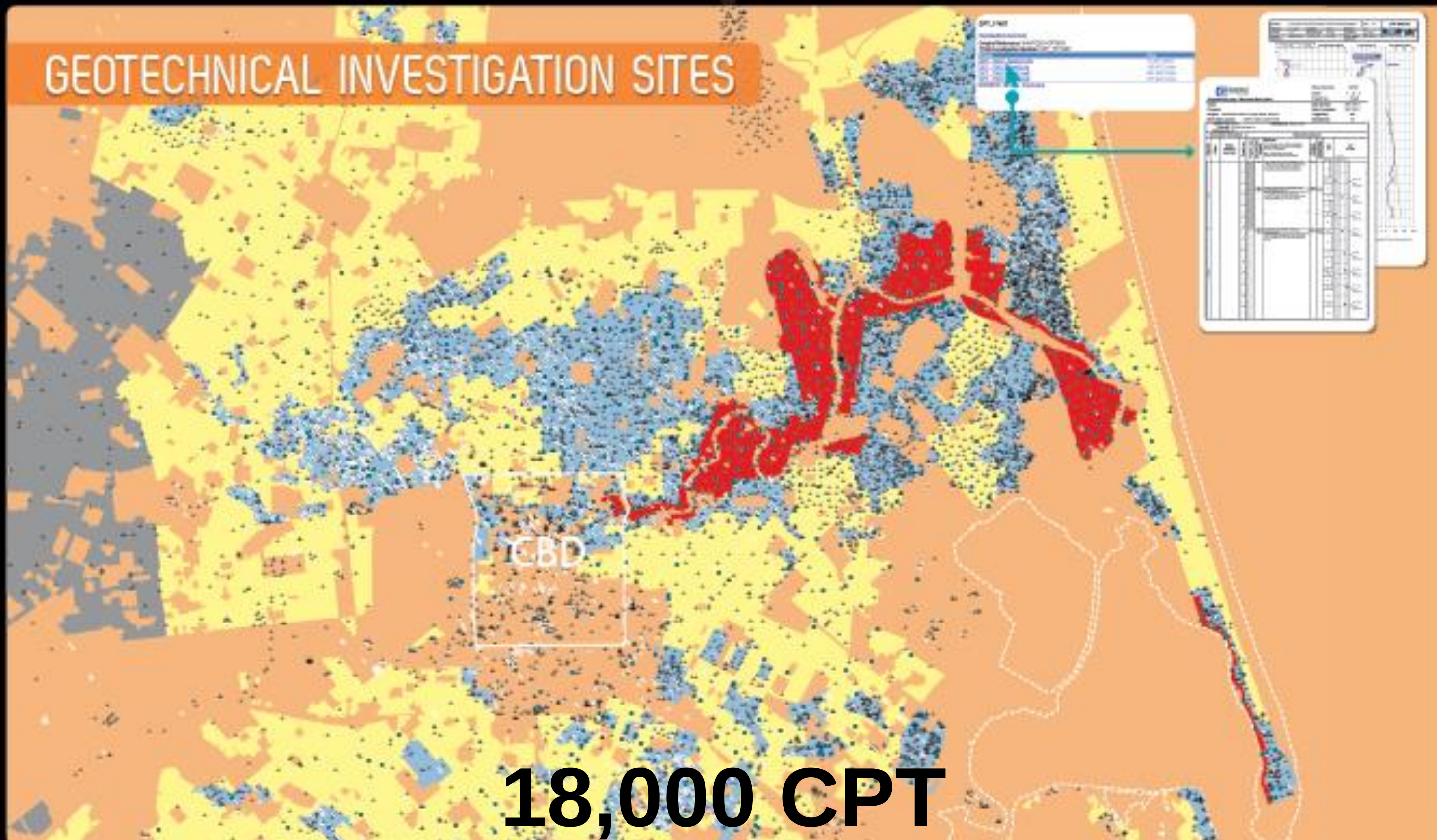
- Robertson & Wride (1998)
- Moss & Seed (2006)
- Idriss & Boulanger (2008)
- Boulanger & Idriss (2014)
- Andrus and Stokoe (2000)
- Kayen et al. (2013)
- Monaco (2005)
- Tsai et al. (2009)
- Robertson (2012)
- Marchetti (2013)

Consequences

- Ishihara Criteria (1985)
- LPI - Iwasaki (1982)
- S_{1VD} - MBIE (2012) calculated settlement index
- LPI_{ISH} – Maurer and Green (2014)
- LSN – van Ballegooy et al. (2014)

Reality check based on observed performance

A WEALTH OF DATA



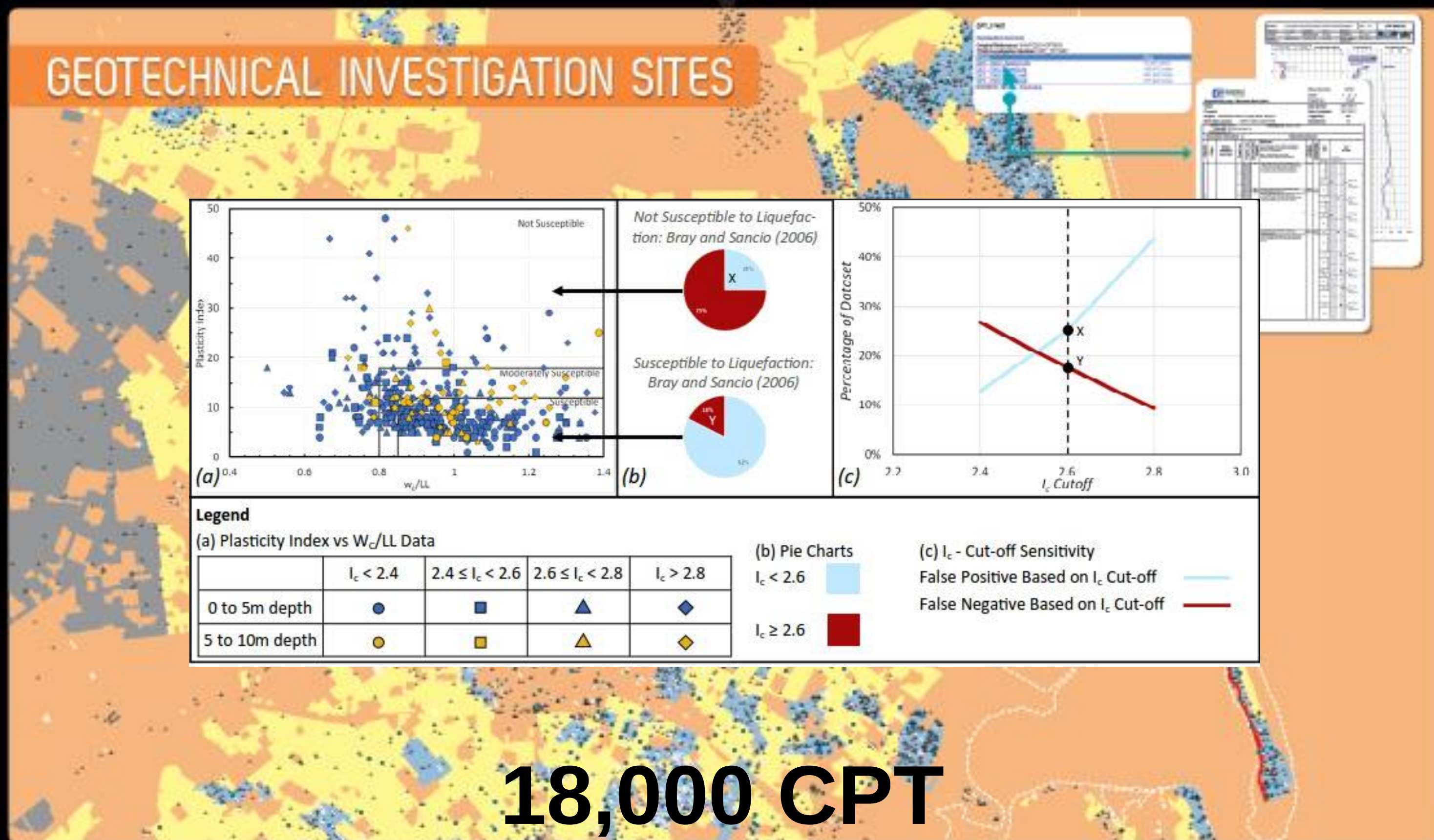
18,000 CPT

4,000 Boreholes with SPT

6,000 Lab Tests

1,000 Piezometers

A WEALTH OF DATA



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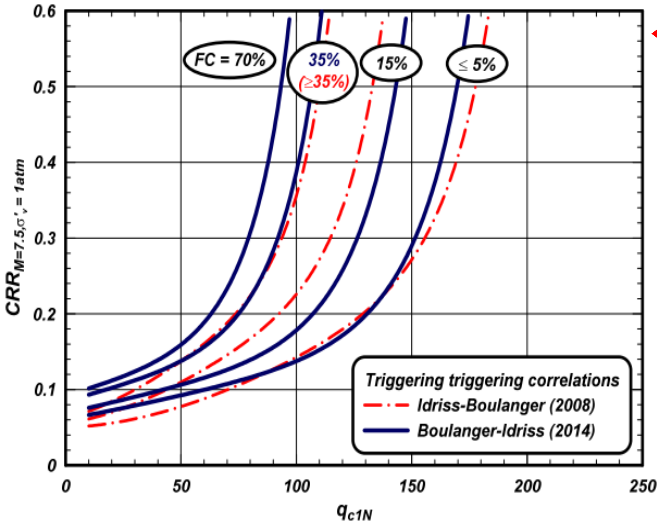
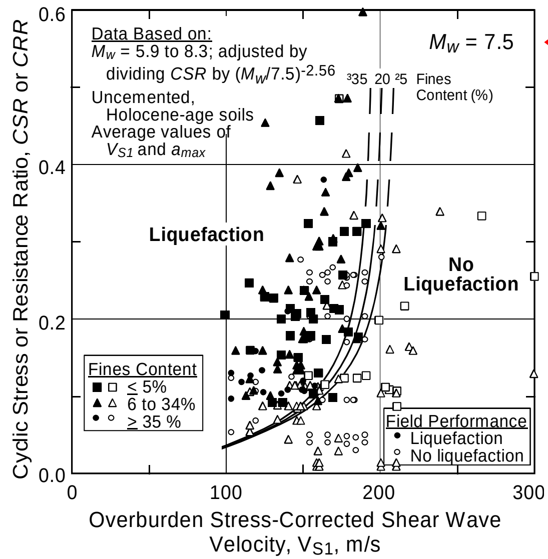
Simplified Liquefaction Triggering Assessment Methods

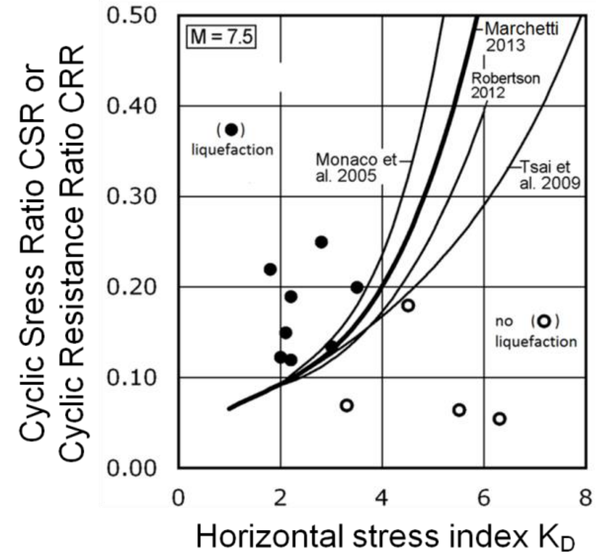


◀ CPT-based CRR Correlations



◀ Shear wave velocity based CRR Correlations

▼ DMT-based CRR Correlations



Which method to use?

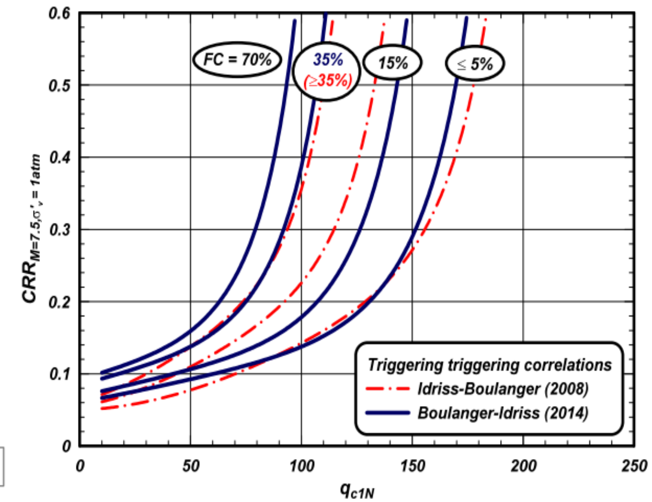
- Robertson & Wride (1998)
- Moss & Seed (2006)
- Idriss & Boulanger (2008)
- Boulanger & Idriss (2014)

- Andrus and Stokoe (2000)
- Kayen et al. (2013)

- Monaco (2005)
- Tsai et al. (2009)
- Robertson (2012)
- Marchetti (2013)

- The one that most appropriate fits the observed land performance?

Boulanger and Idriss (2014)
(Liquefaction triggering method)



No liquefaction when Ic >2.6
(Ic from Zhang et al. 2002)

$$\text{Factor of Safety} = \frac{CRR}{CSR}$$

CRR

CSR

For: P_L = 15%, C_0 = 2.8
P_L = 50%, C_0 = 2.6
P_L = 85%, C_0 = 2.4

$$CRR_{M=7.5,\sigma'_v=1atm} = \exp\left(\frac{q_{c1Ncs}}{113} + \left(\frac{q_{c1Ncs}}{1000}\right)^2 - \left(\frac{q_{c1Ncs}}{140}\right)^3 + \left(\frac{q_{c1Ncs}}{137}\right)^4 - C_0\right)$$

$$CSR_{M=7.5,\sigma'_{vc}=1} = 0.65\frac{a_{max}}{g}\frac{\sigma_{vc}}{\sigma'_{vc}} r_d \frac{1}{MSF}\frac{1}{K_\sigma}$$

K_α = 1.0 for flat ground

$$q_{c1Ncs} = q_{c1N} + \Delta q_{c1N}$$

$$MSF = 1 + (MSF_{max} - 1)\left(8.64\exp\left(\frac{-M}{4}\right) - 1.325\right)$$

$$MSF_{max} = 1.09 + \left(\frac{q_{c1Ncs}}{180}\right)^3 \le 2.2$$

$$\Delta q_{c1N} = \left(11.9 + \frac{q_{c1N}}{14.6}\right)\exp\left(1.63 - \frac{9.7}{FC+2} - \left(\frac{15.7}{FC+2}\right)^2\right)$$

$$q_{c1N} = \frac{q_{c1}}{p_a}$$

$$q_{c1} = q_c C_N$$

$$FC = 80(I_C + C_{FC}) - 137$$
$$0\% \le FC \le 100\% \qquad C_{FC} = 0$$

Iterative Loop

$21 < q_{c1Ncs} < 254$

$$K_\sigma = 1 - C_\sigma \ln\left(\frac{\sigma'_{vc}}{p_a}\right) \le 1.1$$

$$C_\sigma = \frac{1}{37.3 - 8.27(q_{c1Ncs})^{0.264}} \le 0.3$$

$$I_c = \left[(3.47 - \log(Q))^2 + (1.22 + \log(F))^2\right]^{0.5}$$

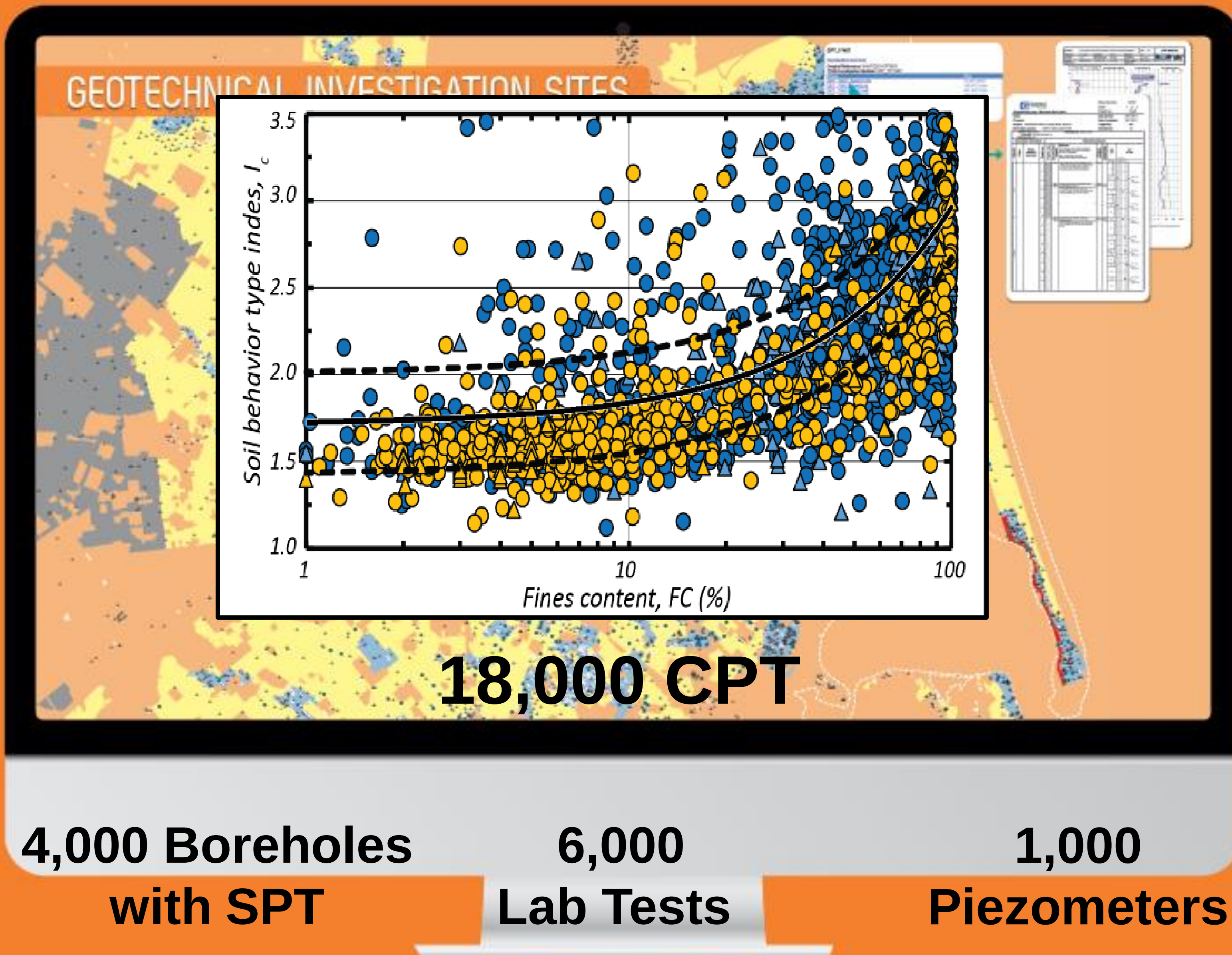
$$r_d = e^{(\alpha(z) + \beta(z)M)}$$

$$C_N = \left(\frac{p_a}{\sigma'_{vc}}\right)^{1.338 - 0.249(q_{c1Ncs})^{0.264}} \le 1.7$$

$$\alpha(z) = -1.012 - 1.126\sin\left(\frac{z}{11.73} + 5.133\right)$$

$$\beta(z) = 0.106 + 0.118\sin\left(\frac{z}{11.28} + 5.142\right)$$

A WEALTH OF DATA



18,000 CPT

4,000 Boreholes with SPT

6,000 Lab Tests

1,000 Piezometers

Prediction of Liquefaction Consequences (Vulnerability)

Depends on:

- Crust thickness, strength, integrity
- Liquefaction triggering susceptibility
- Relative density of the liquefying layers
- Thickness of the liquefying materials
- Location of the liquefying materials
- Topography
- Foundation type
- Surface penetrations
- Interaction with structures
- Earthquake shaking characteristics
- Geological transitions
- Void redistribution, trapped water layers, pore pressure migration & unravelling
- Foreshocks & aftershocks
- Site response & base isolation from deeper liquefaction
- Whether the neighbor left the sprinkler running
- Murphy's law

CPT-based Liquefaction Consequence Index Parameters

$$\boldsymbol{LPI} = \int F(FS)(10 - 0.5z)\,dz$$

$$F(FS) = 1 - FoS \text{ for } FoS < 1.0$$

$$F(FS) = 0 \text{ for } FS \geq 1.0$$

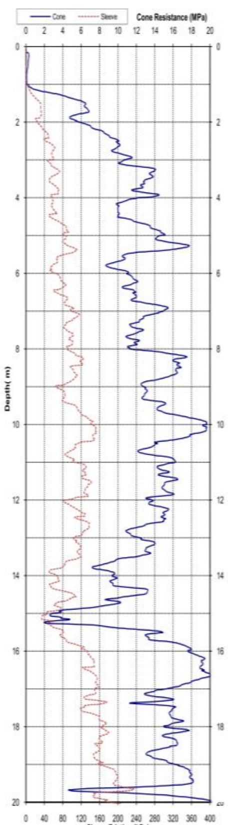
$$S_{1VD} = \int \varepsilon_v \mathrm{d}z$$

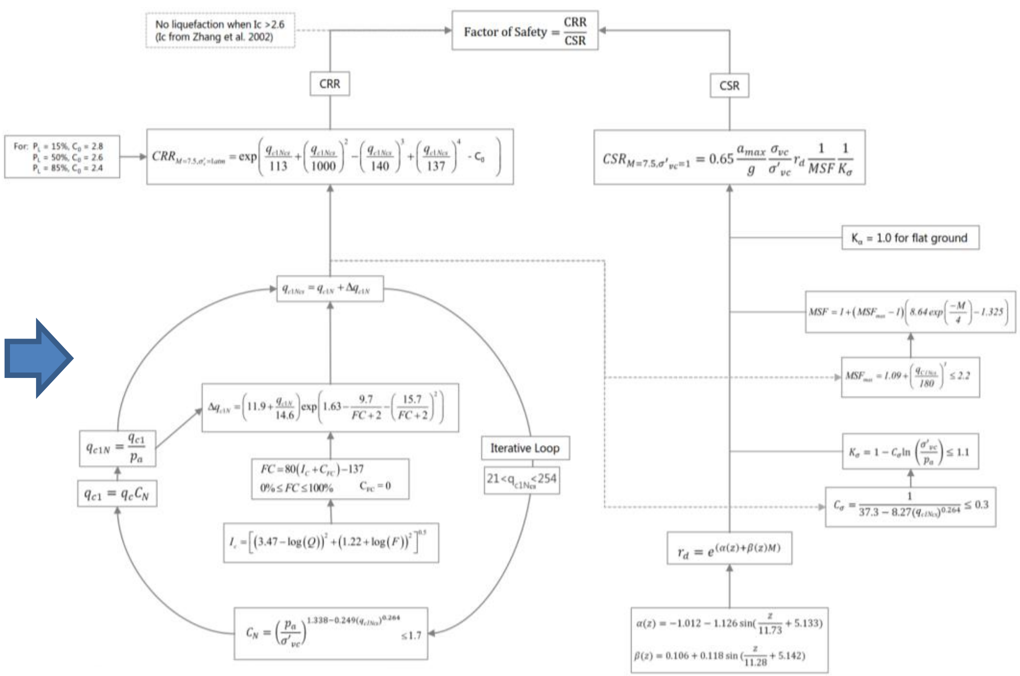
$$\boldsymbol{LPI_{ISH}} = \int F(FS)\frac{25.56}{z}\,dz$$

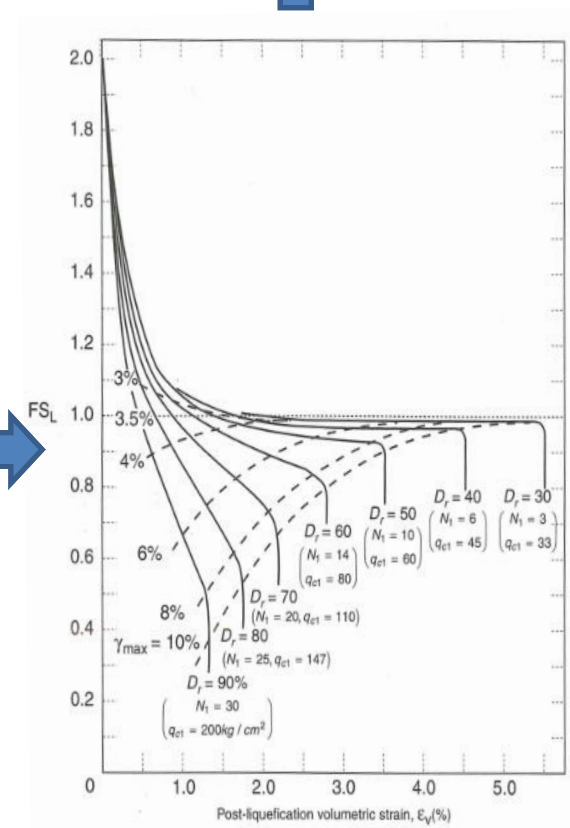
$$F(FS) = \begin{cases} 1 - FS \;\; if\ FS \leq 1 \cap H_1 \cdot m(FS) \leq 3 \\ \;\; 0 \;\; otherwise \end{cases}$$

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

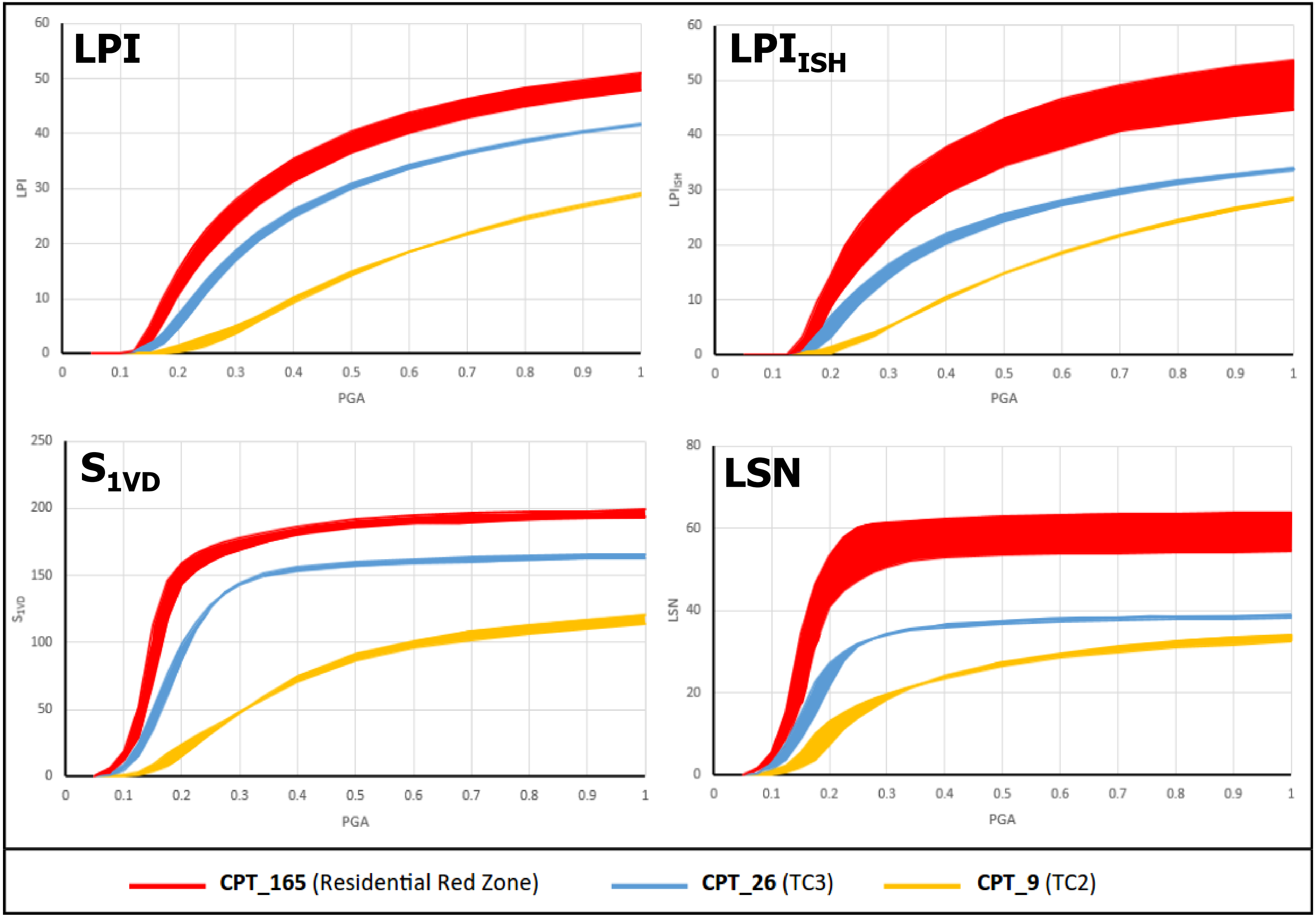
$$LSN = 1000 \int \frac{\varepsilon_v}{z}\mathrm{d}z$$



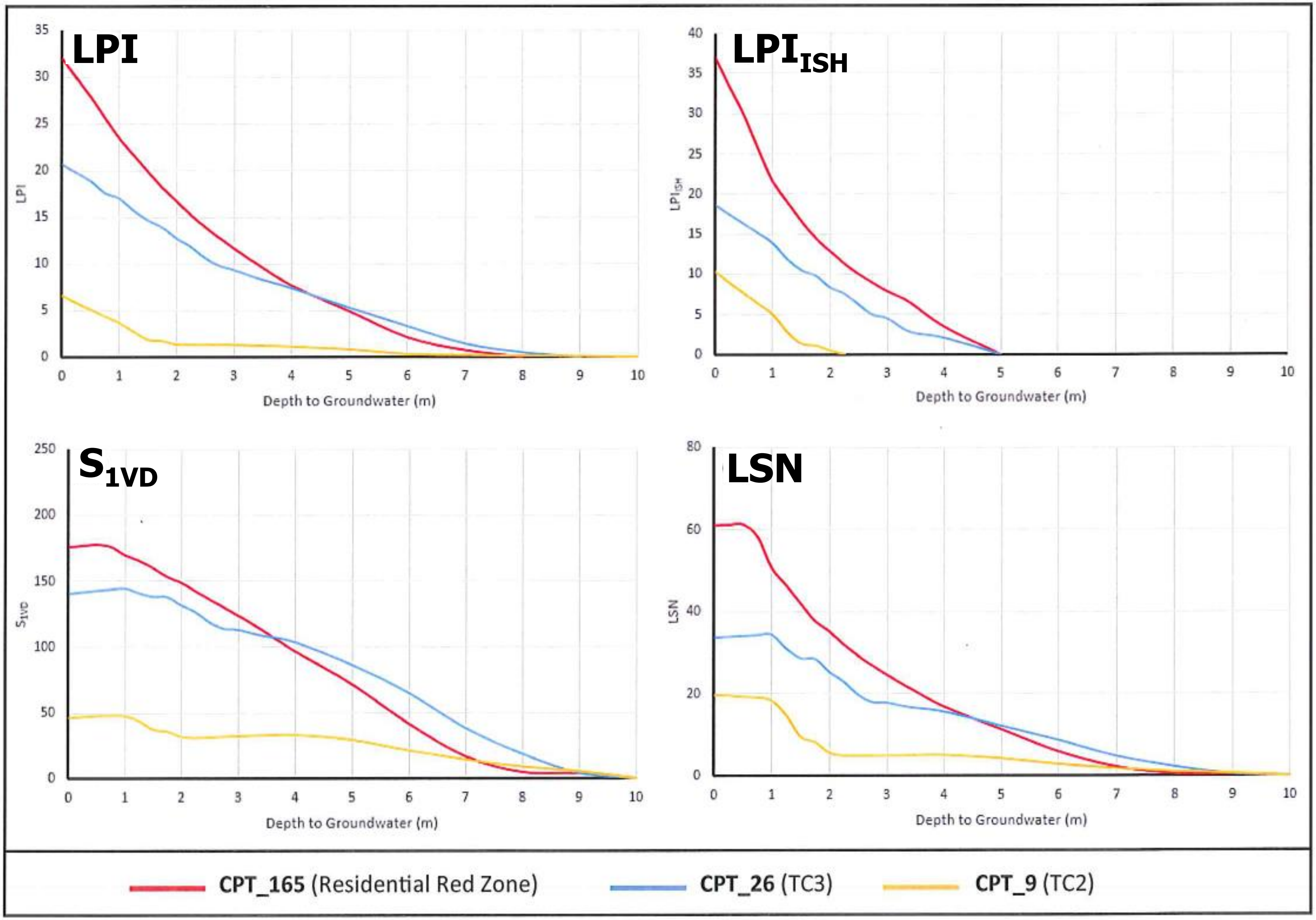




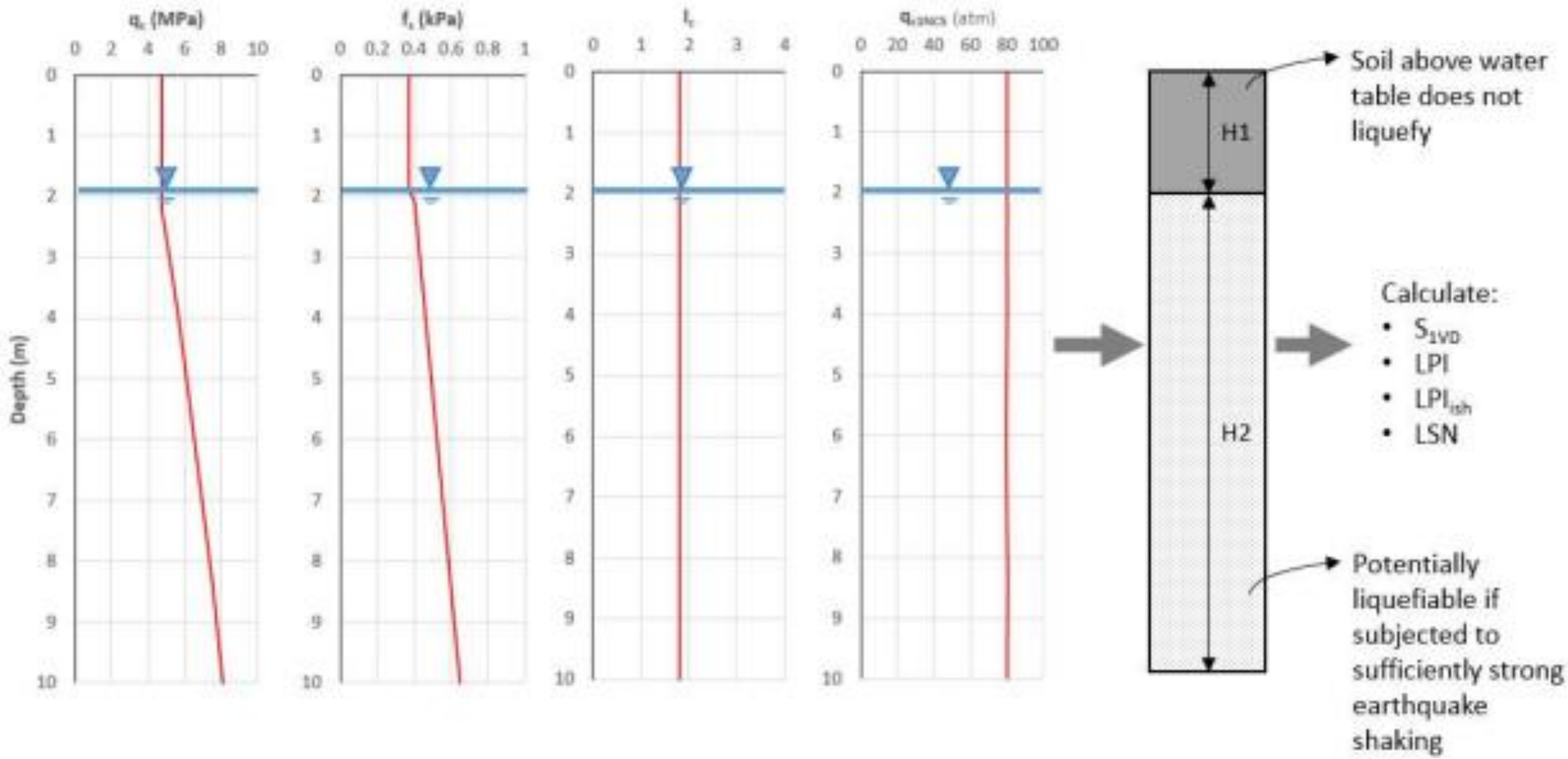
CPT-based Liquefaction Consequence Index Parameters
(sensitivity to PGA)



CPT-based Liquefaction Consequence Index Parameters
(sensitivity to depth to groundwater)



Comparison of the LSN Parameter with the Ishihara (1985) Criteria



Based on an idealised CPT trace

- Calculated for a range of H_1 by varying the depth to the groundwater surface
- Calculated for a range of H_2 by varying the depth of the CPT trace
- Calculated for a range of PGA and relative densities (q_{c1N})

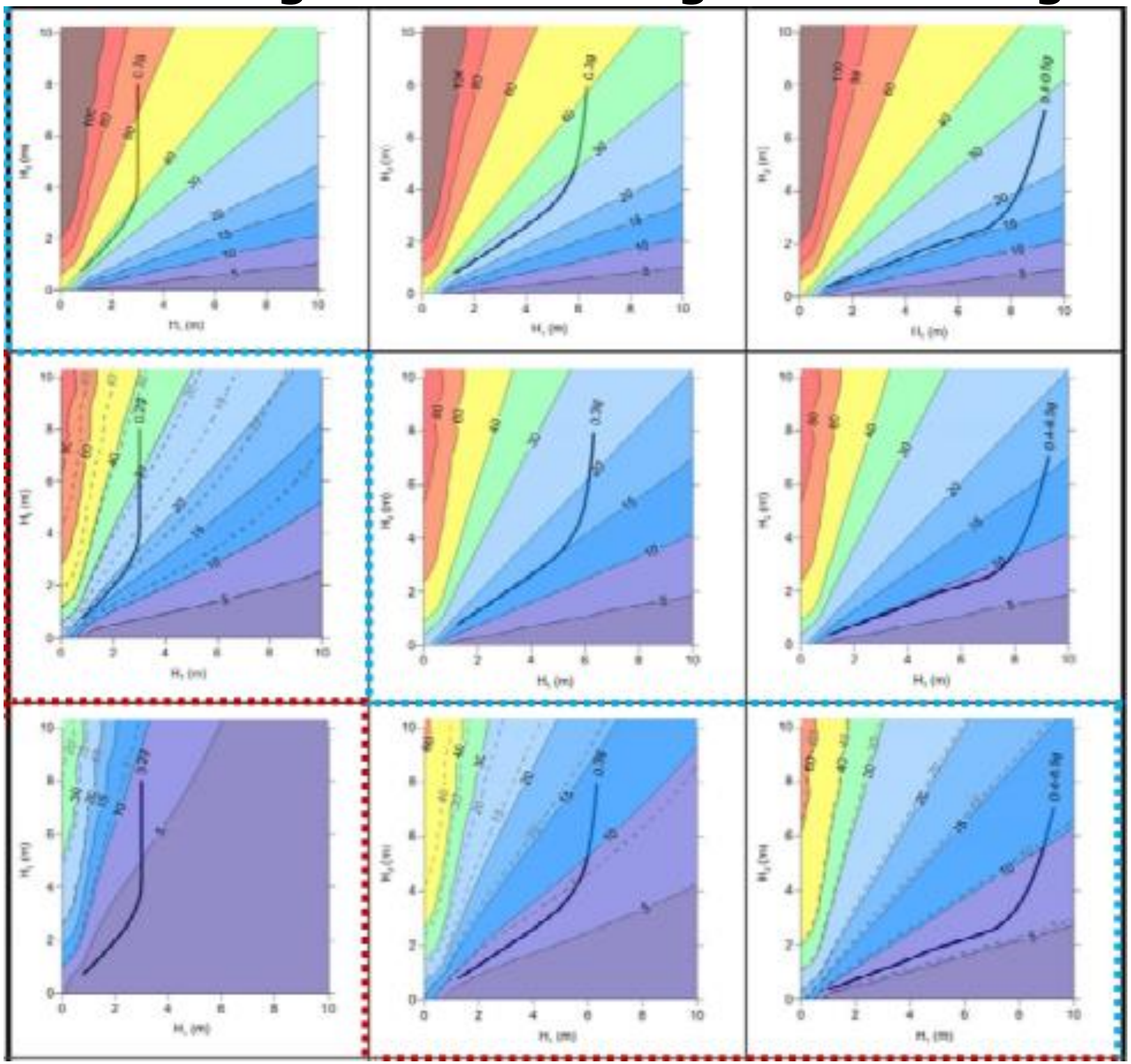
Comparison of the LSN Parameter with the Ishihara (1985) Criteria

PGA=0.2g | PGA = 0.35g | PGA = 0.5g

q_{c1N}=40 atm

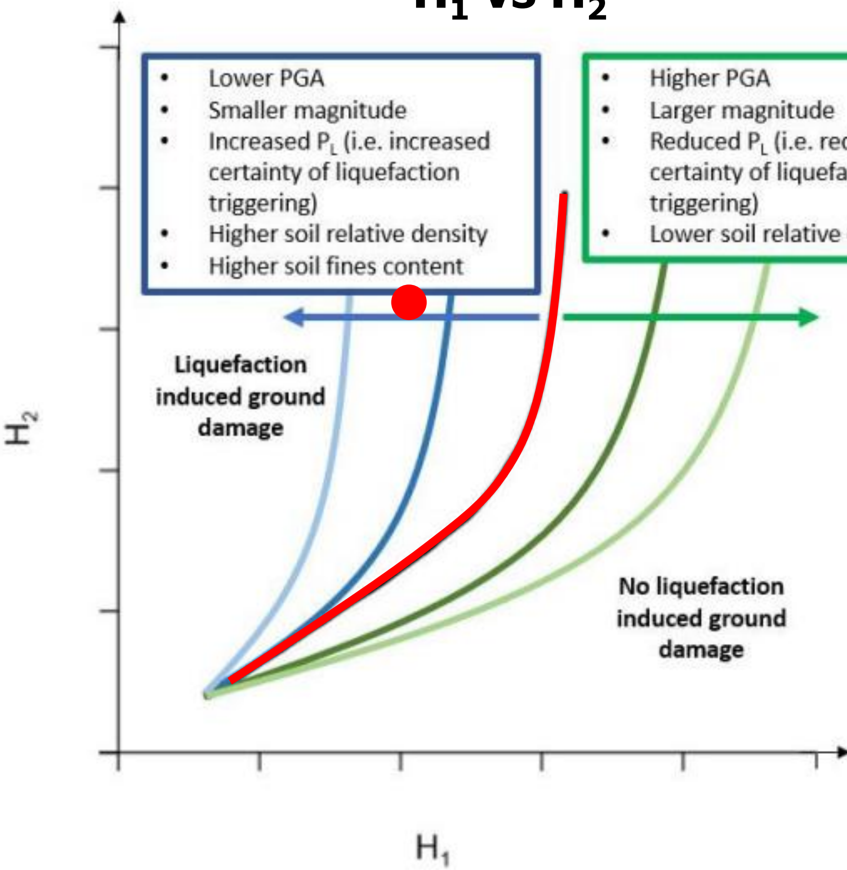
q_{c1N}=80 atm

q_{c1N}=120 atm

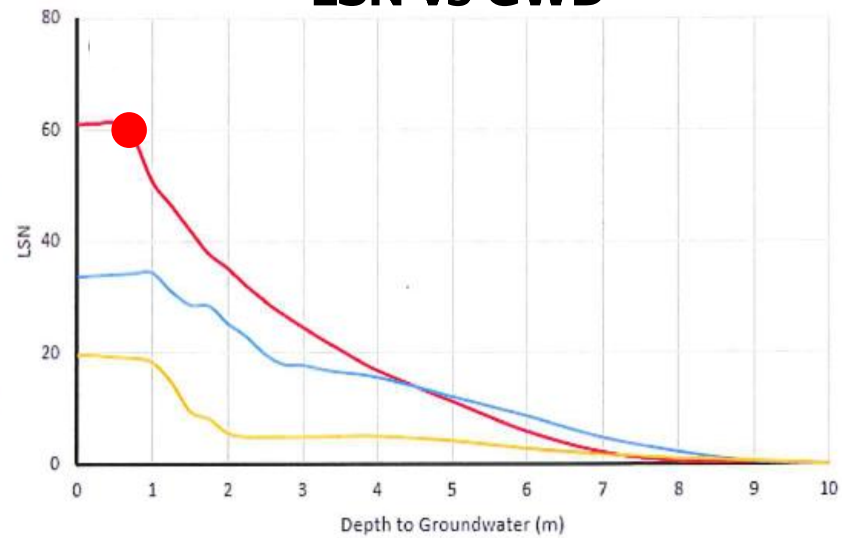


Response of the Liquefaction Vulnerability Parameters to Shallow Ground Improvements

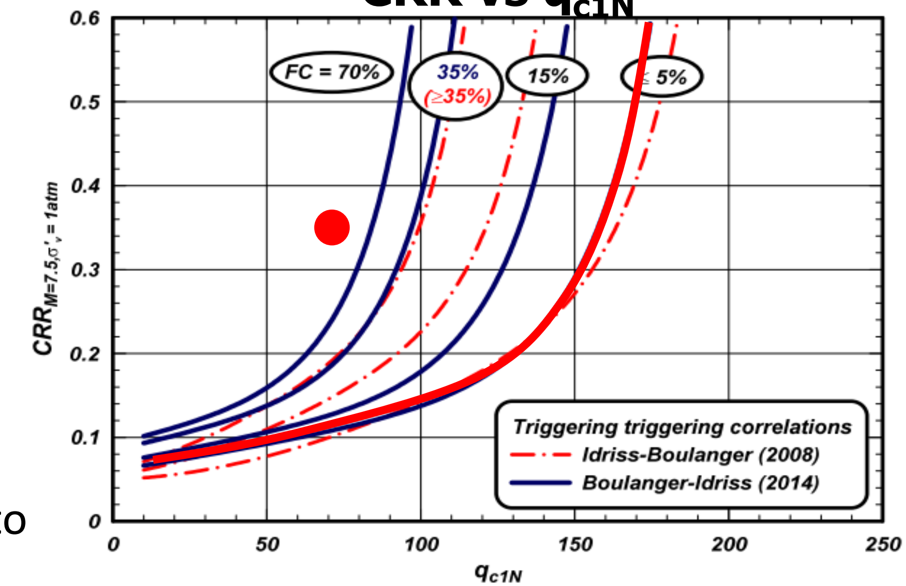
H_1 vs H_2



LSN vs GWD



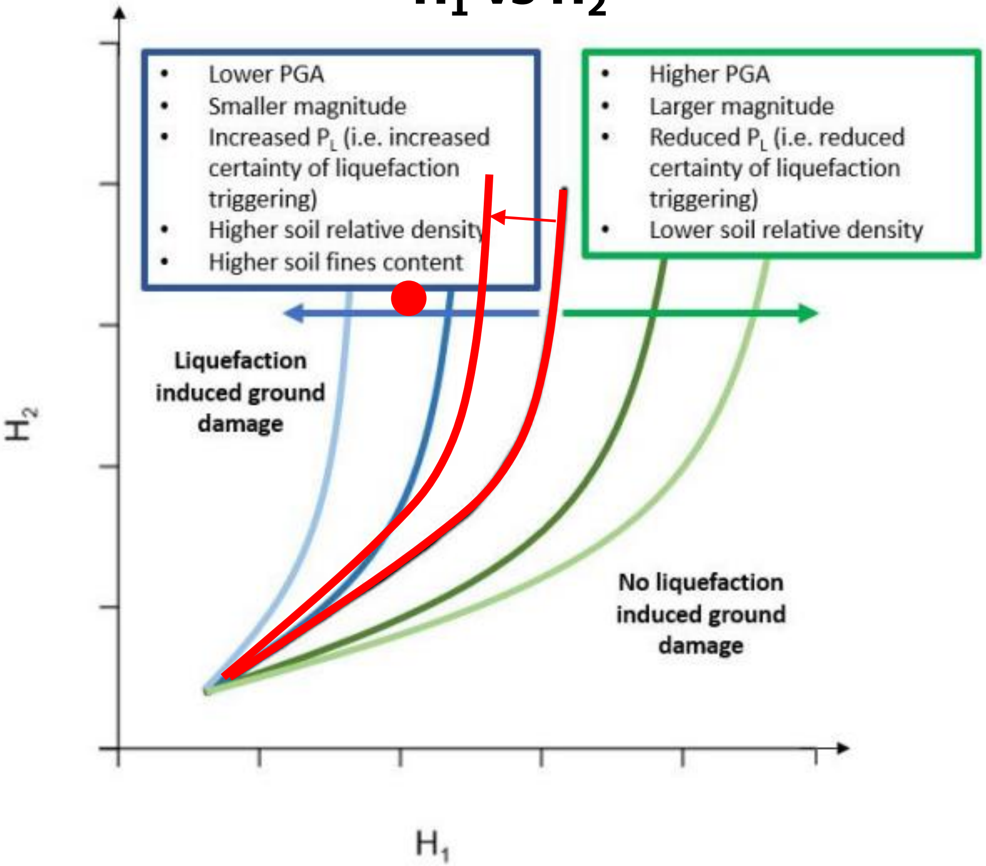
CRR vs q_{c1N}



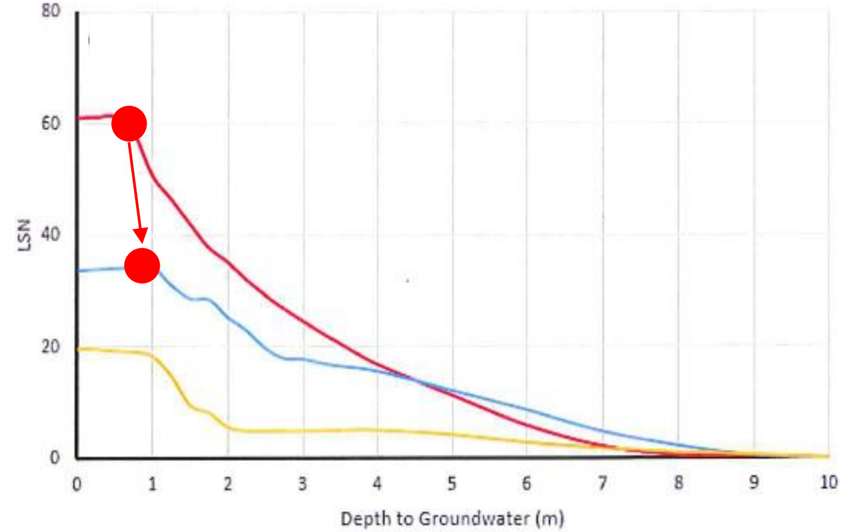
Based on empirical theory, shallow ground improvements decrease the vulnerability of land to the liquefaction hazard

Response of the Liquefaction Vulnerability Parameters to Shallow Ground Improvements

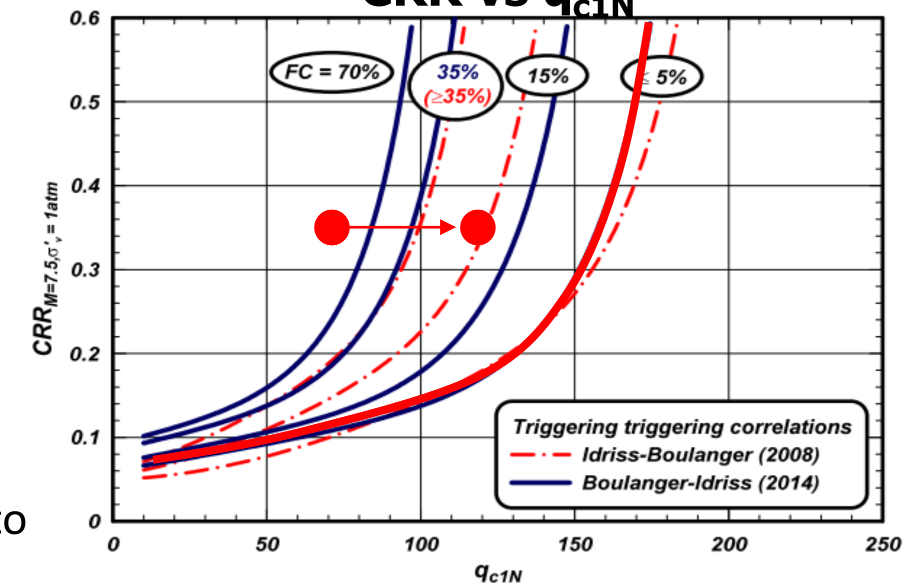
H_1 vs H_2



LSN vs GWD



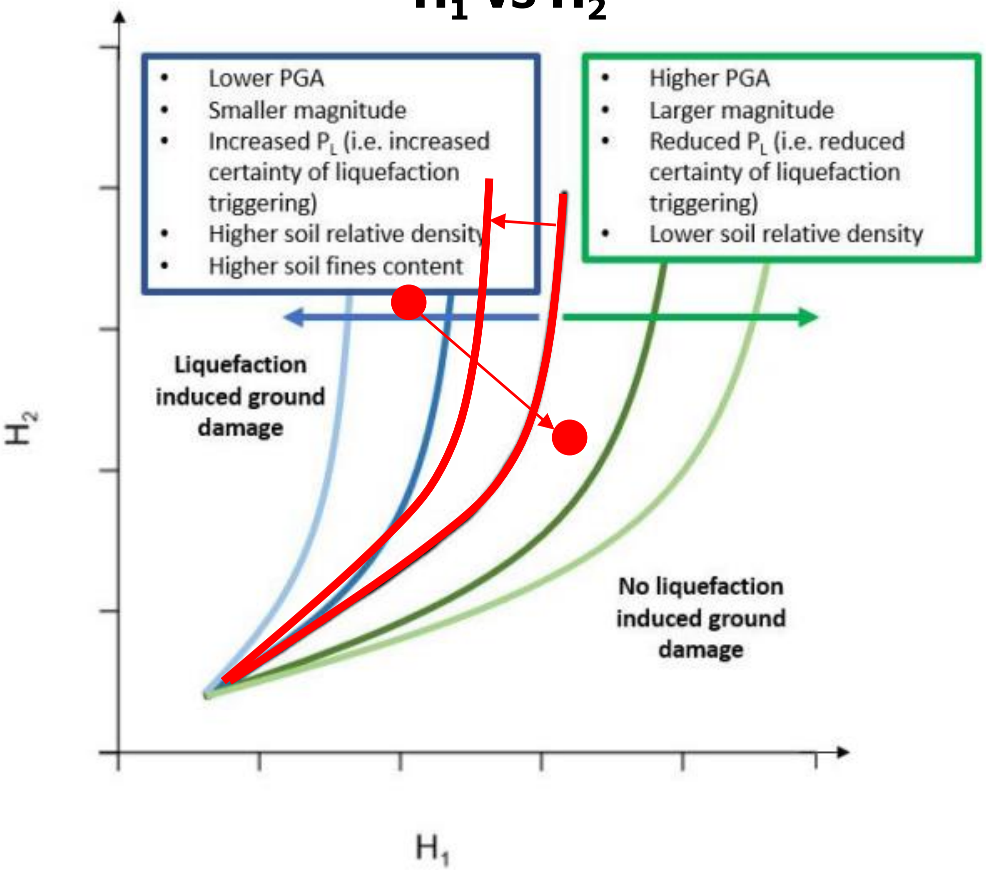
CRR vs q_{c1N}



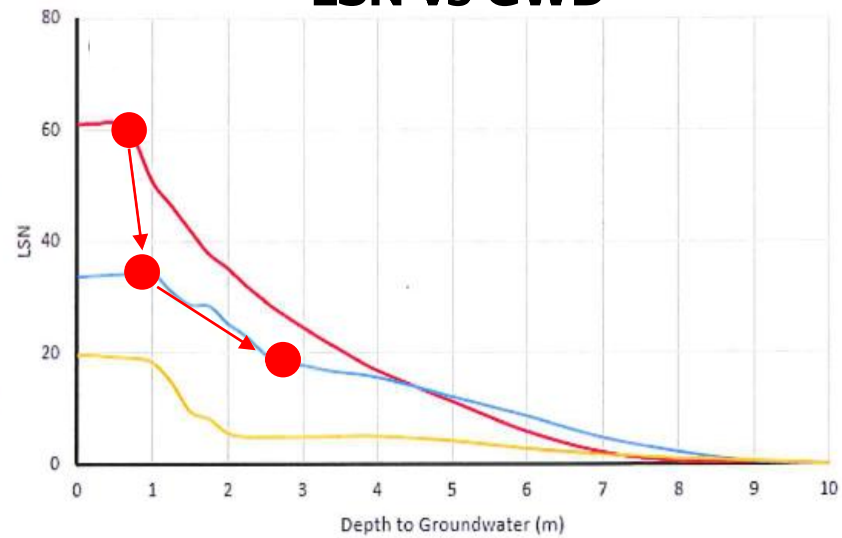
Based on empirical theory, shallow ground improvements decrease the vulnerability of land to the liquefaction hazard

Response of the Liquefaction Vulnerability Parameters to Shallow Ground Improvements

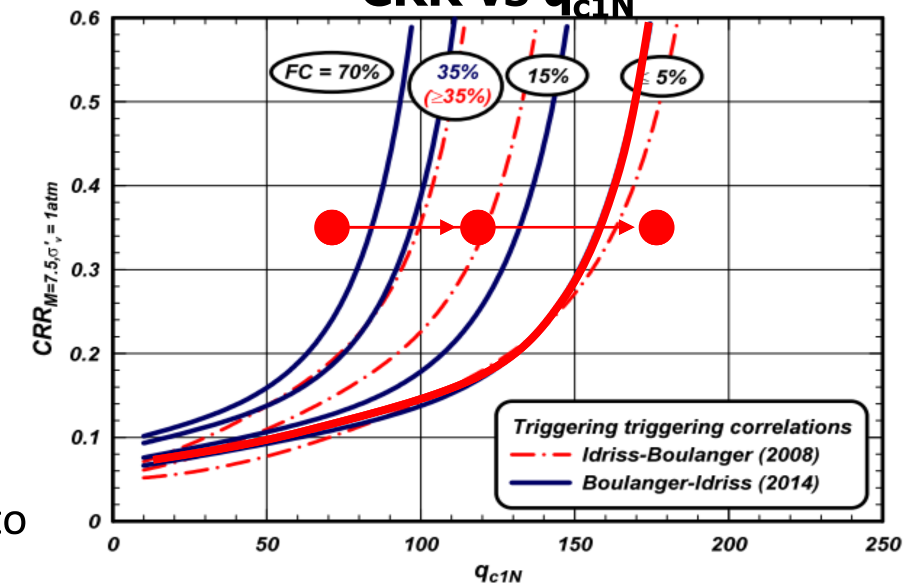
H_1 vs H_2



LSN vs GWD

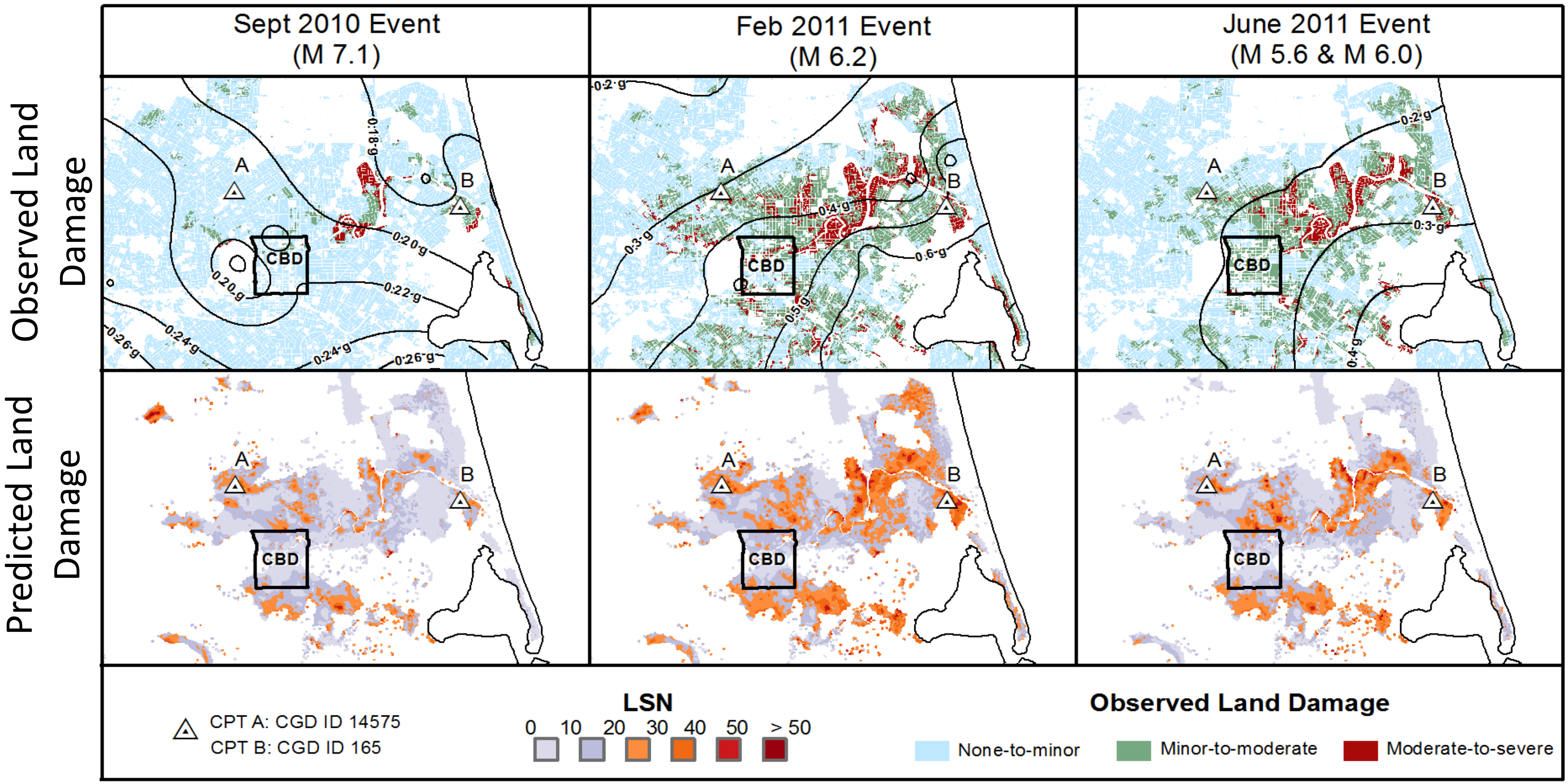


CRR vs q_{c1N}



Based on empirical theory, shallow ground improvements decrease the vulnerability of land to the liquefaction hazard

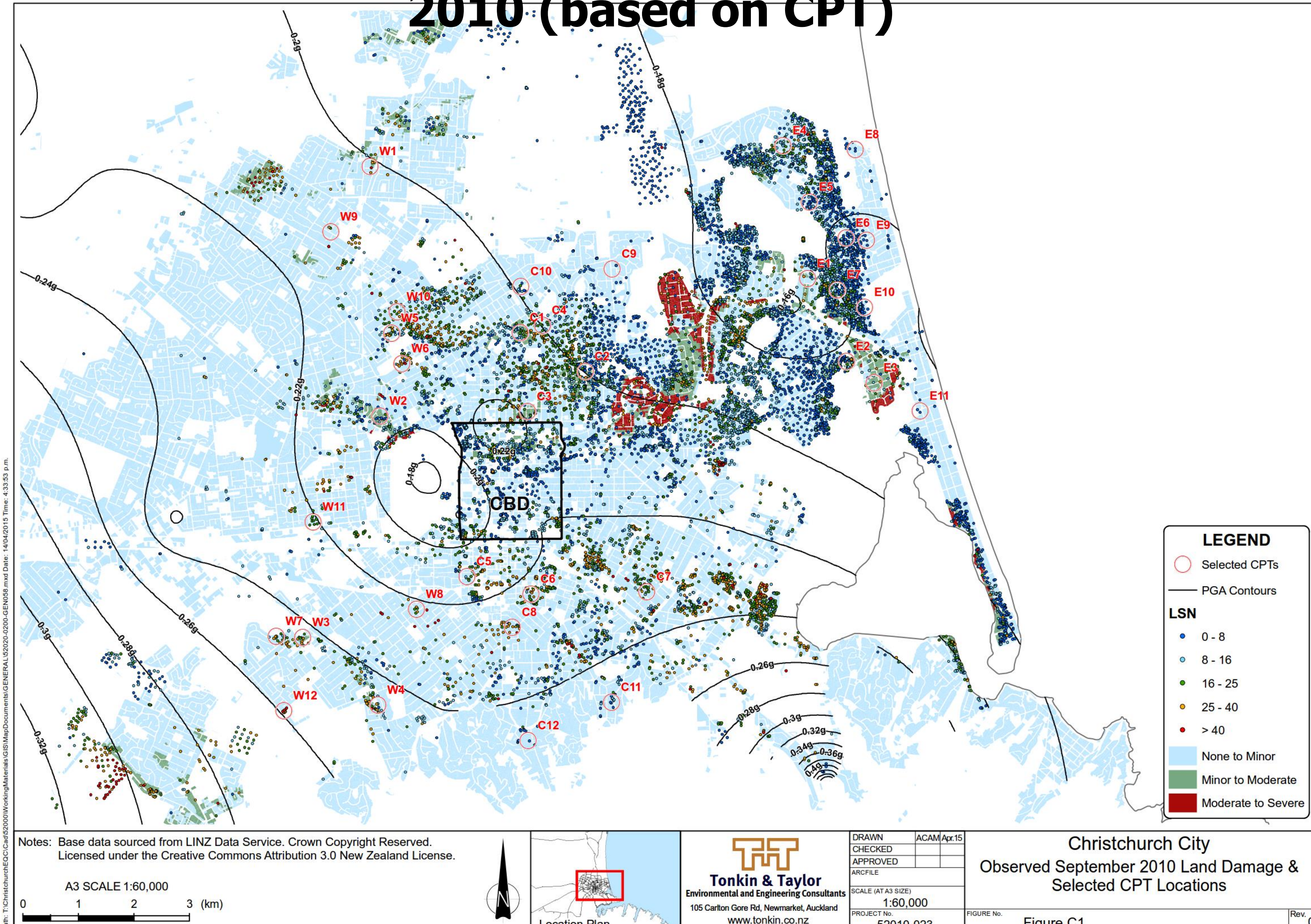
Observed vs Predicted Liquefaction Land Damage (based on CPT)



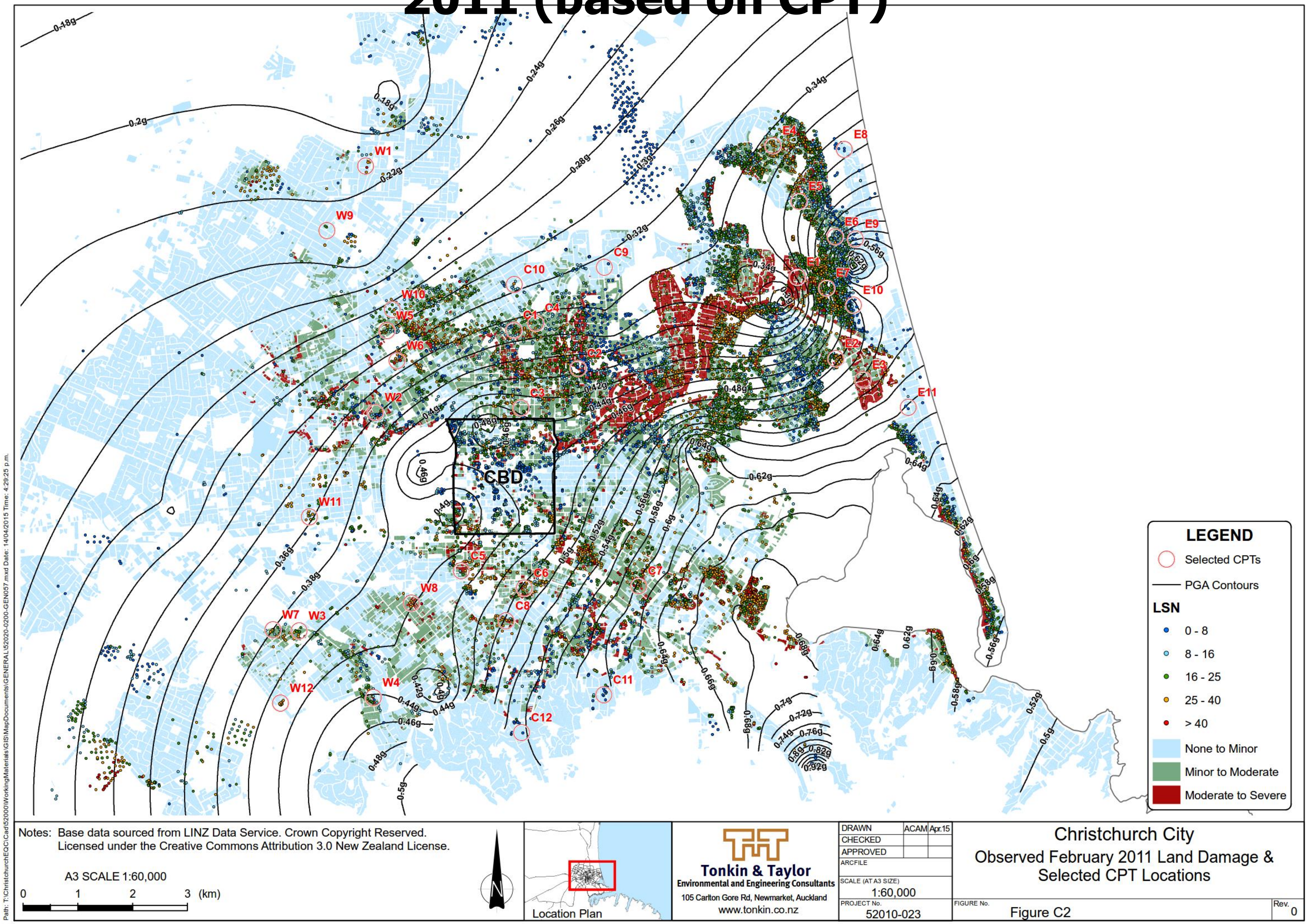
The CPT has proven to be a great screening tool for assessing liquefaction triggering in ChCh. However, in some natural soils with higher fines content it tends to over-estimate triggering

The Boulanger and Idriss (2014) CPT method gave the best fit to the Christchurch observations

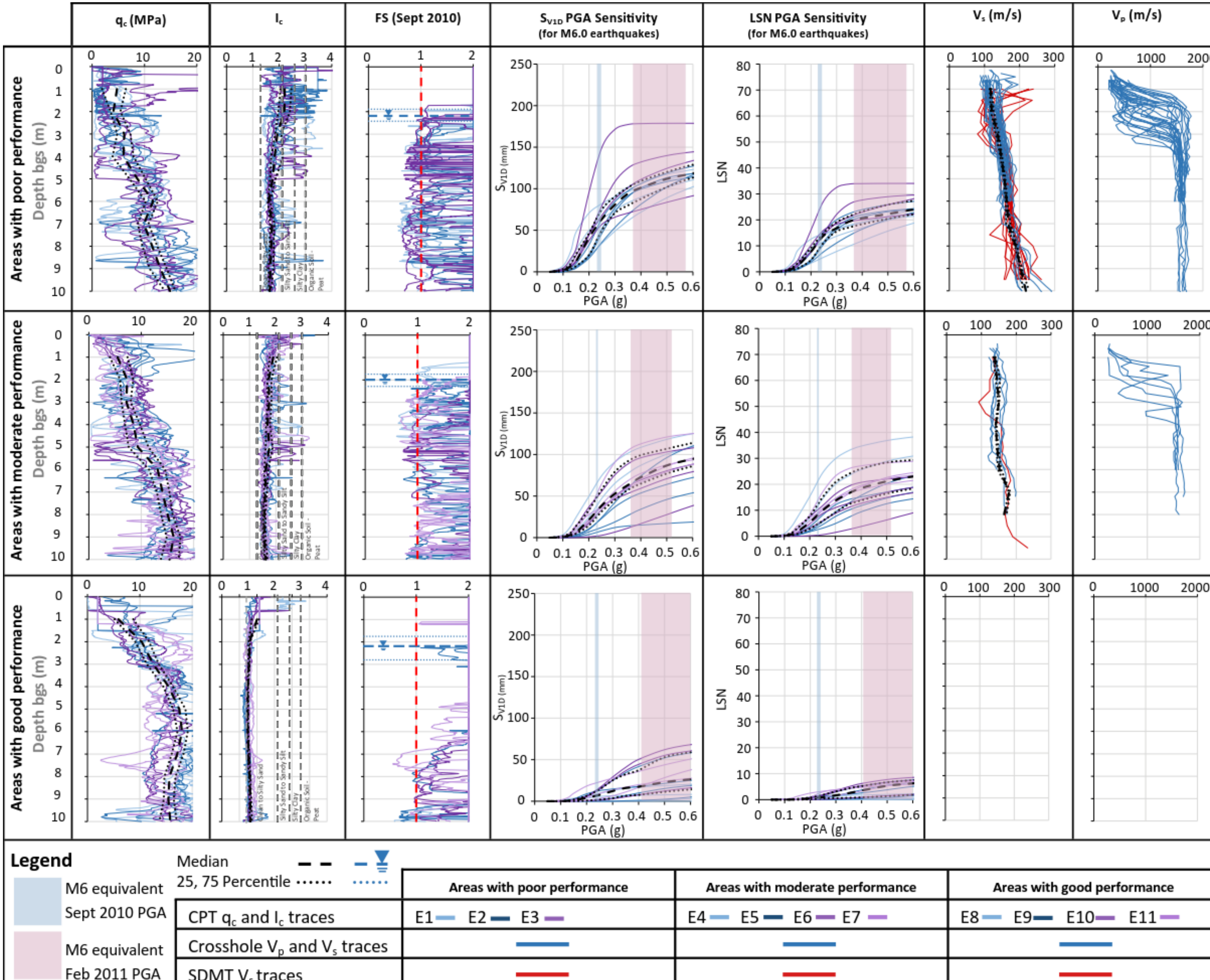
Observed vs Predicted Liquefaction Land Damage in Sept 2010 (based on CPT)



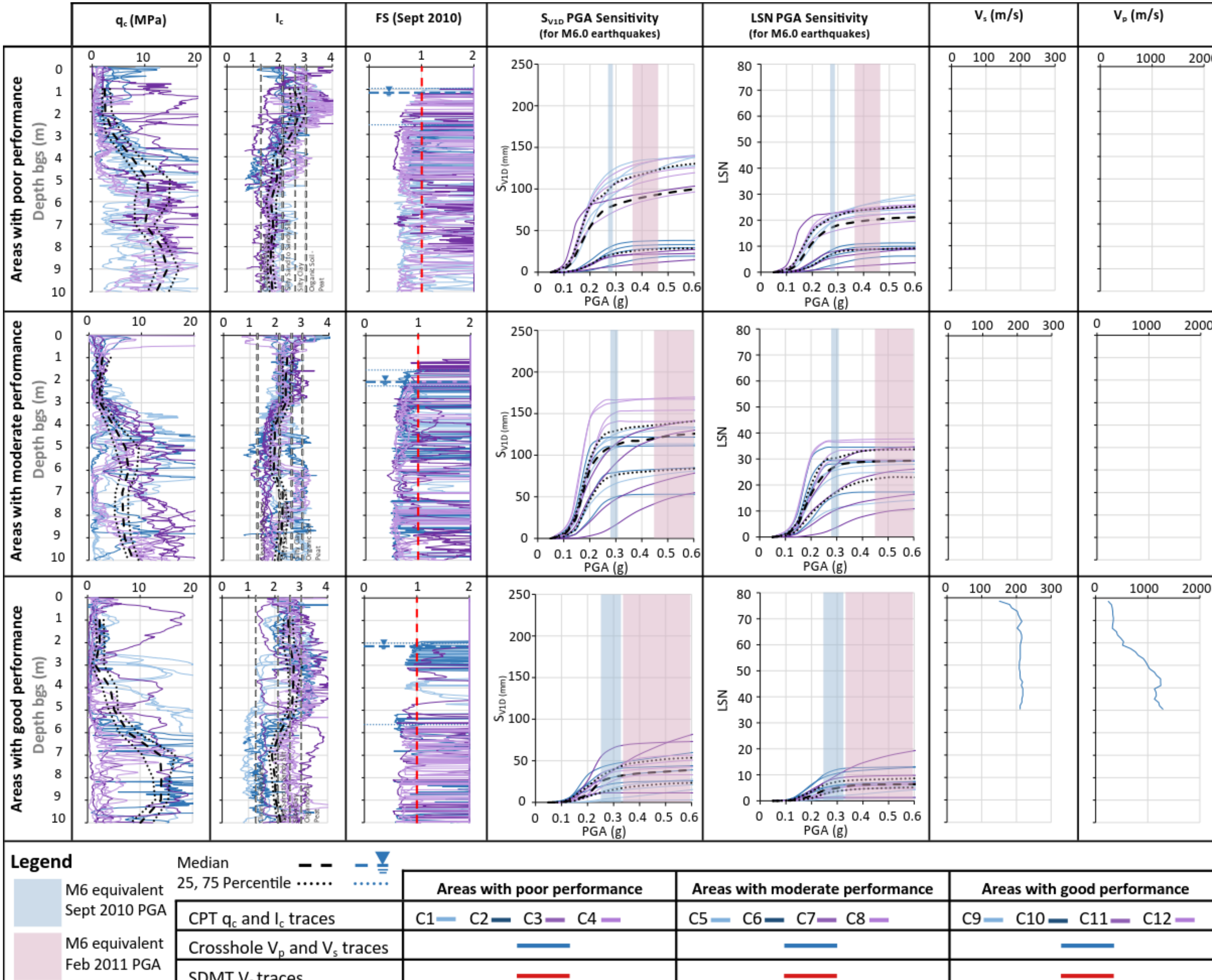
Observed vs Predicted Liquefaction Land Damage in Feb 2011 (based on CPT)



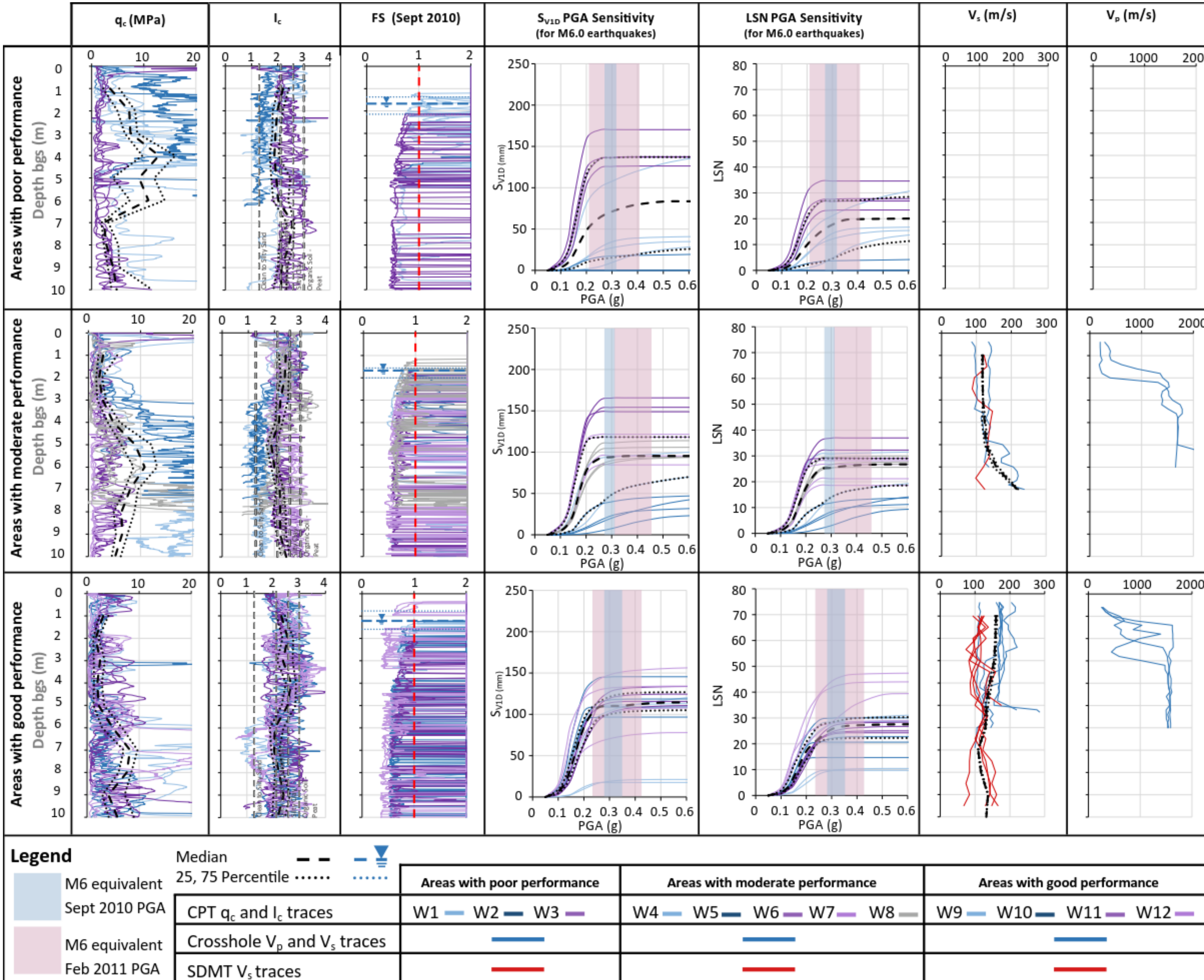
Examination of CPT and V_s-V_p Traces in the East



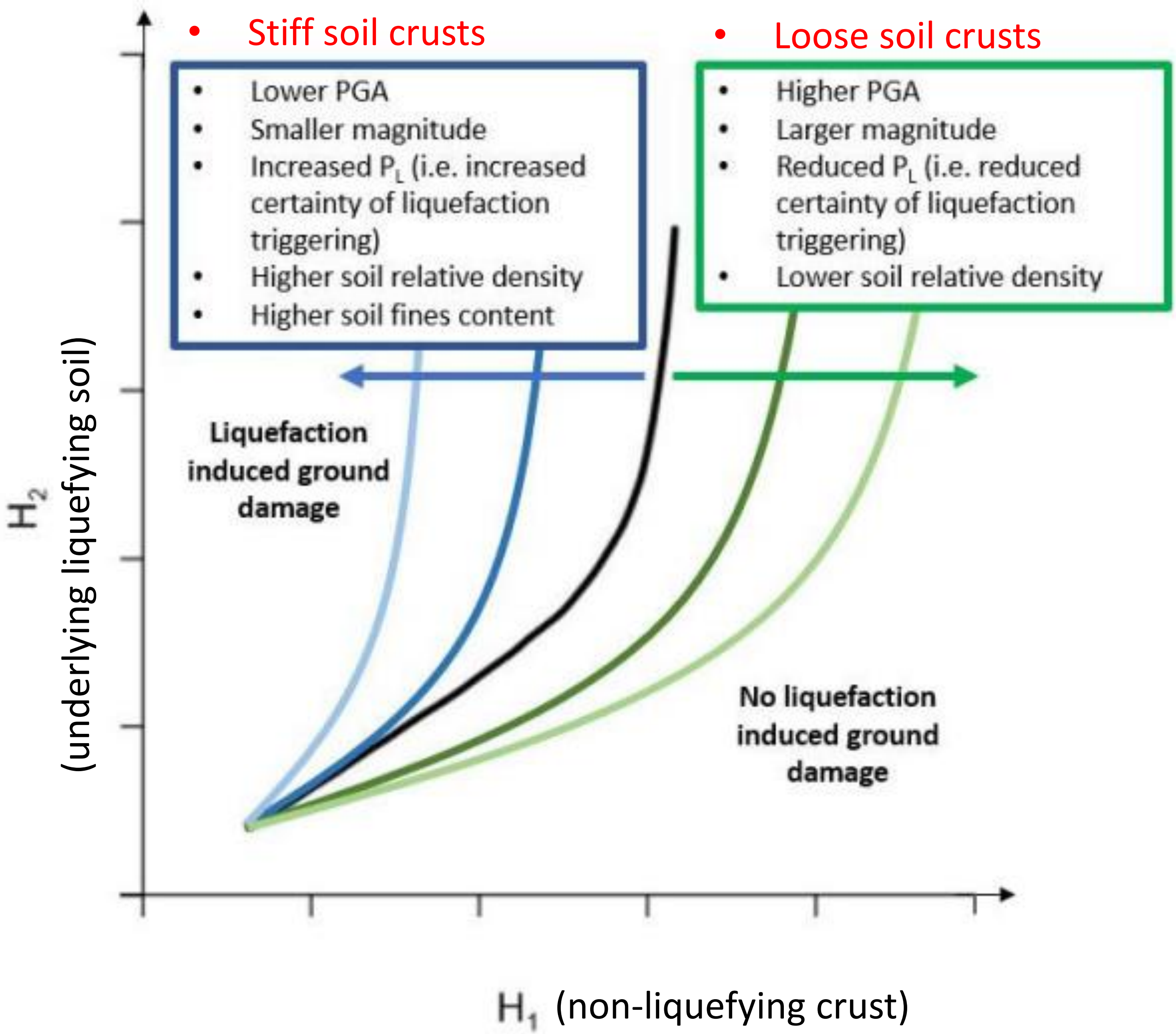
Examination of CPT and V_s-V_p Traces in the Central Area



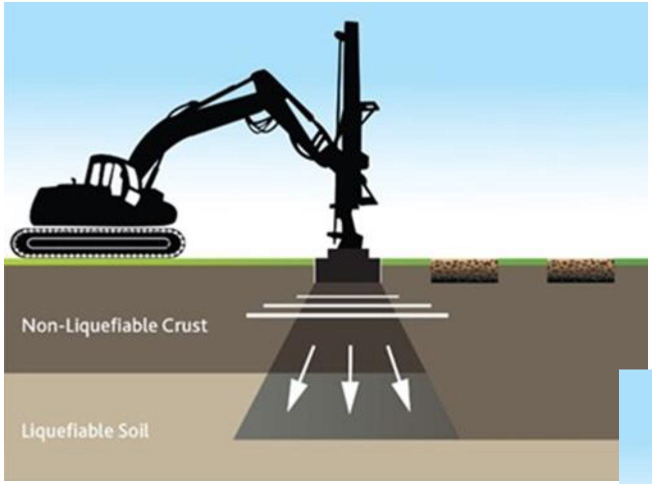
Examination of CPT and V_s-V_p Traces in the West



The Christchurch Liquefaction Laboratory Observations are Consistent with the Observations from Ishihara (1985)

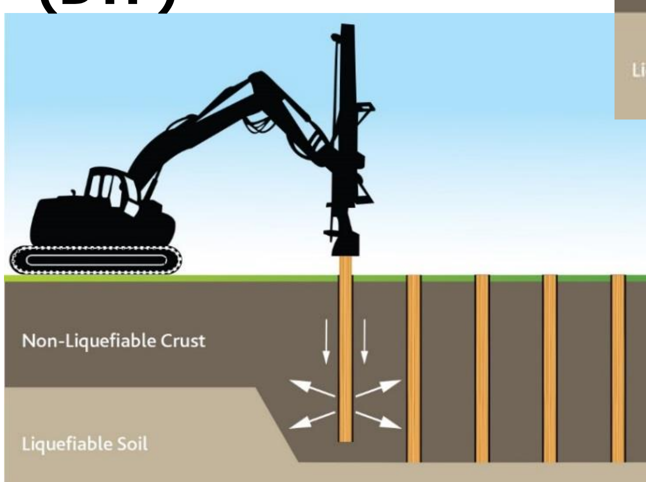


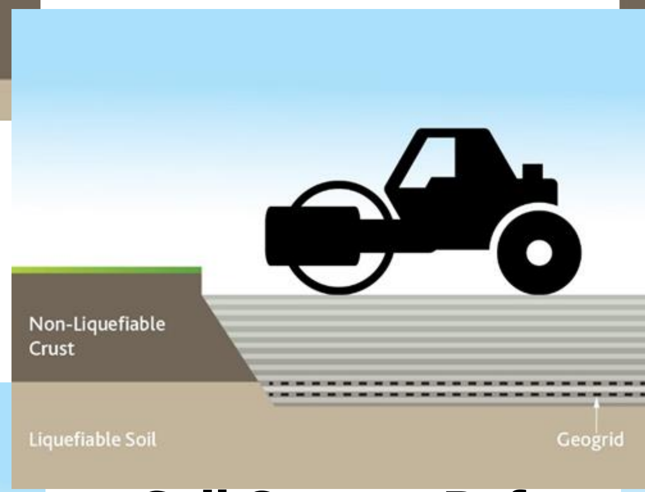
‘Cleared Land’ Ground Improvement Methods Trialled



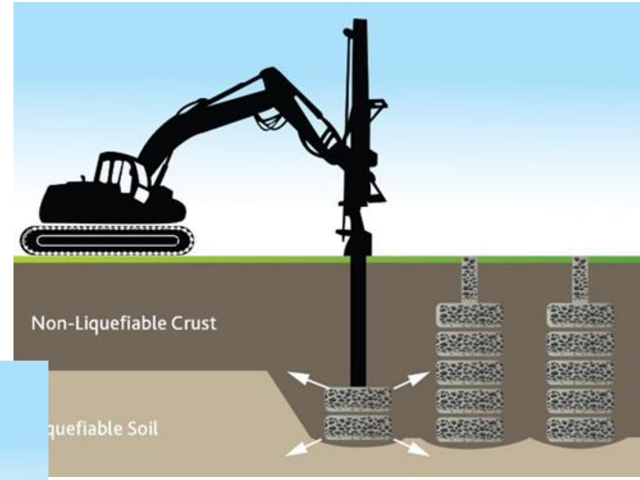
▲ **Rapid Impact Compaction (RIC)**

▼ **Driven Timber Poles (DTP)**



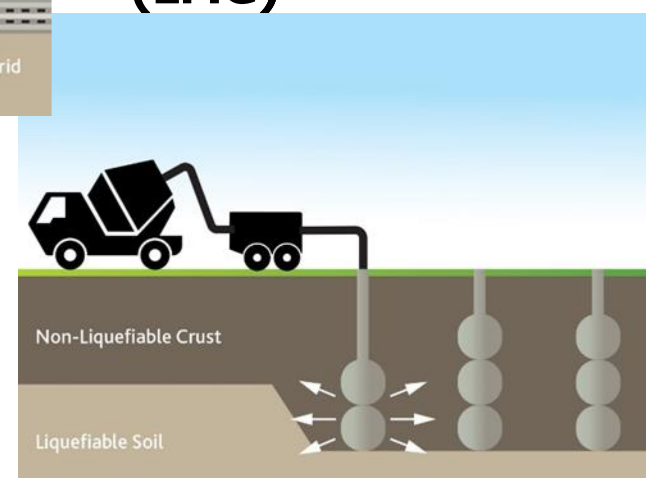


▲ **Soil Cement Rafts (SCR) and Gravel Rafts (GR)**



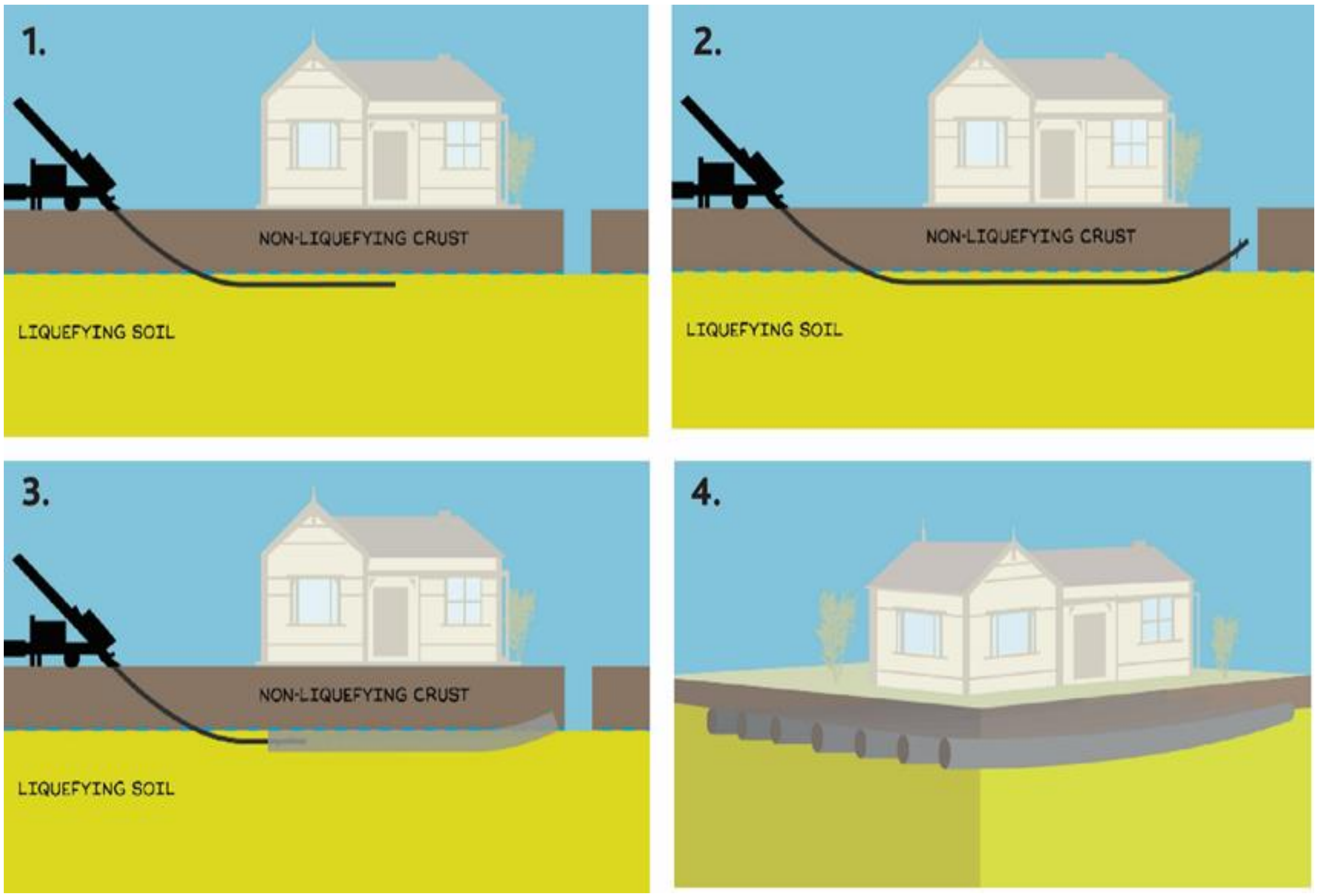
▲ **Rammed Aggregate Piers (RAP)**

▼ **Low Mobility Grout (LMG)**



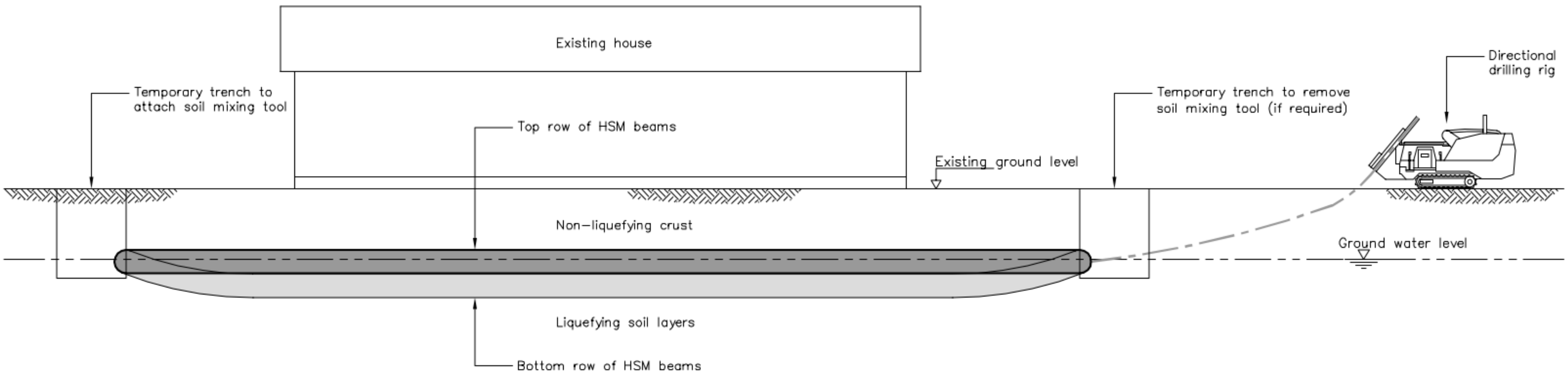
Resin Injection (RES)

Ground Improvement Methods Beneath Existing Houses

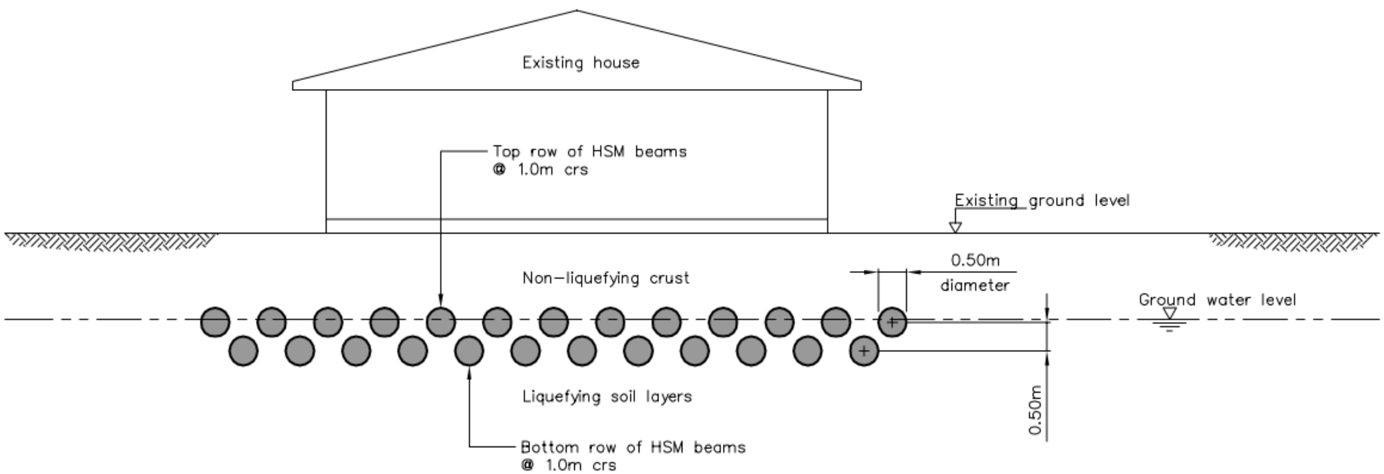


▲ **Horizontal Soil Mixed (HSM) Beams**

Horizontal Soil Mixed (HSM) Beams
(typical cross section and long section layout of HSM beams beneath a residential house)



LONG-SECTION

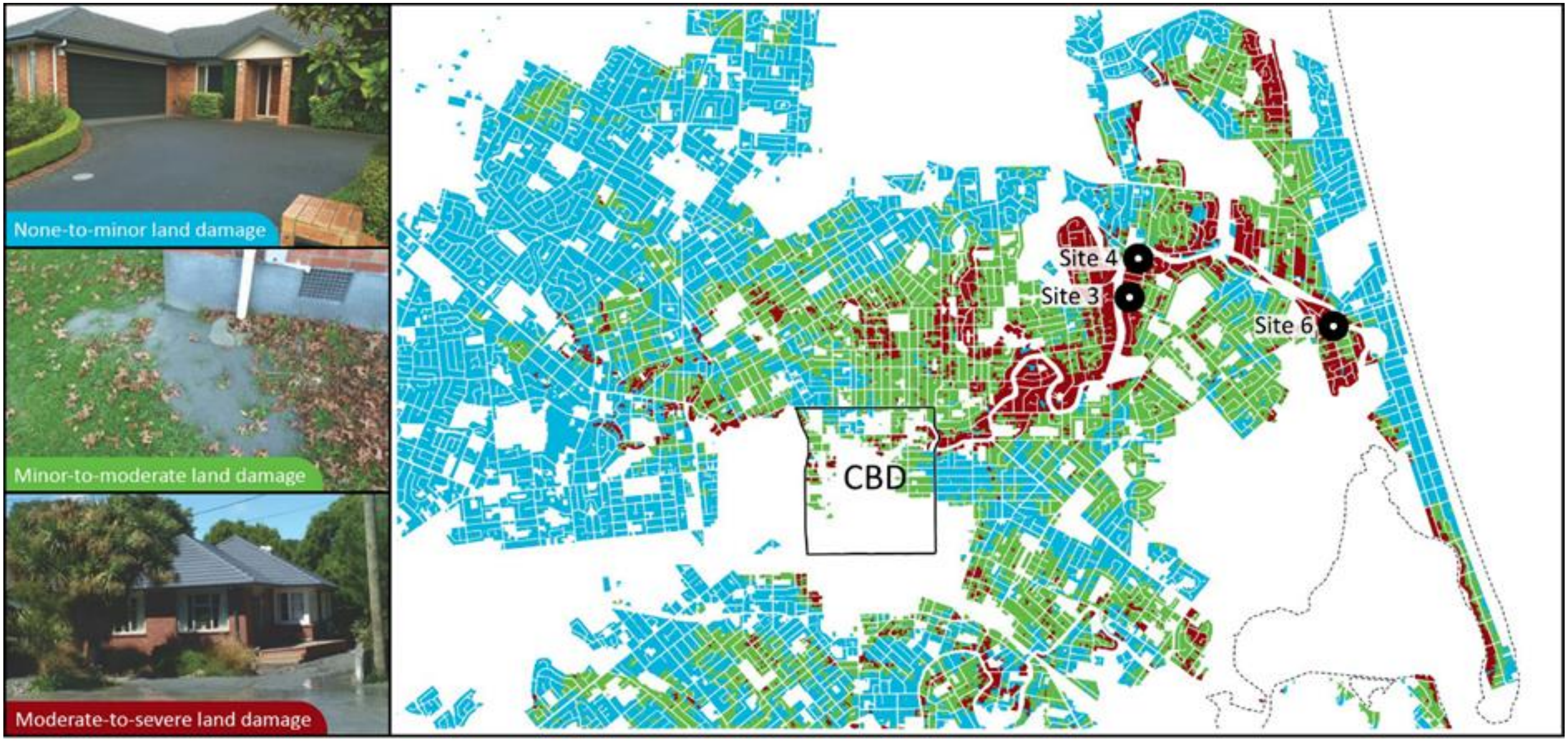


CROSS-SECTION

Horizontal Soil Mixed (HSM) Beams

(photo of exposed HSM beams constructed beneath a residential house)

Ground Improvement Trial Locations



Ground Improvement Testing Methodology

Spacing trials

- Pre-improvement CPT, crosshole V_S-V_P and SDMT testing
- Ground improvement panel construction
- Monitoring of construction effects
- 14, 28,60 and 90 day post-improvement CPT testing
- Selection of ground improvement spacing

Production test panels

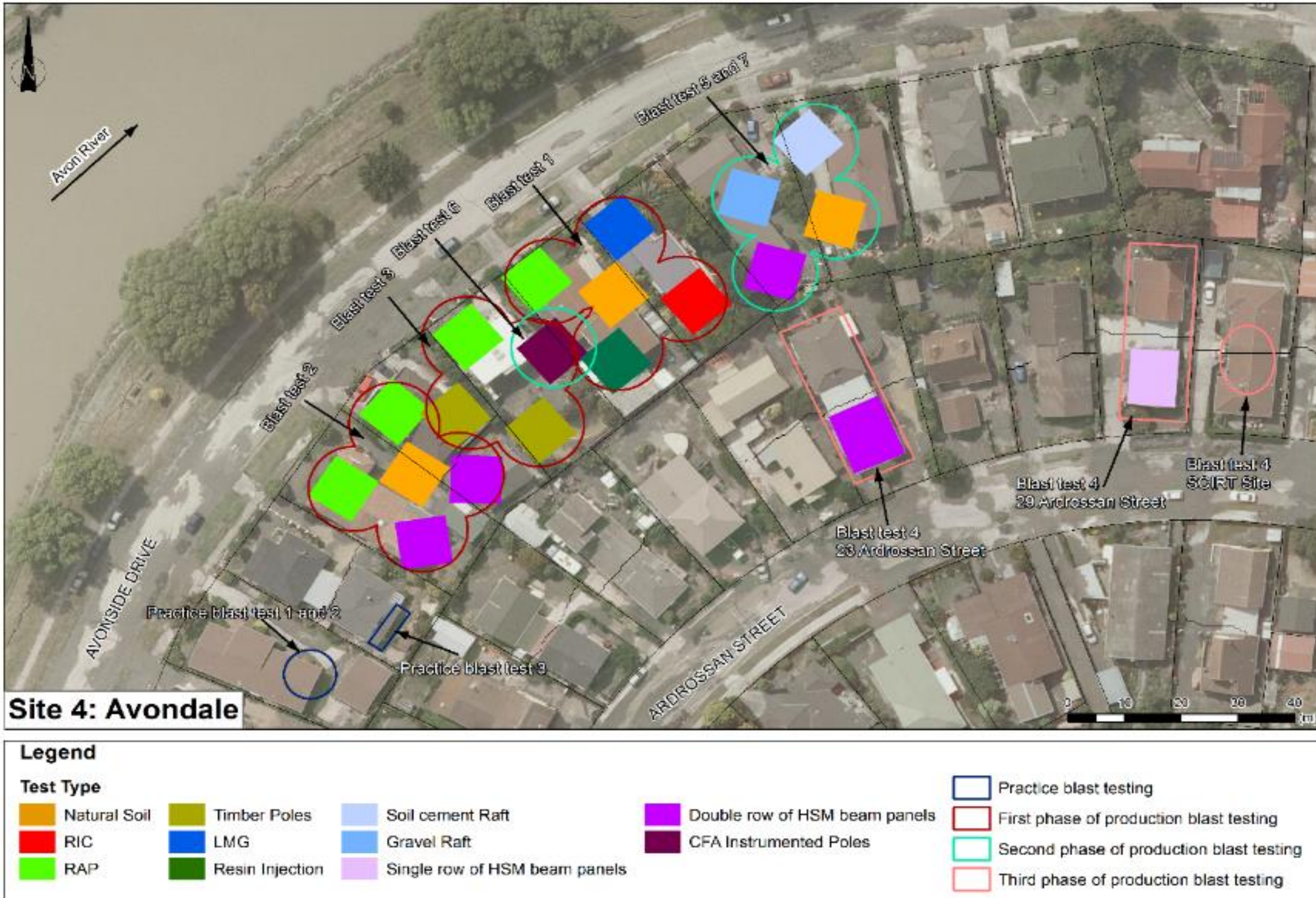
- Pre-improvement CPT, crosshole V_S-V_P and SDMT testing
- Ground improvement panel construction
- Monitoring of construction effects
- 14, 28,60 and 90 day post-improvement CPT, crosshole V_S-V_P and sDMT testing
- Instrumentation and T-Rex shake testing
- Instrumentation and liquefaction-induced blast testing
- Trenching and logging of as-built ground improvements

Spacing Trial Layout with Pre and Post-improvement CPT

Pre and Post-improvement CPT Crosshole V_P & V_S Testing Layout Plan

T-Rex Shake Testing Layout Plan

Blast-induced Liquefaction Trial Layout Plan



Evaluating Effectiveness of Creating Non-liquefying Crust

CPT

density/strength

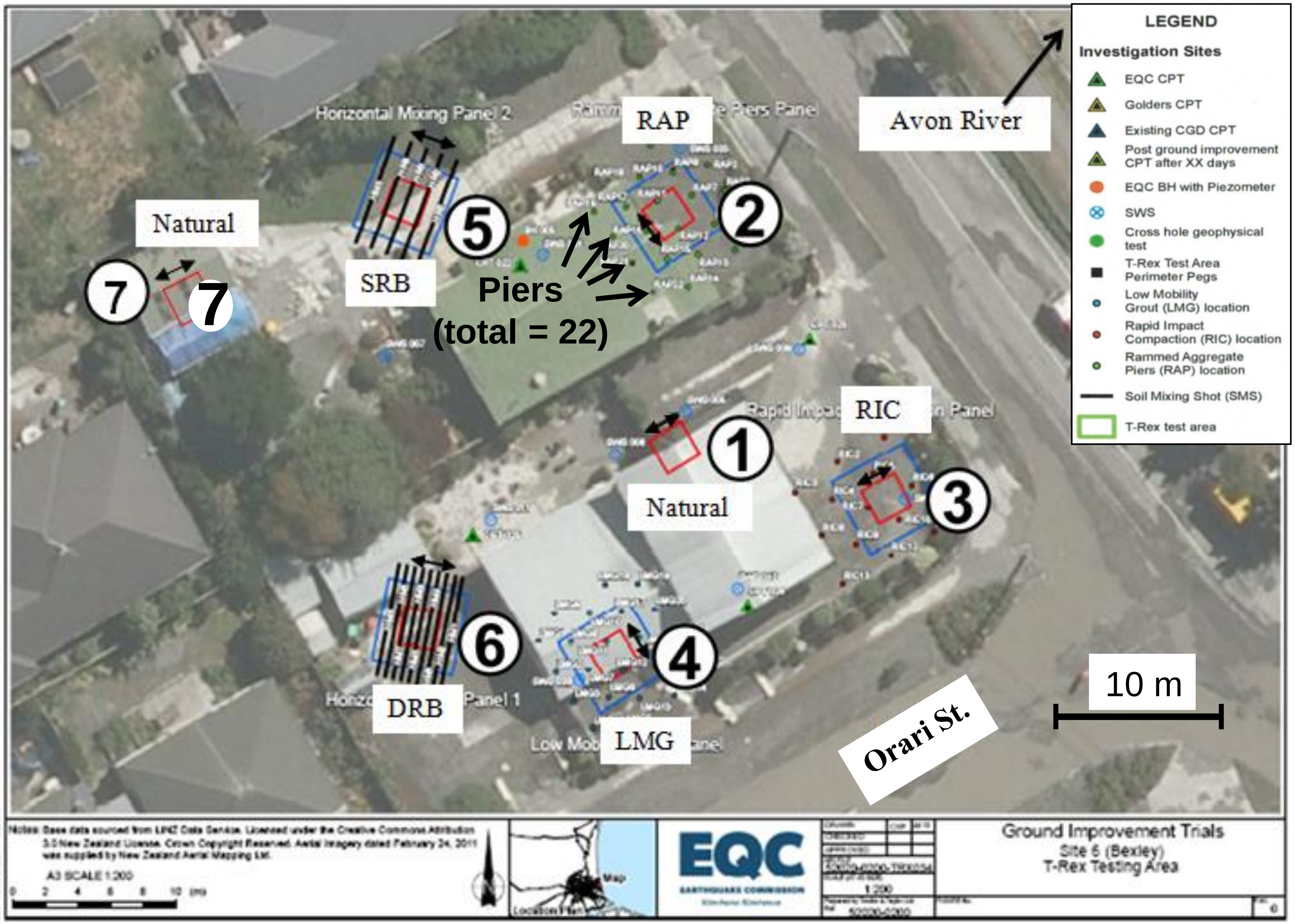
Shear Wave (Vs) and Compression Wave (Vp) Velocity

stiffness/modulus

Full Scale Shaking Tests with T-Rex

stress/strain/pore pressure response

General Site Layout: Site 6



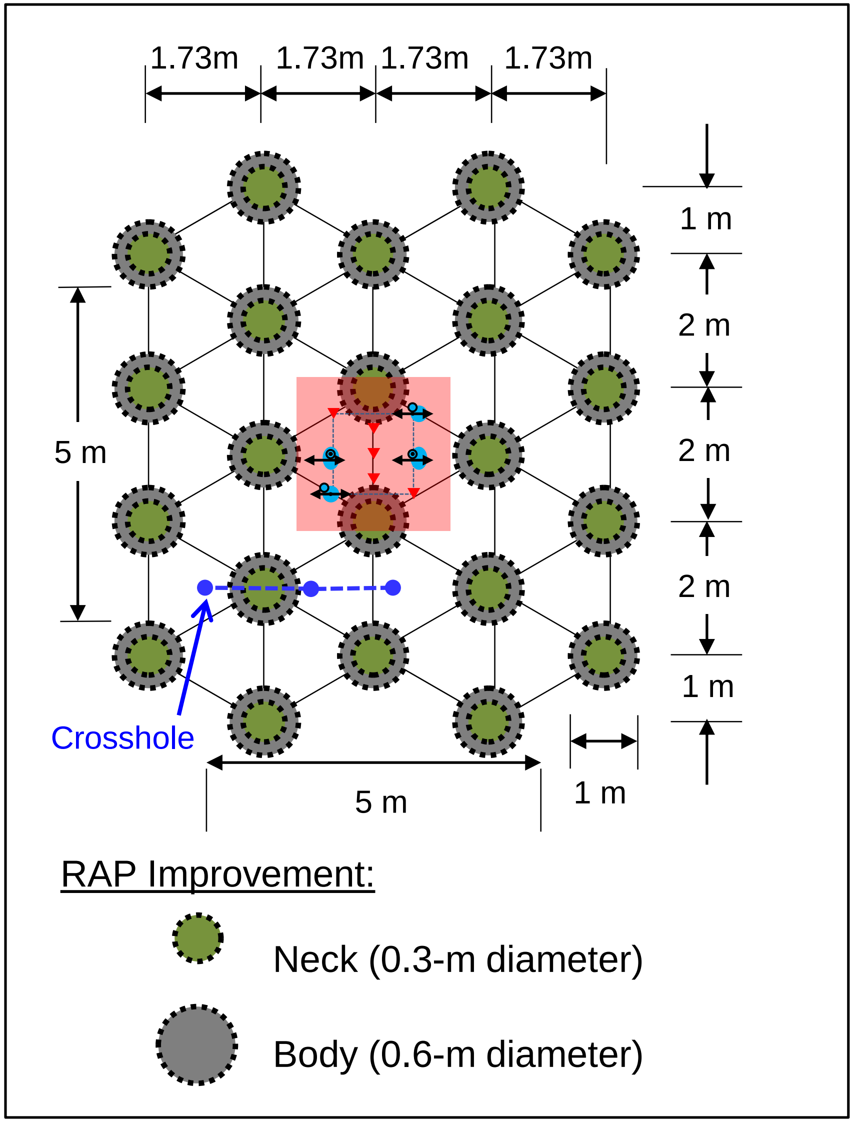
Test Panels ~ 7m x 7m

Pre- & Post-Improvement CPT

Pre- & Post-Improvement Crosshole Vs/Vp

T-Rex Shake Testing of Natural & Improved Panels

General Crosshole Vs/Vp and T-Rex Locations



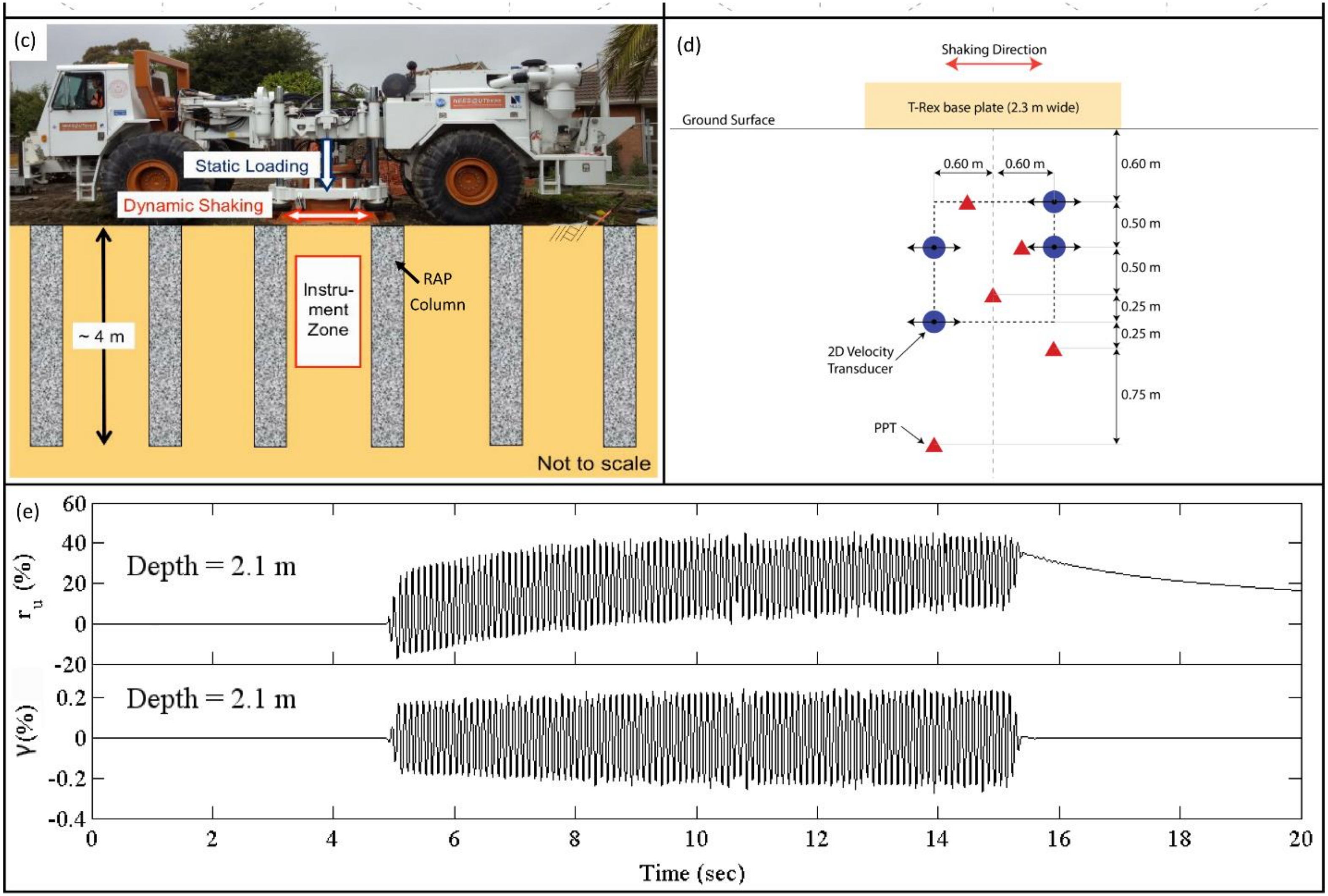
Crosshole Vs/Vp Testing

- Performed Before T-Rex Shake Testing
- Direct-push Source and Sensor
- Composite Stiffness Across Columns
- Soil Stiffness Between Columns

T-Rex Shake Testing

- 2.3 m x 2.3 m Plan Area
- Direct-push Vibration and Pressure Sensors
- Monitor Strain and Pore Pressure Response

Overview: Full-Scale Shaking Tests with T-Rex



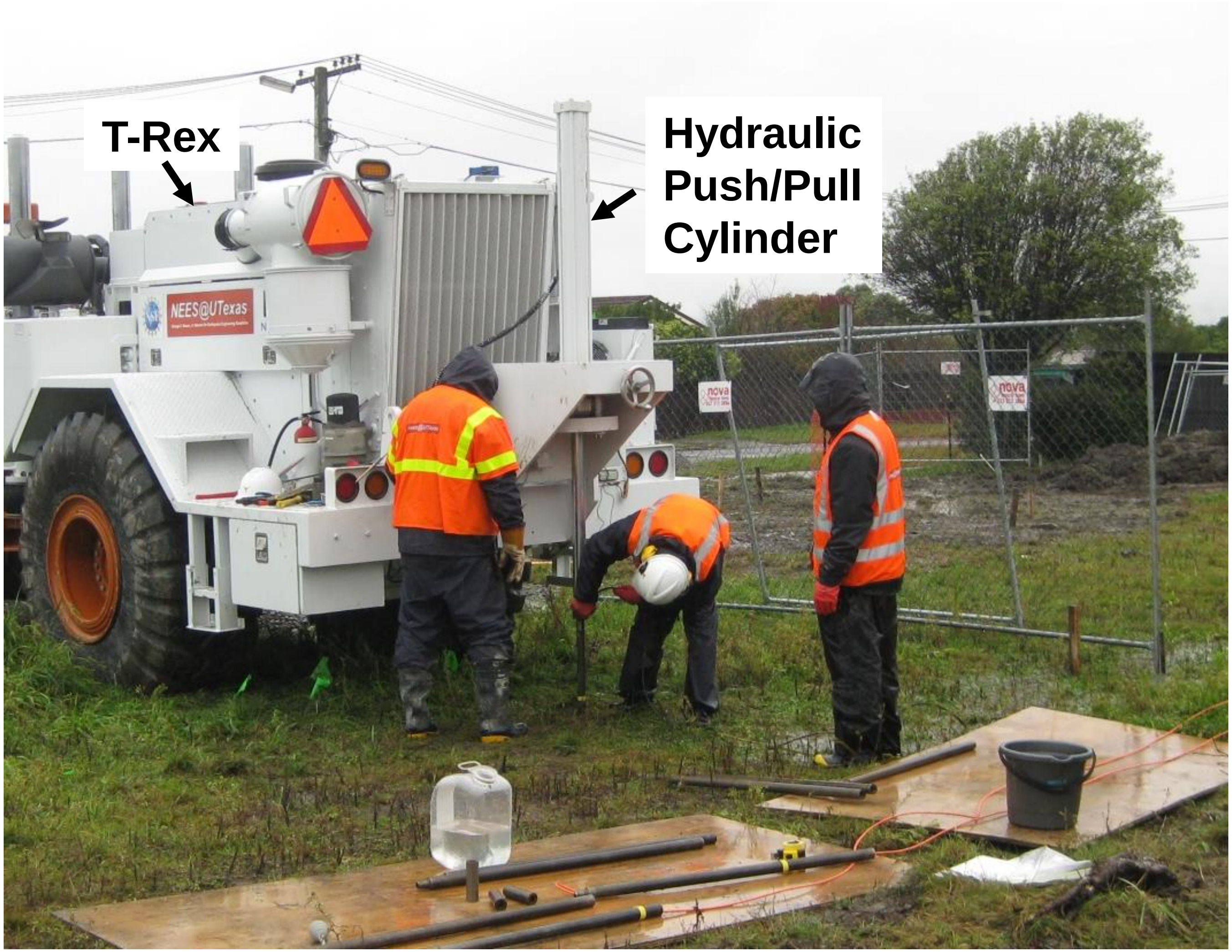
In-Situ Liquefaction Test Methodology: Cox et al. (2009)

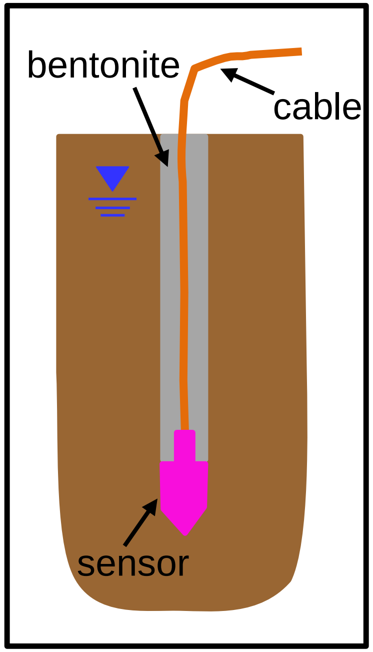
Push-In Sensors

Vibration Transducers (geophones)

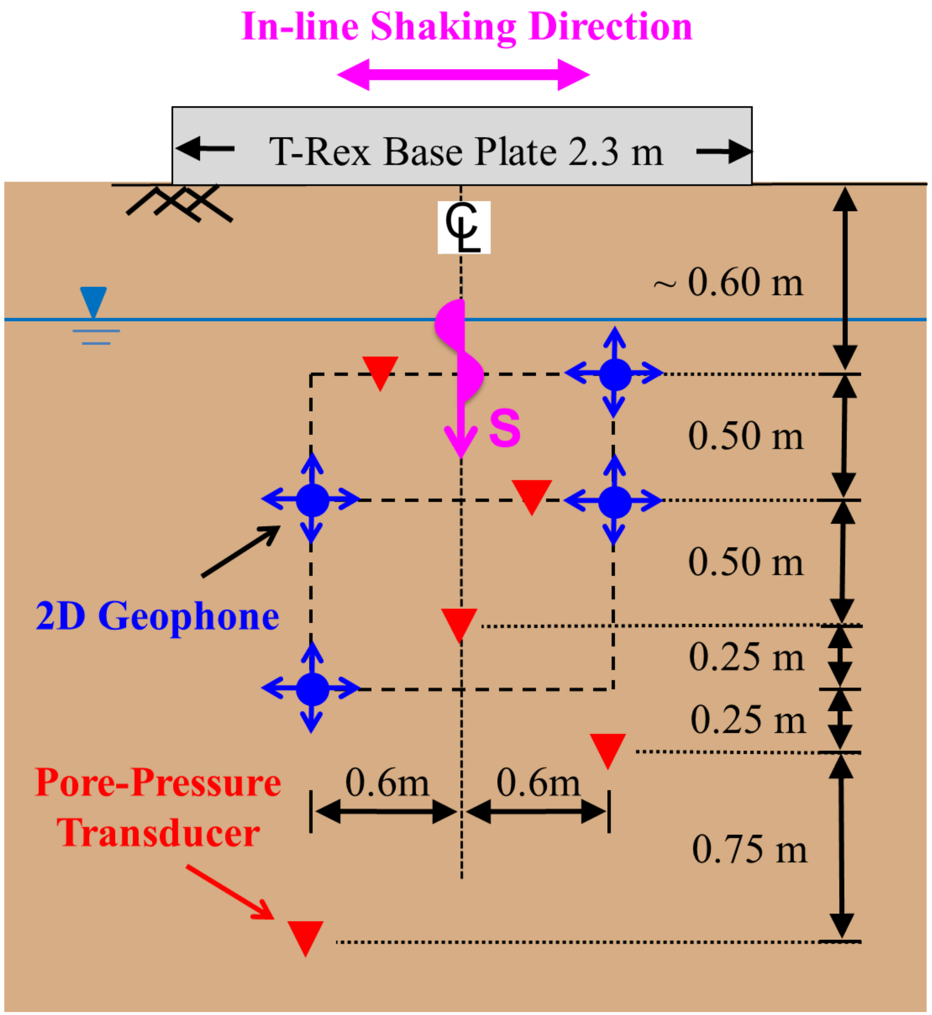
Pore Pressure Transducers (PPTs)

Sensor Installation with T-Rex

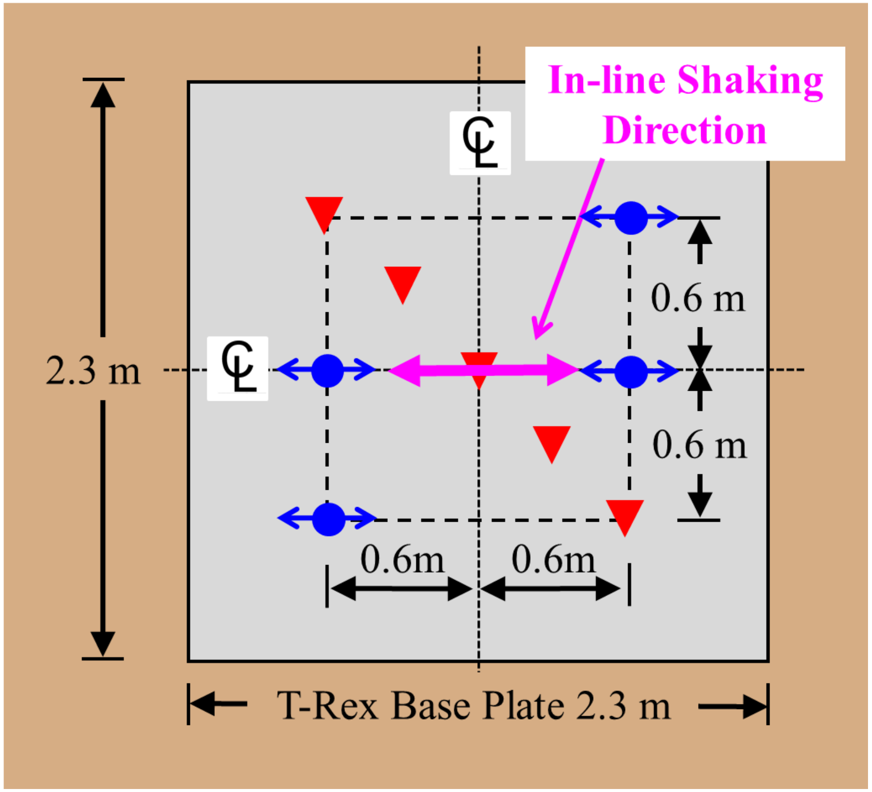




General Sensor Layout



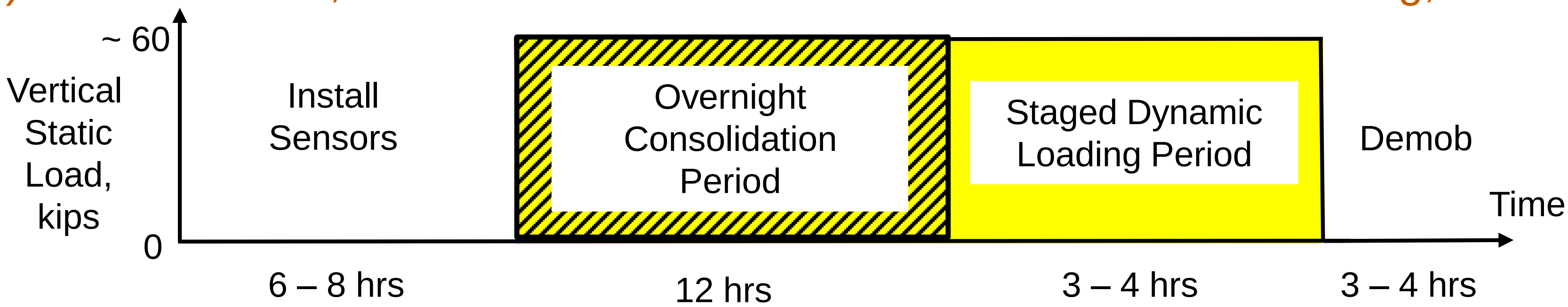
(a) Cross Section



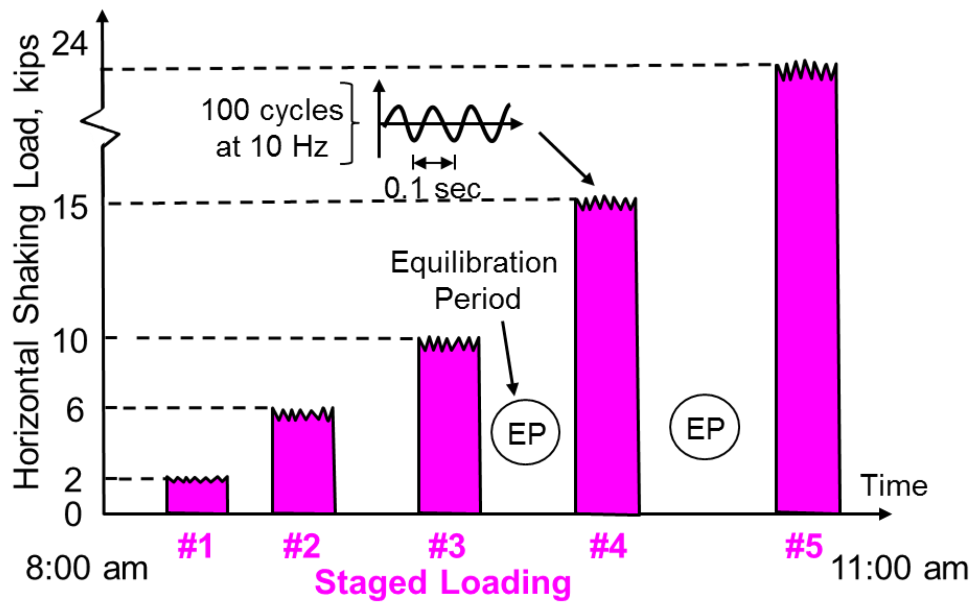
(b) Plan View

Staged Dynamic Loading: ~ 2 days/panel

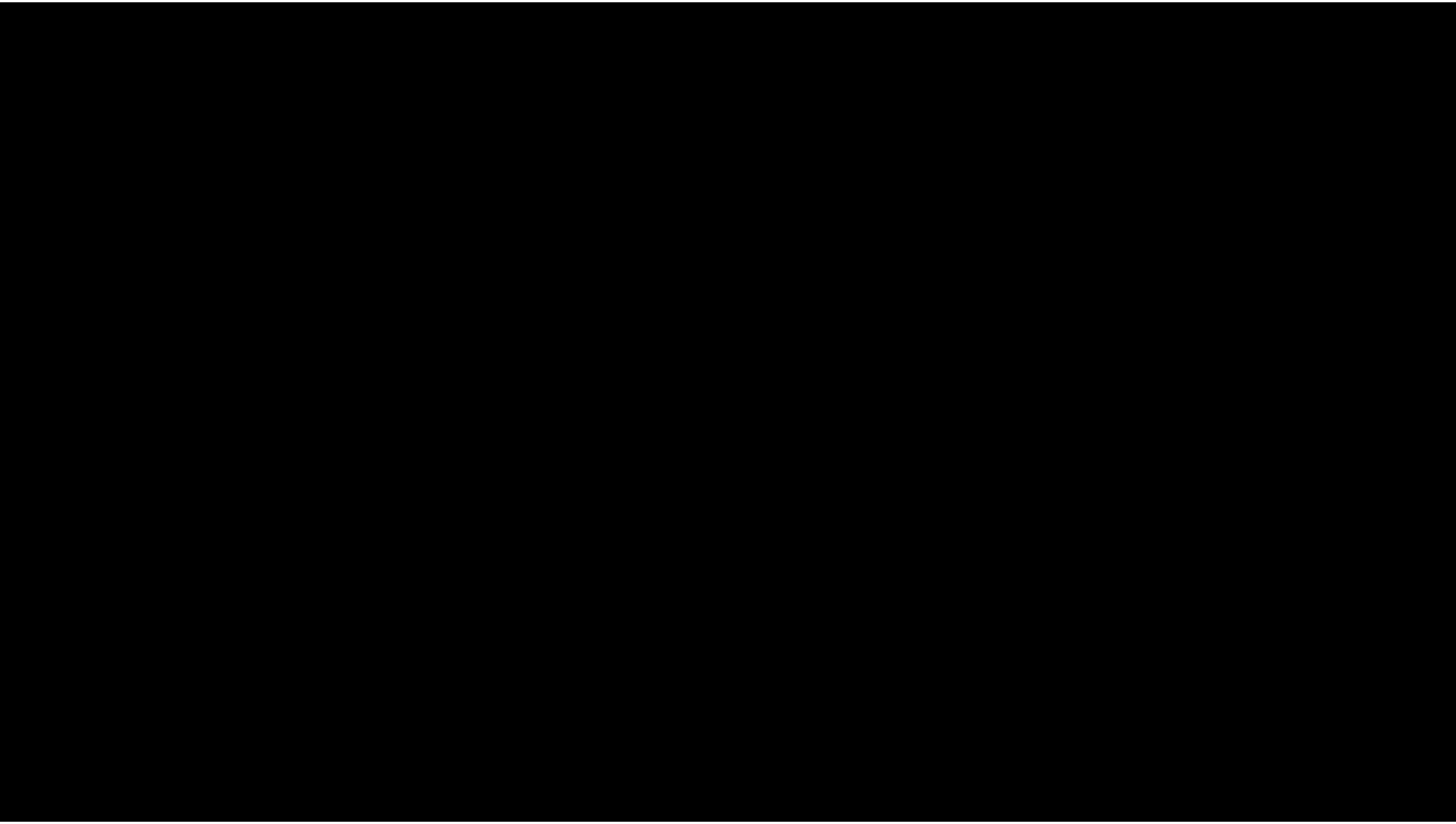
(a) Install Sensors, Constant Vertical Load for Consolidation and Shaking, Demob



(b) Staged, Horizontal Shaking with T-Rex



T-Rex Shake Testing Video

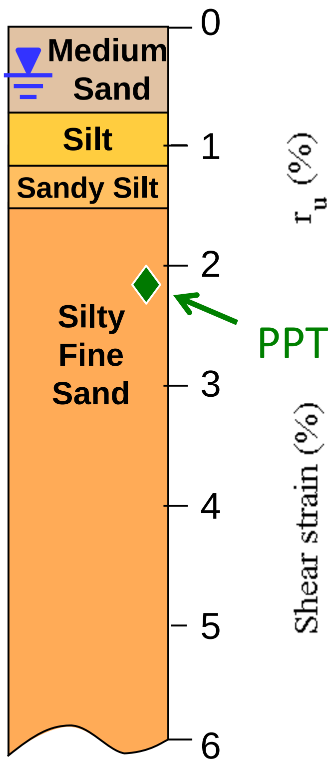


Natural Soil Test Panel at Site 6

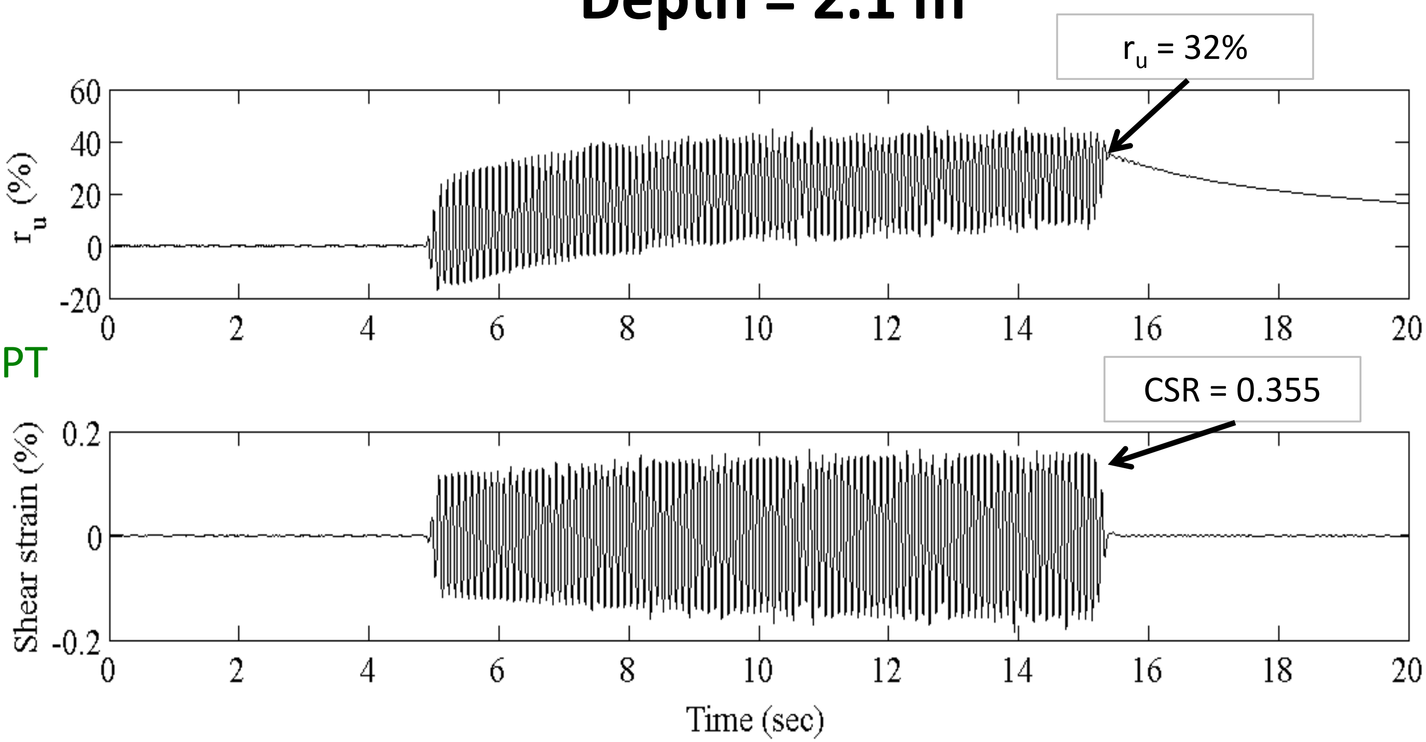
Stage 5 - Pore Water Pressure Ratio (r_u) and Shear Strain (γ) vs. Time

Shaking: 100 cycles at 10 Hz;

Peak horizontal surface stress: ~ 25 kPa



Depth = 2.1 m

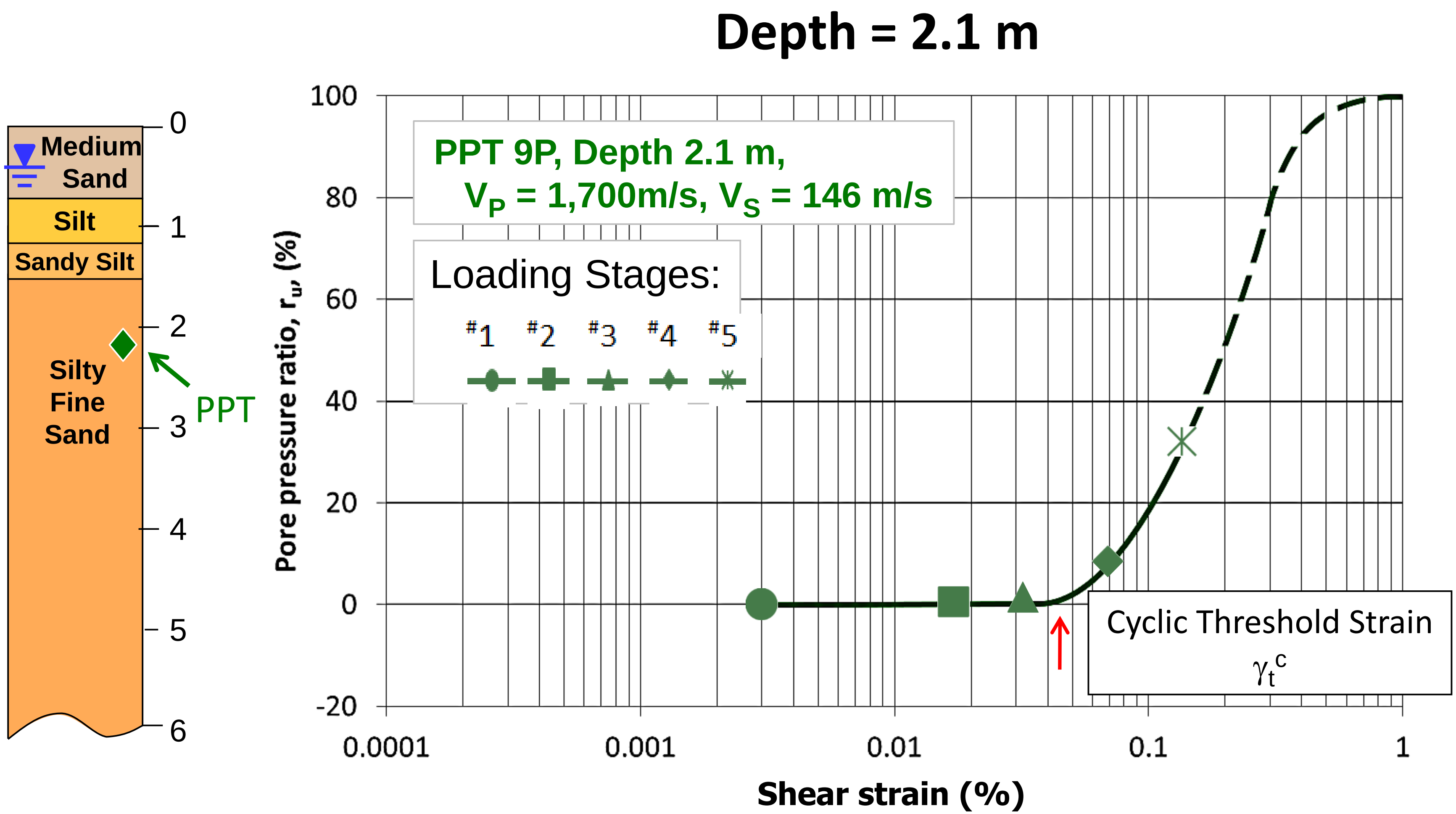


Notes:

$r_u = u_{excess}/\sigma_v'$ $\quad$ $CSR = \tau/\sigma_v'$

Natural Soil Test Panel at Site 6

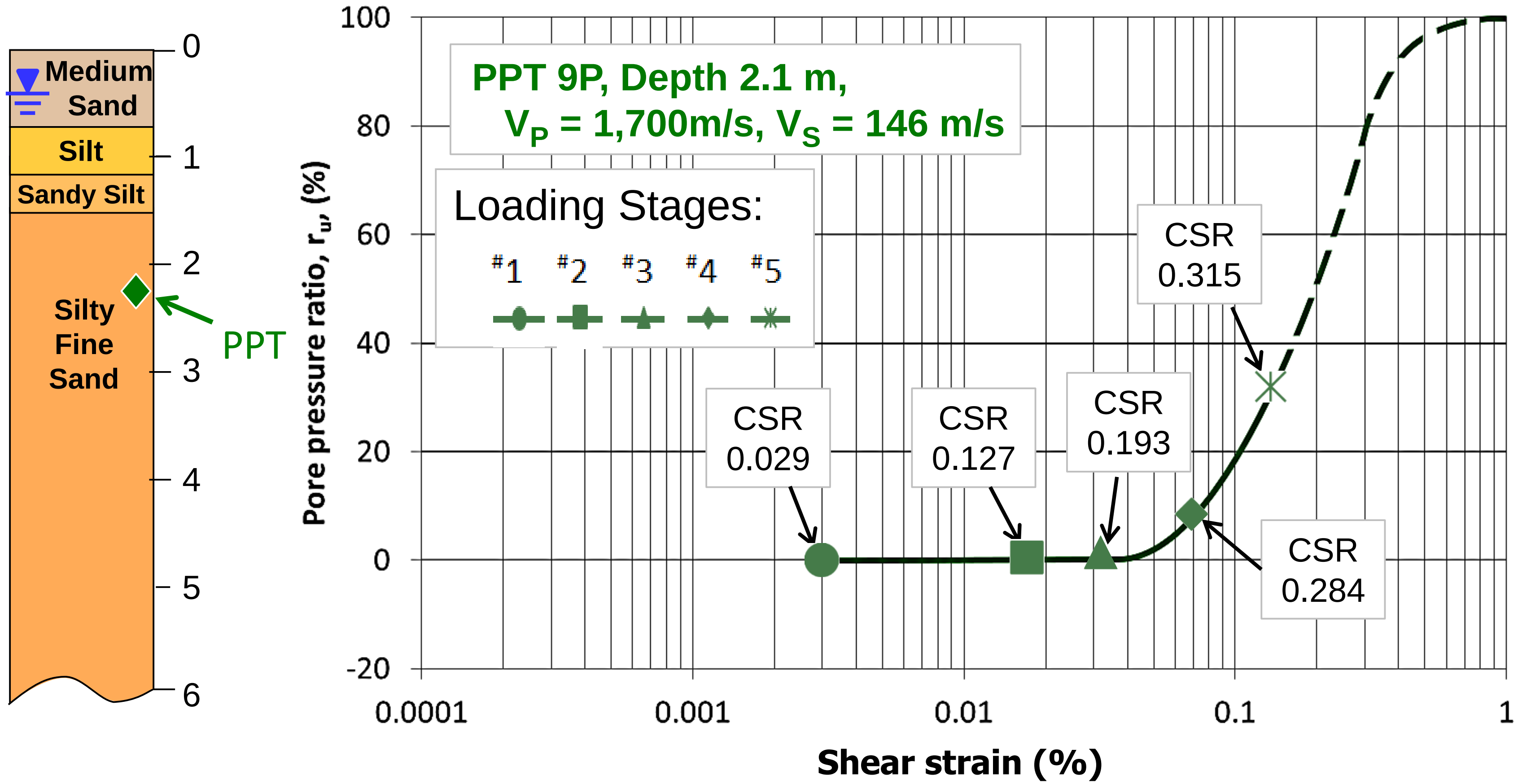
All Loading Stages - Pore Water Pressure Ratio (r_u) vs. Shear Strain (γ)



Natural Soil Test Panel at Site 6

All Loading Stages – Cyclic Stress Ratio's (CSR)

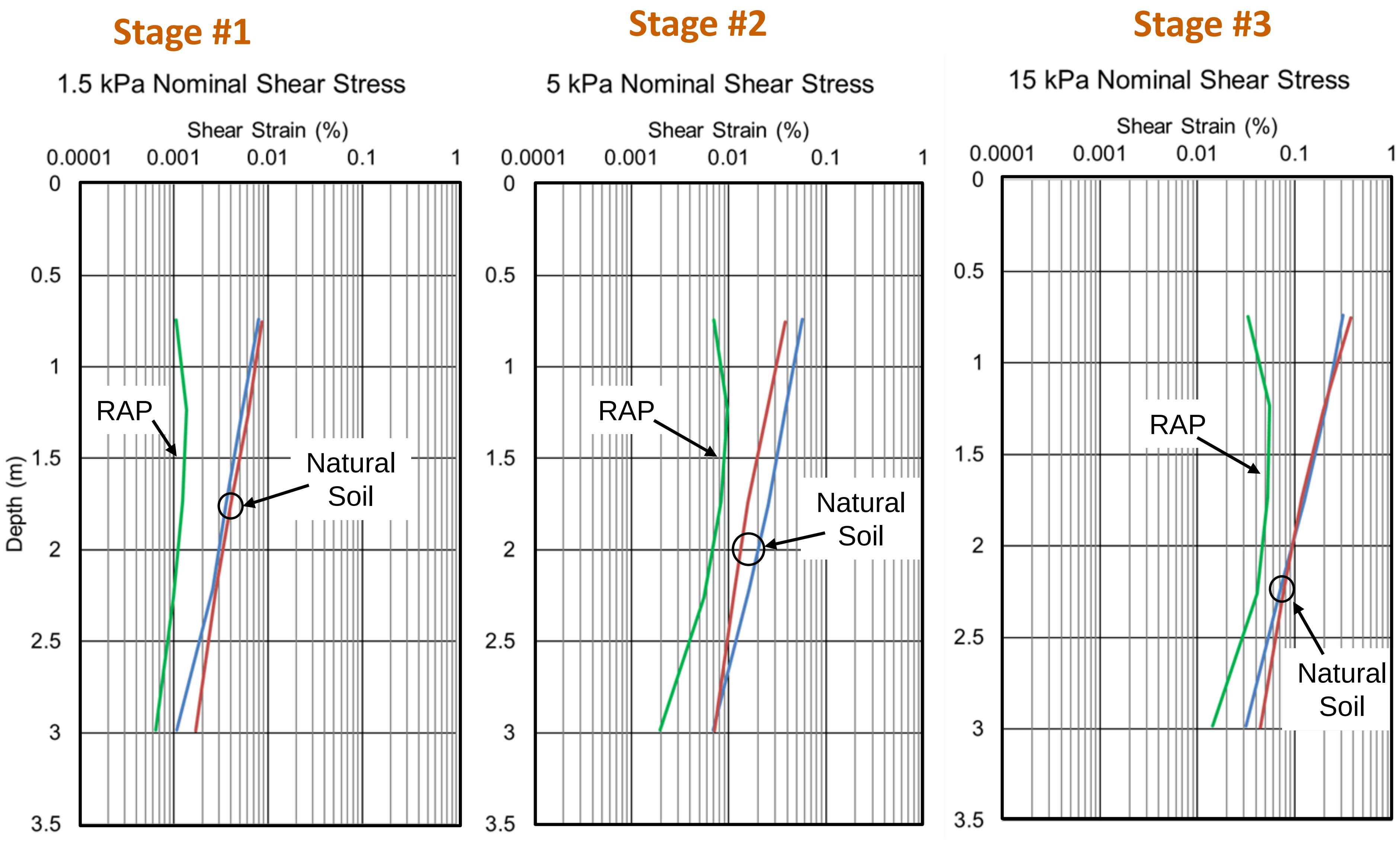
Depth = 2.1 m



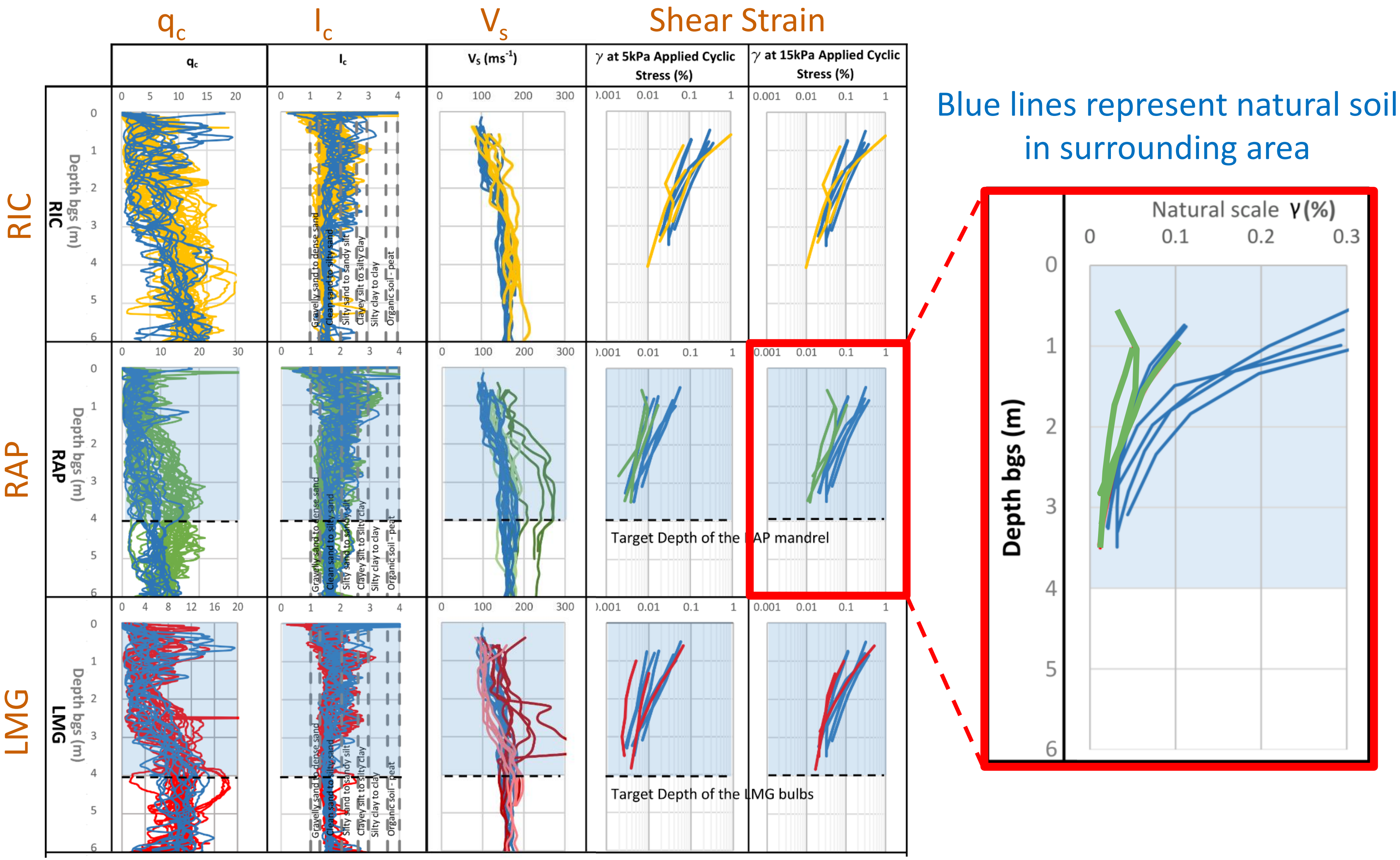
Notes:

$r_u = u_{excess}/\sigma_v'$ $CSR = \tau/\sigma_v'$ $G = \tau/\gamma \rightarrow \tau = G(\gamma)$

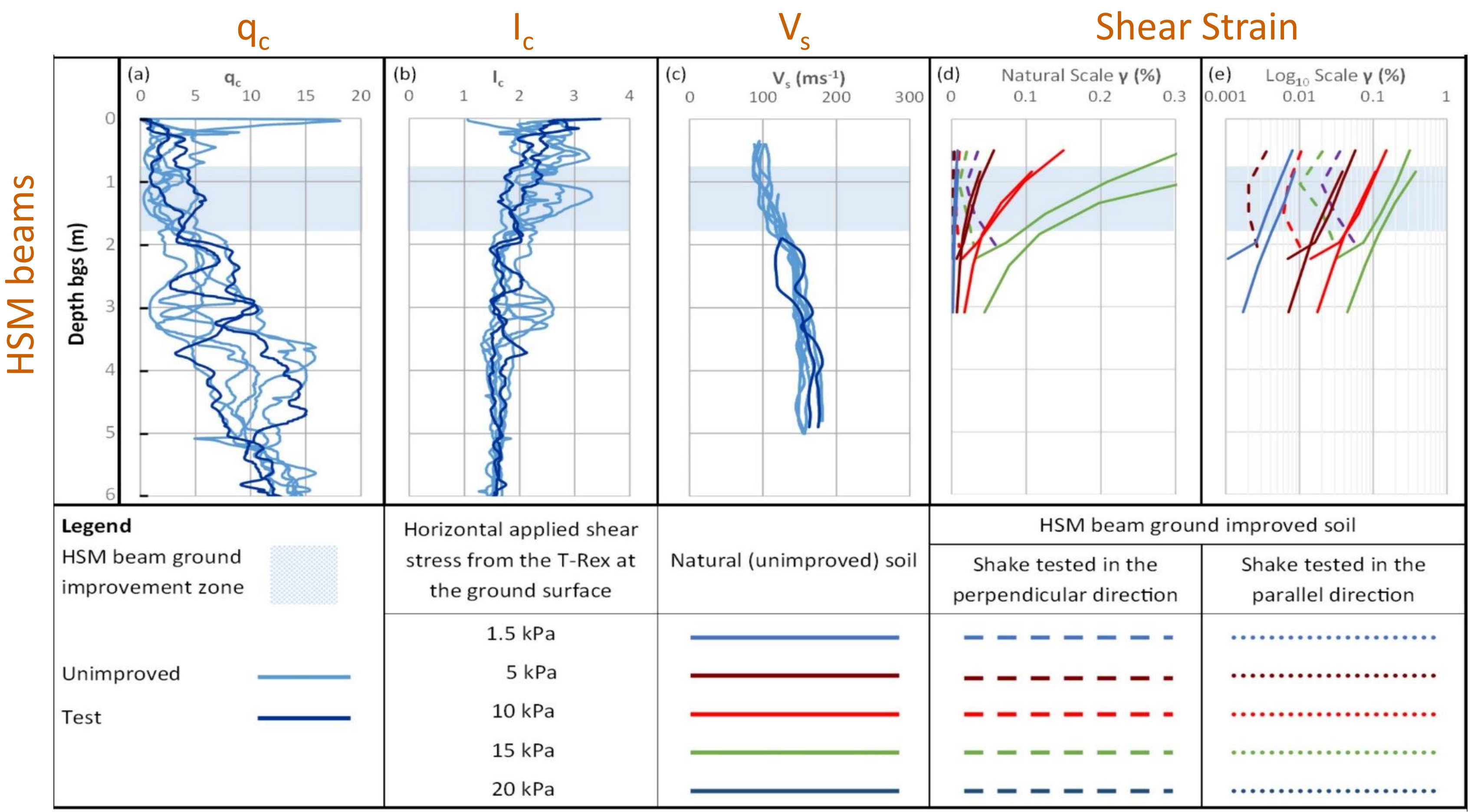
Overall Stiffness: Natural Soil vs. RAP at Site 6



Overall Comparison of RIC, RAP and LMG



Overall Comparison of HSM beams

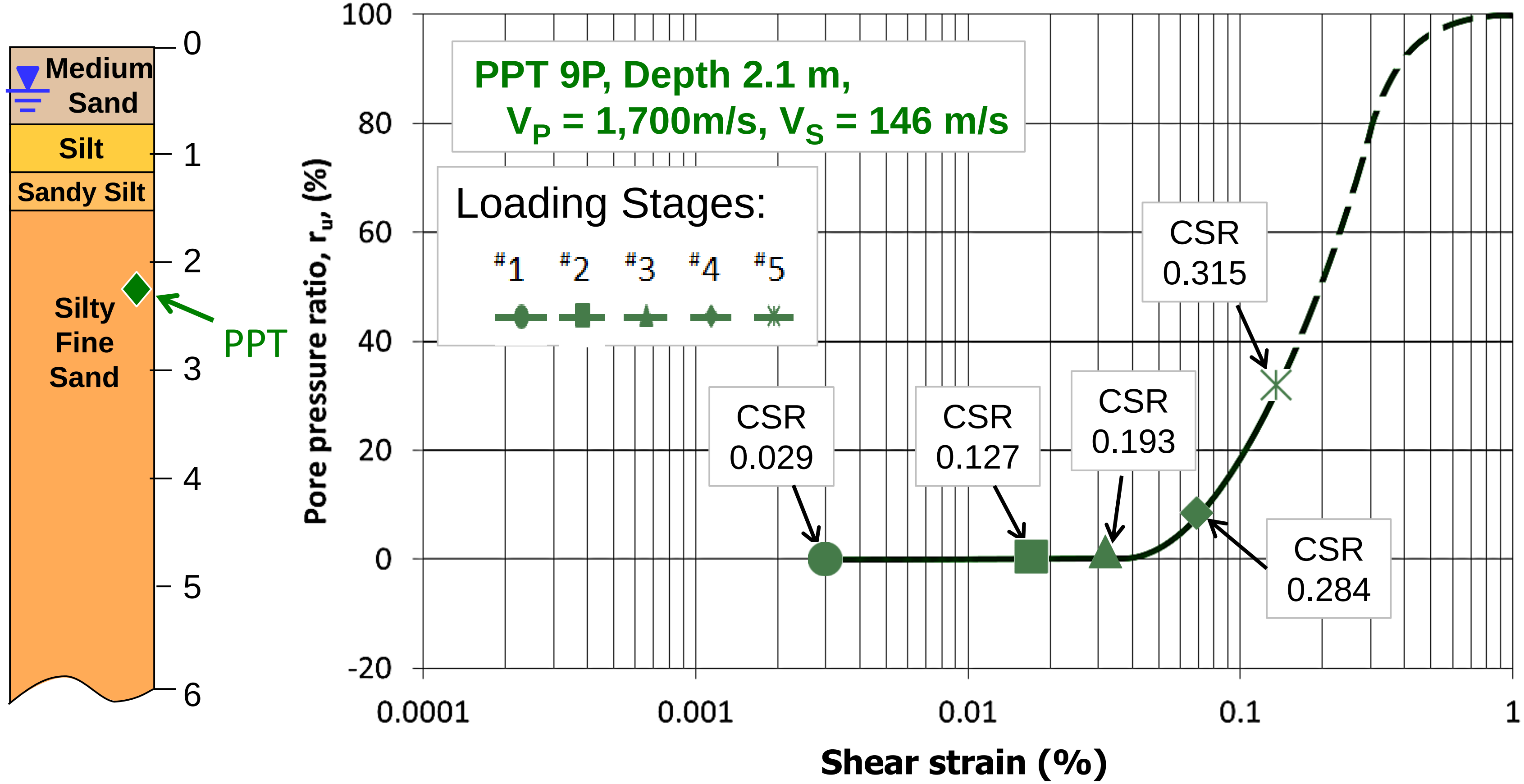


Blue lines represent natural soil in surrounding area

Natural Soil Test Panel at Site 6

All Loading Stages – Cyclic Stress Ratio's (CSR)

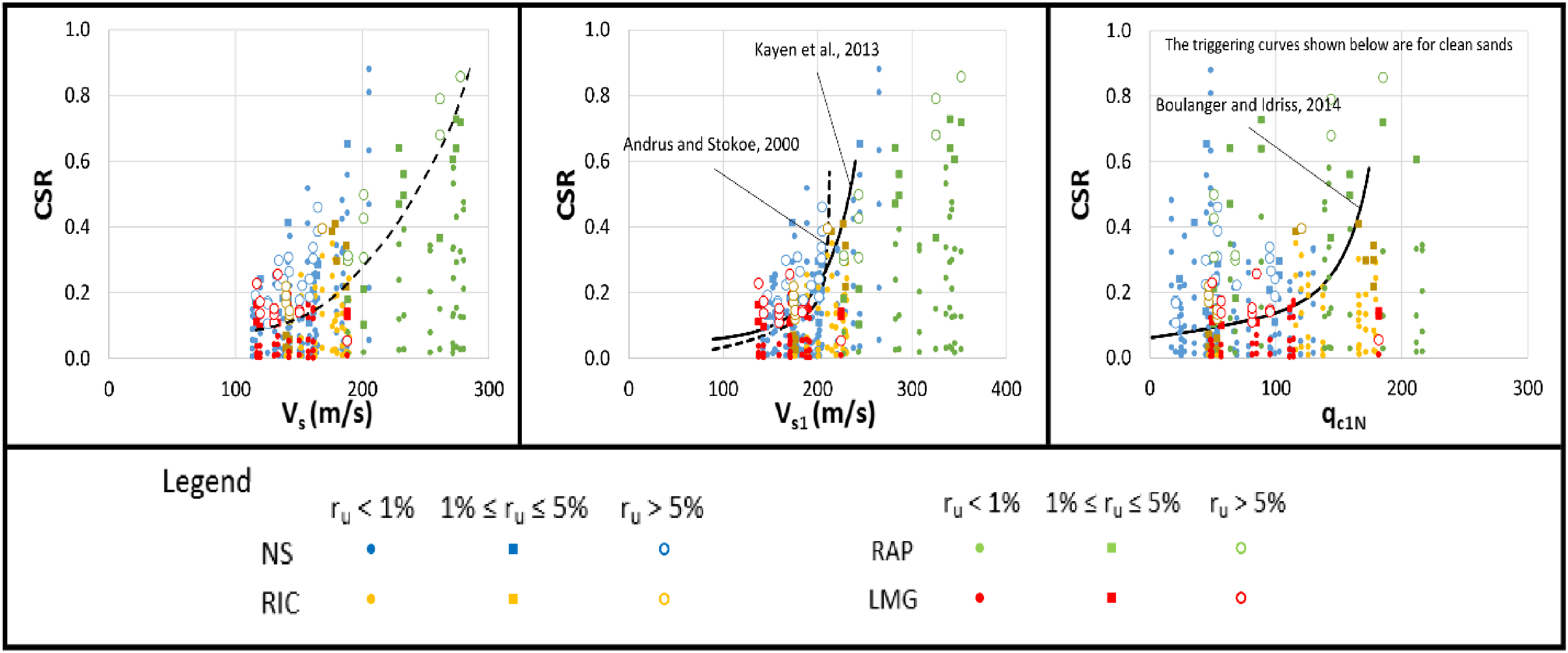
Depth = 2.1 m



Notes:

$r_u = u_{excess}/\sigma_v'$ $CSR = \tau/\sigma_v'$ $G = \tau/\gamma \rightarrow \tau = G(\gamma)$

T-Rex CSR Versus V_S, V_{S1} and q_{c1N} Summary (for all ground improvements)

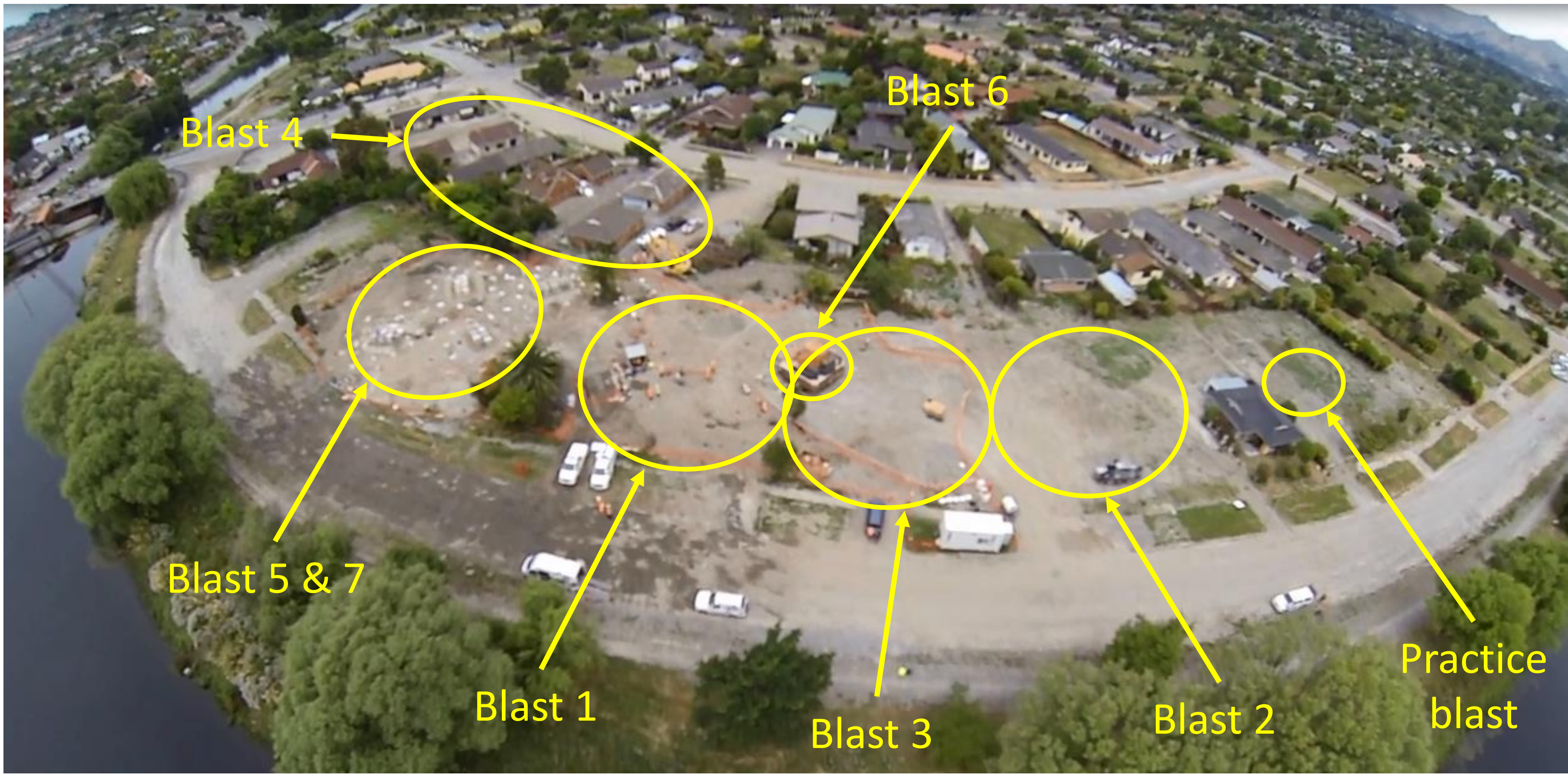


- The Boulanger and Idriss (2014) CPT based liquefaction triggering curves bound the data points where excess pore water pressure development occurred
- The CPT-based liquefaction triggering assessment is conservative for ground improvements which have zones of higher stiffness (i.e. RAP)
- Crosshole V_s measurements better capture and envelope the composite stiffness

Evaluating Deformation Performance of Non-liquefying Crust

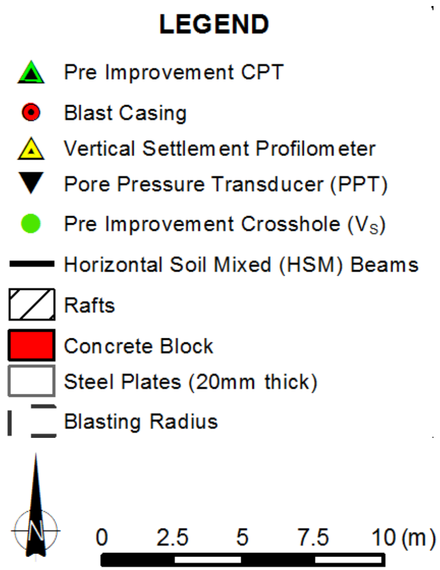
Blast Liquefaction Testing

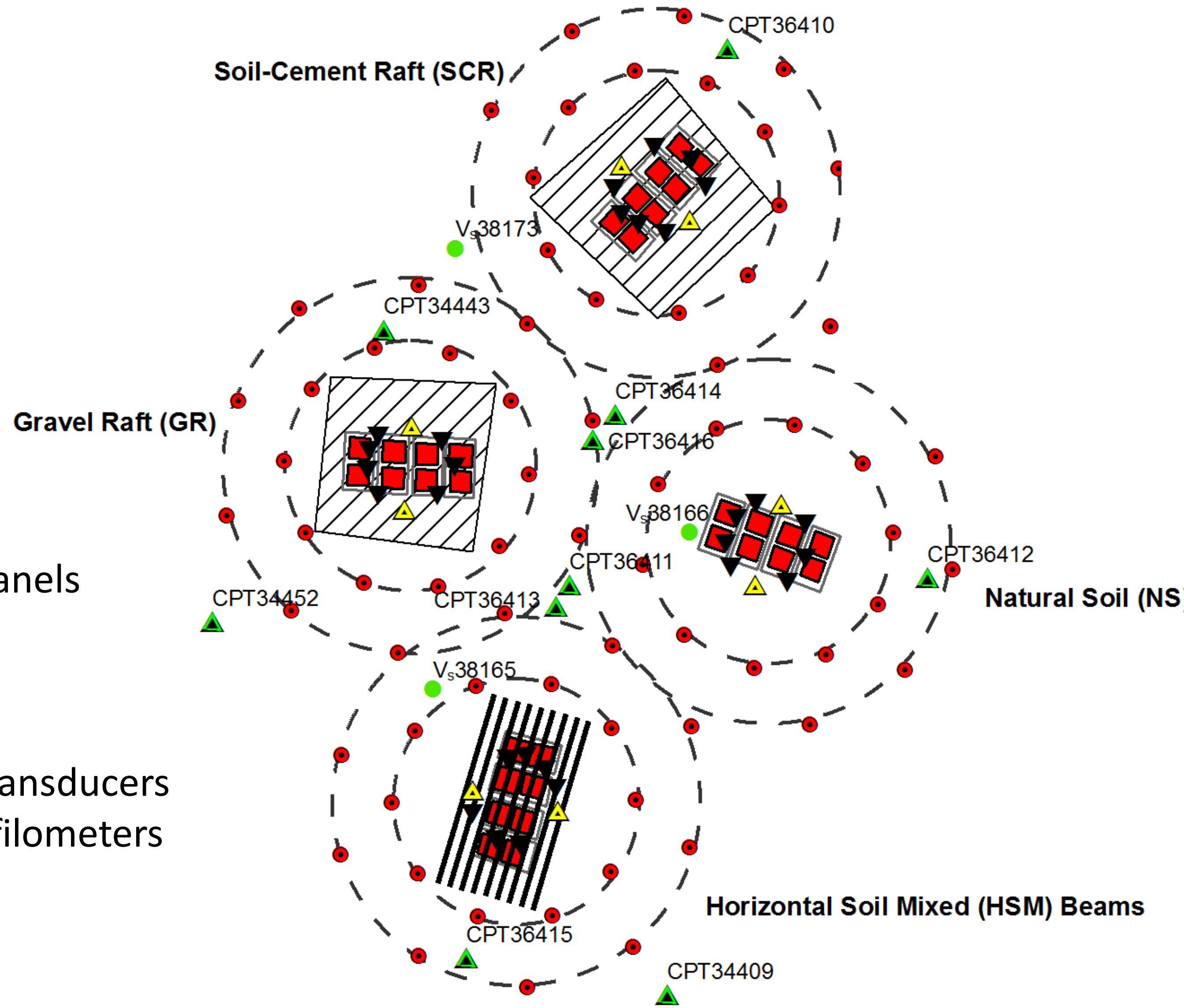
Blast-induced Liquefaction Trials
(site layout)



- 7 blasting trials – blasted in stages
- 17 ground improvement test panels
- 4 houses
- 1 site with manholes and pipes
- 3 fully instrumental CFA piles

Example Blast Test Layout Plan
(blast #5)

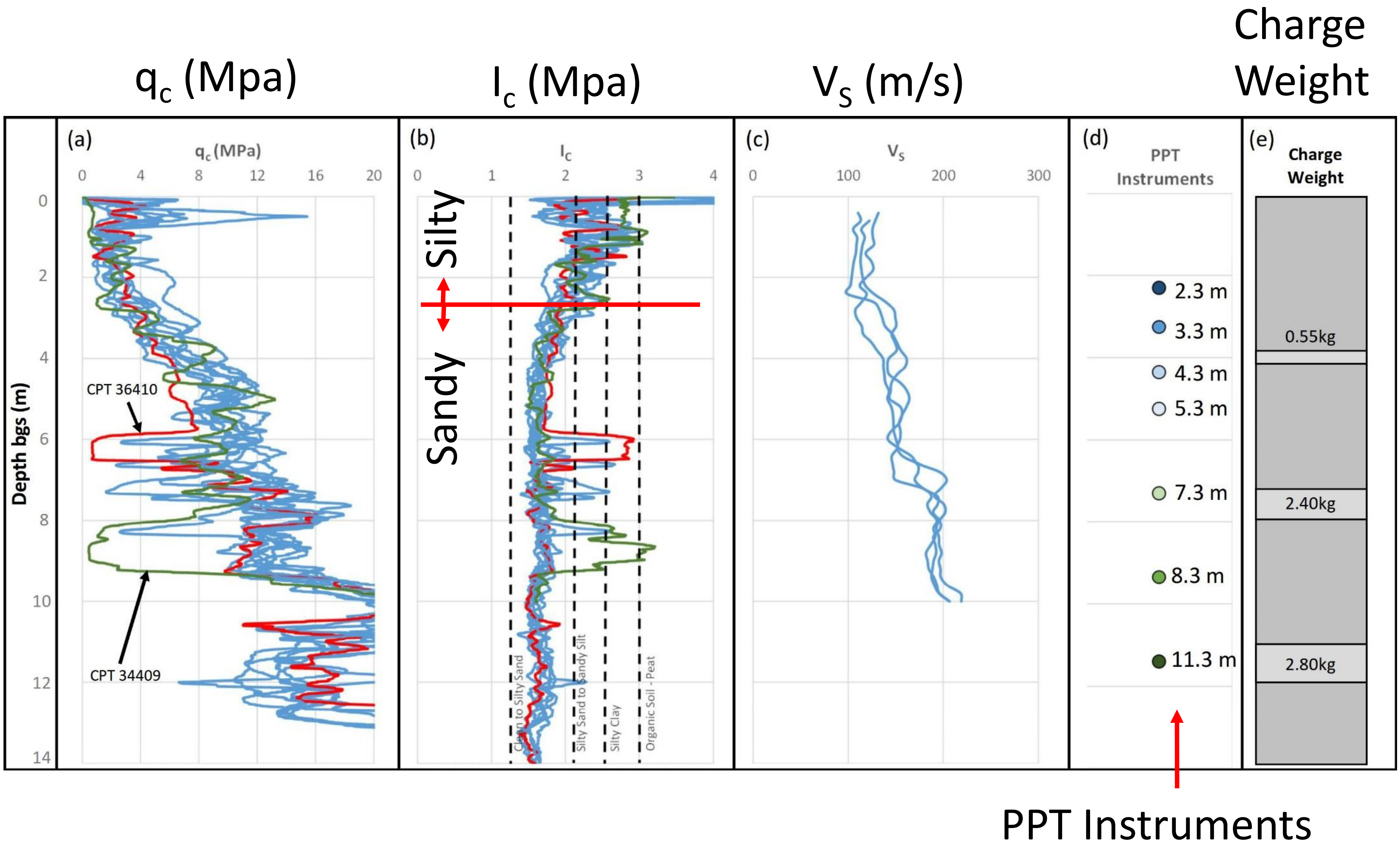




Key Statistics

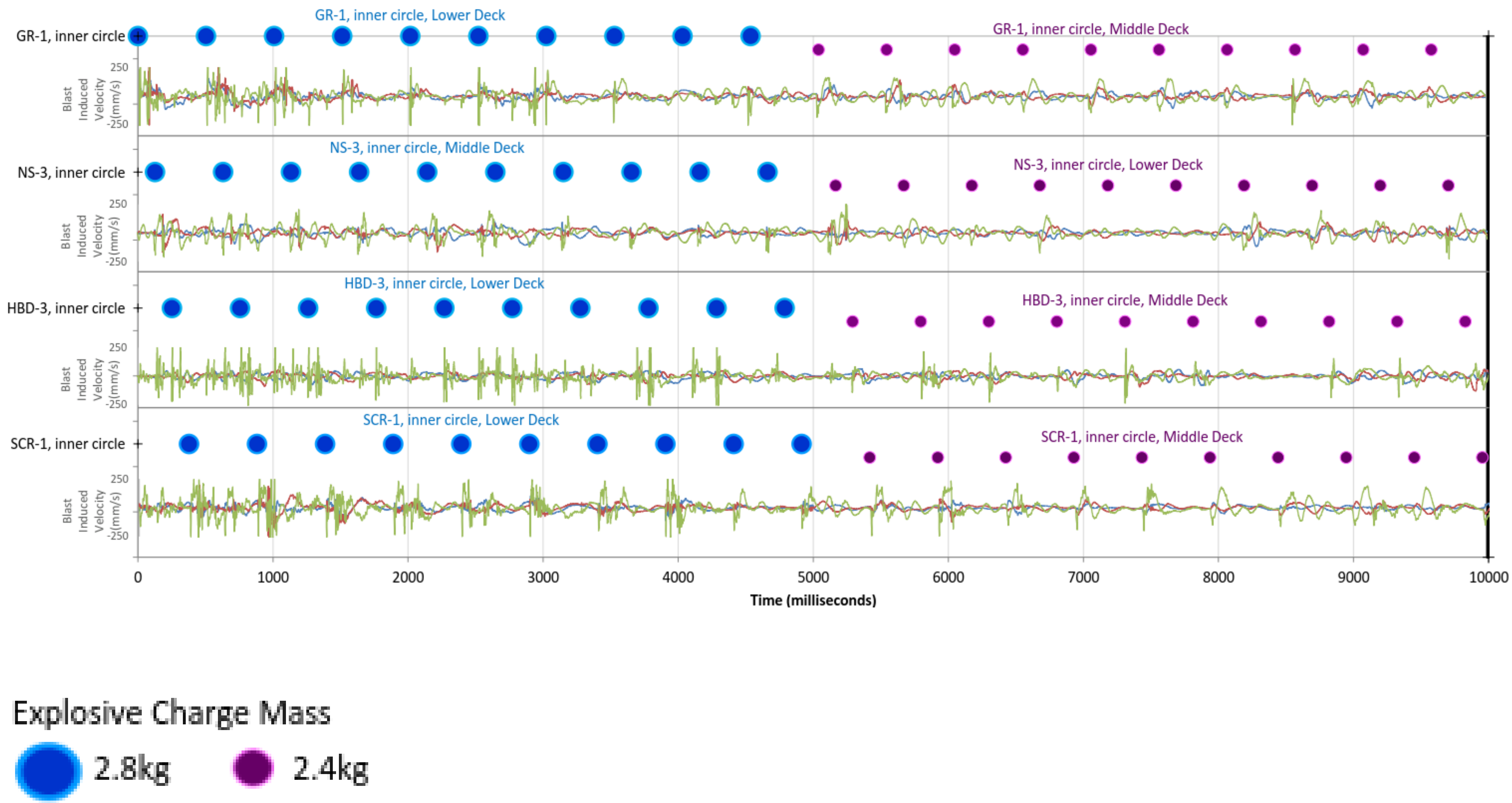
4 ground improvement panels
16 steel plates
32 concrete blocks
40 accelerometers
28 Pore water pressure transducers
8 Vertical Settlement Profilometers
70 blast casings
1088 m of drilling
402.5 kg of explosives

Subsurface Soil Profile, Instrument and Charge Depths
(blast #5)



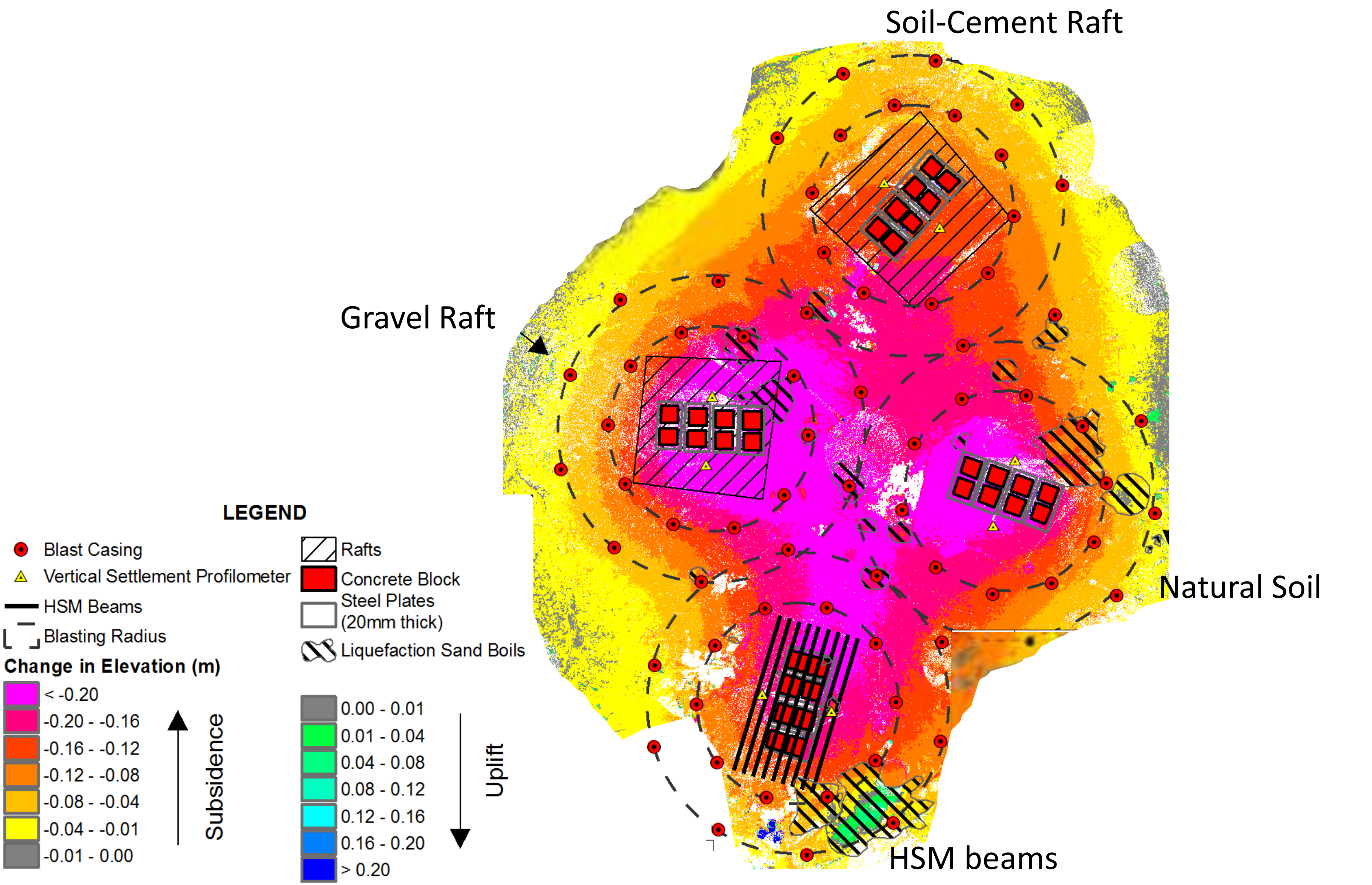

PANEL 6
PANEL 8

Example Blast Detonation Sequence Chart
(blast #5 inner blast rings)

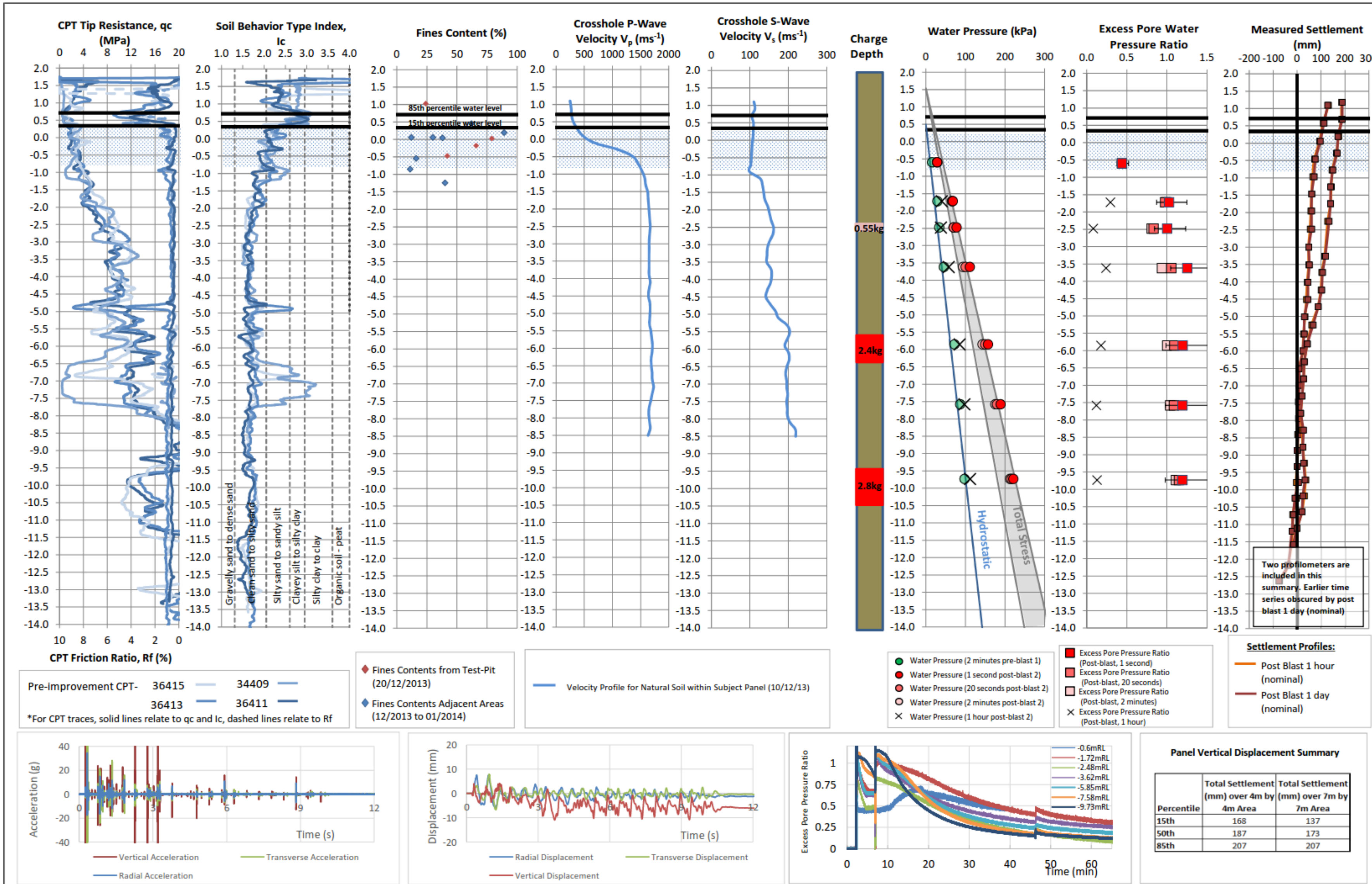


Blast-induced Liquefaction Trials of Shallow Ground Improvement Methods for Cleared Sites - Video

Example Blast Liquefaction-induced Subsidence Map
(blast #5)



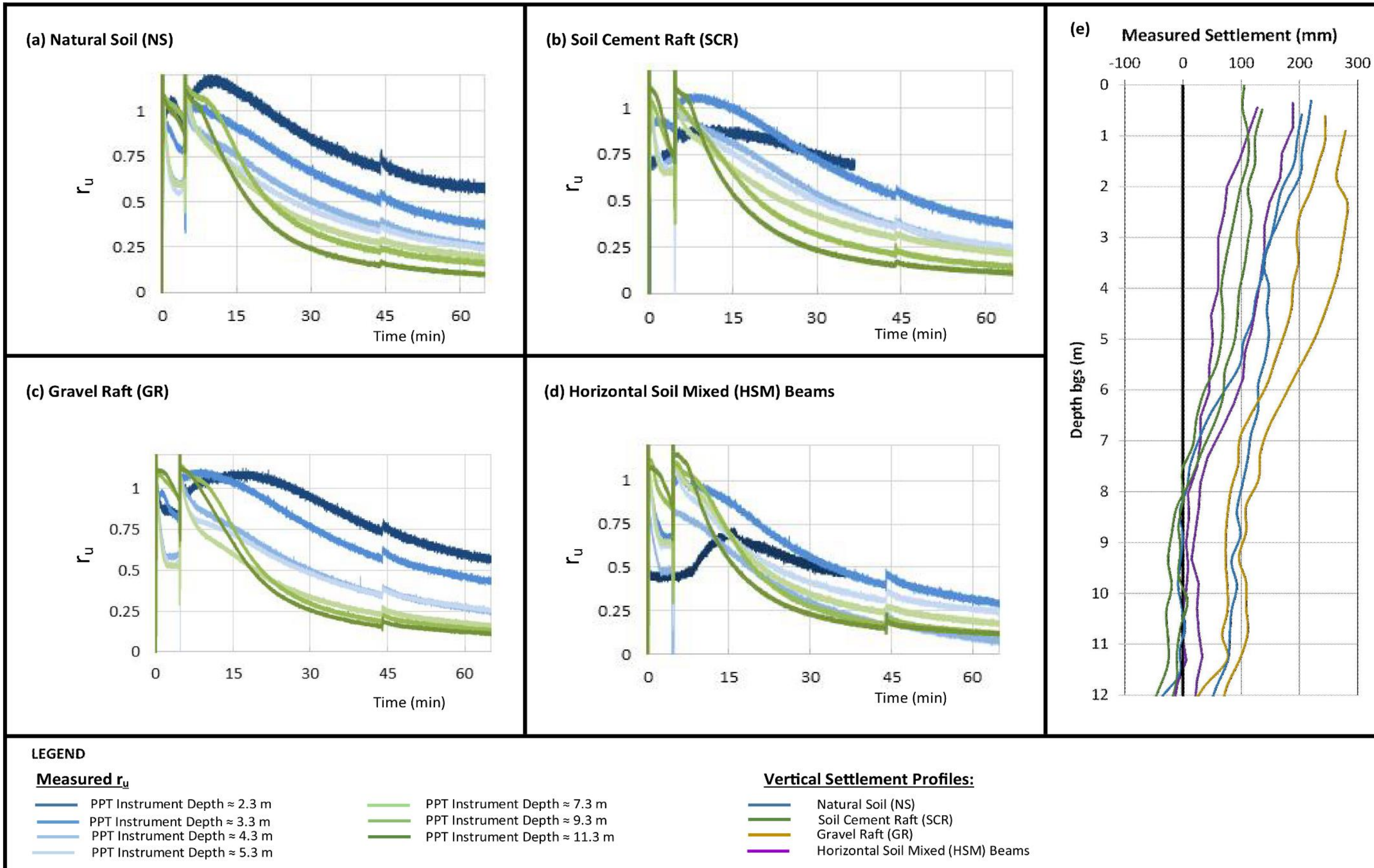
Example Results Summary for an HSM Beam Test Panel
(blast #5)



Percentile	Total Settlement (mm) over 4m by 4m Area	Total Settlement (mm) over 7m by 7m Area
15th	168	137
50th	187	173
85th	207	207

- 17 ground improvement test panels
- 4 test houses
- 1 site with manholes and pipes
- 3 fully instrumental CFA piles

Example Excess Pore Water Pressure and Vertical Settlement Profilometer Results
(blast #5)



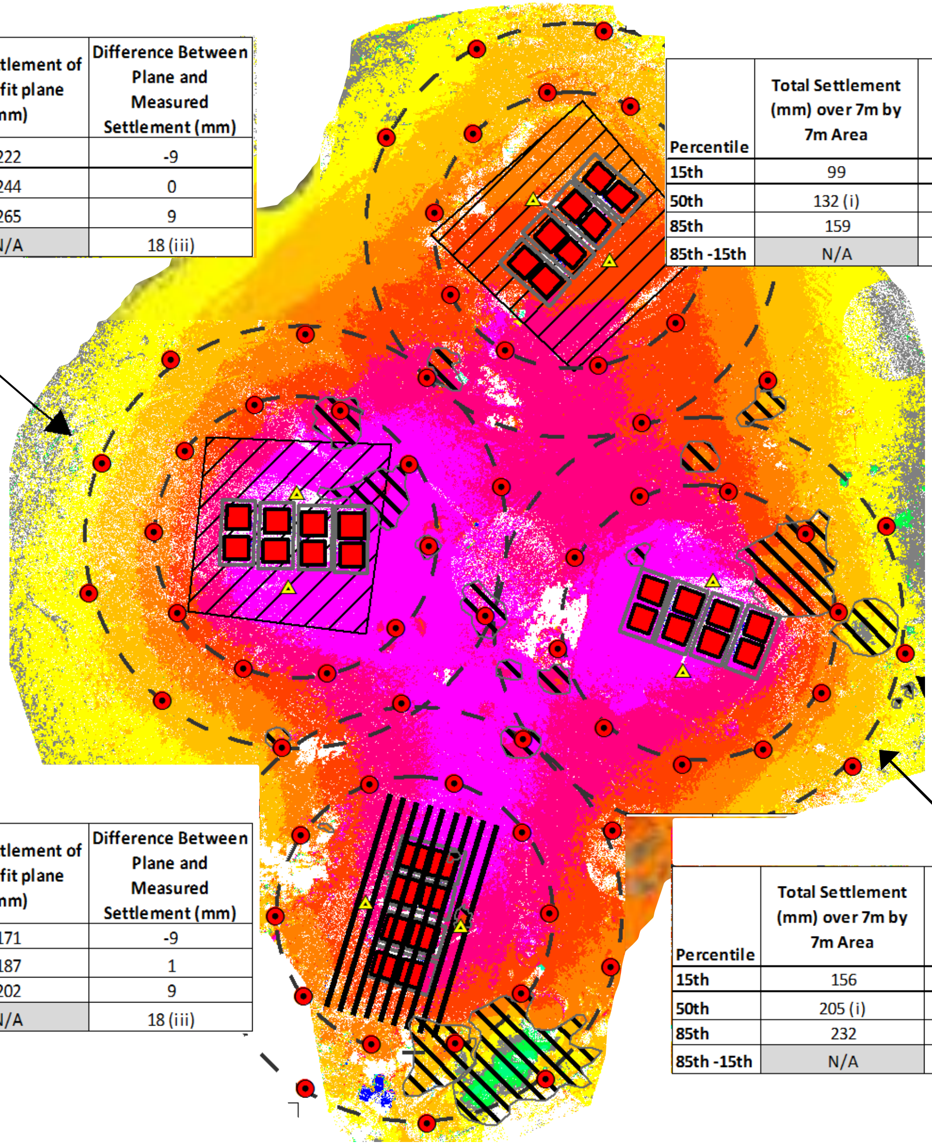
Example Blast Liquefaction-induced Subsidence Map
(blast #5)

Gravel Raft (GR)

Percentile	Total Settlement (mm) over 7m by 7m Area	Total Settlement (mm) over 4m by 4m Area	Total Settlement of a best fit plane (mm)	Difference Between Plane and Measured Settlement (mm)
15th	183	219	222	-9
50th	230 (i)	246	244	0
85th	261	266	265	9
85th -15th	N/A	47 (ii)	N/A	18 (iii)

Soil-Cement Raft (SCR)

Percentile	Total Settlement (mm) over 7m by 7m Area	Total Settlement (mm) over 4m by 4m Area	Total Settlement of a best fit plane (mm)	Difference Between Plane and Measured Settlement (mm)
15th	99	118	120	-4
50th	132 (i)	134	134	0
85th	159	149	147	4
85th -15th	N/A	31 (ii)	N/A	8 (iii)



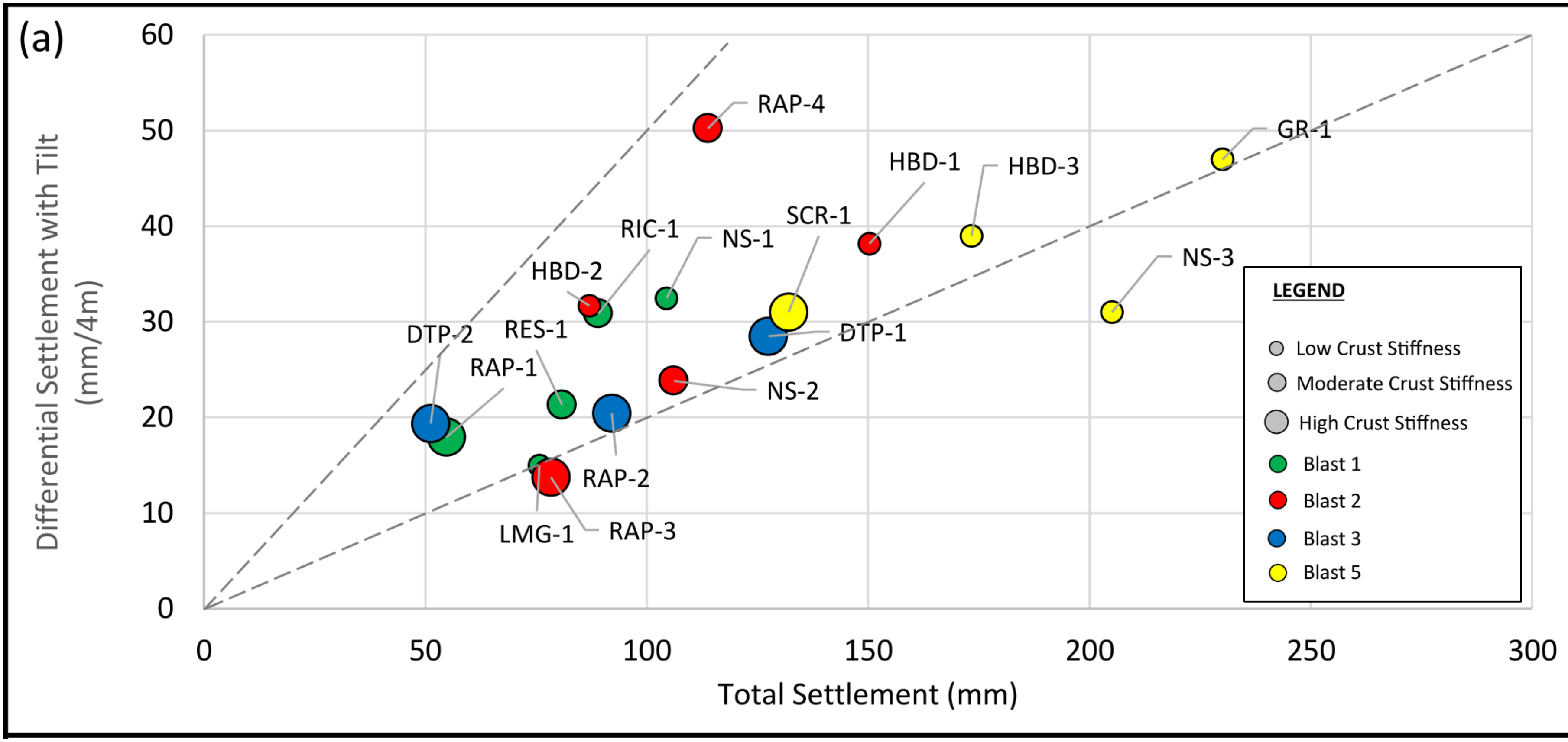
Horizontal Soil Mixed (HSM) Beams

Percentile	Total Settlement (mm) over 7m by 7m Area	Total Settlement (mm) over 4m by 4m Area	Total Settlement of a best fit plane (mm)	Difference Between Plane and Measured Settlement (mm)
15th	137	168	171	-9
50th	173 (i)	187	187	1
85th	207	207	202	9
85th -15th	N/A	39 (ii)	N/A	18 (iii)

Natural Soil (NS)

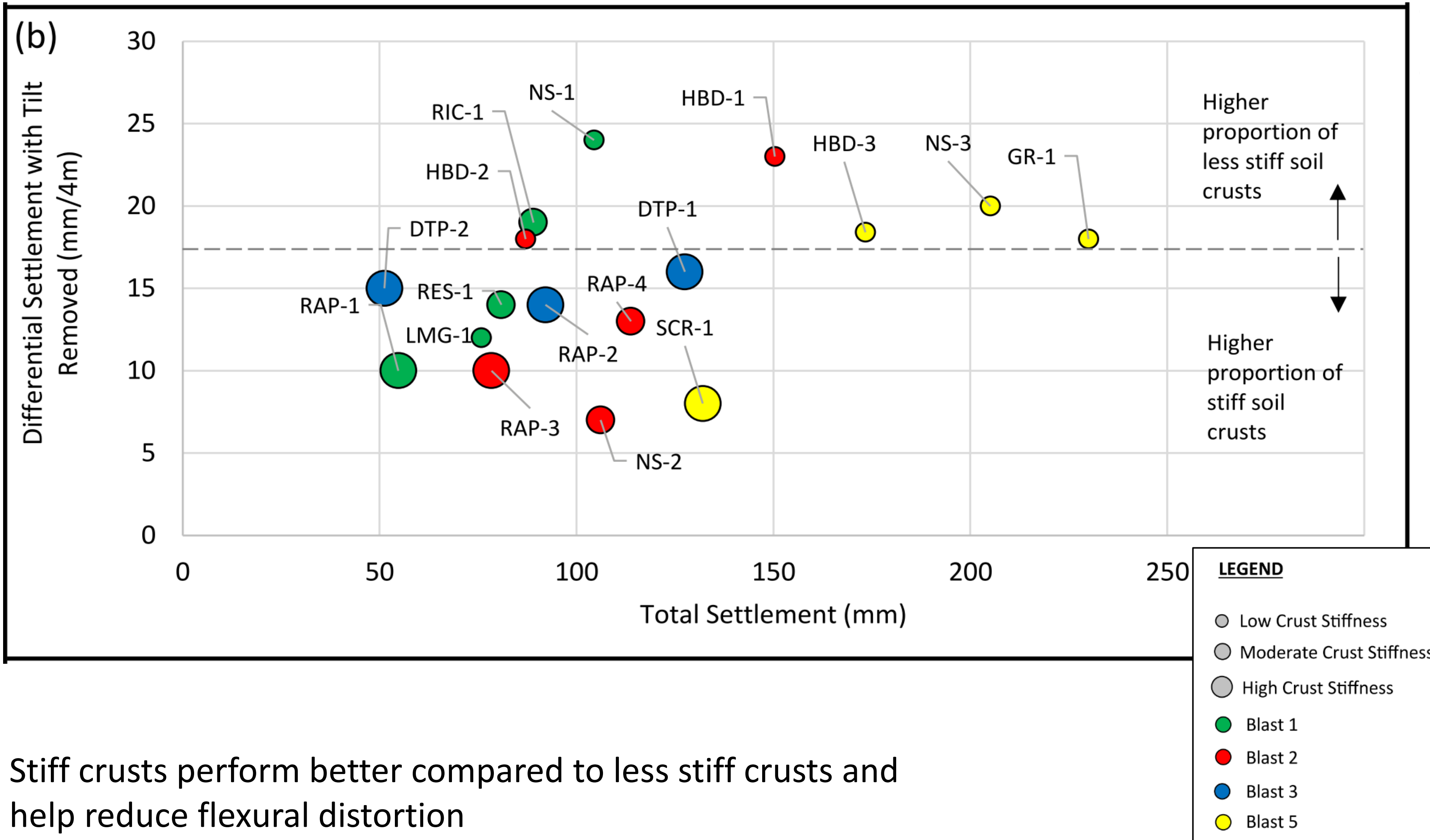
Percentile	Total Settlement (mm) over 7m by 7m Area	Total Settlement (mm) over 4m by 4m Area	Total Settlement of a best fit plane (mm)	Difference Between Plane and Measured Settlement (mm)
15th	156	203	206	-9
50th	205 (i)	220	220	-3
85th	232	234	231	11
85th -15th	N/A	31 (ii)	N/A	20 (iii)

Blast-induced Liquefaction Results Summary
(differential settlement versus total settlement)



As the total settlement increases, the differential settlement also increases

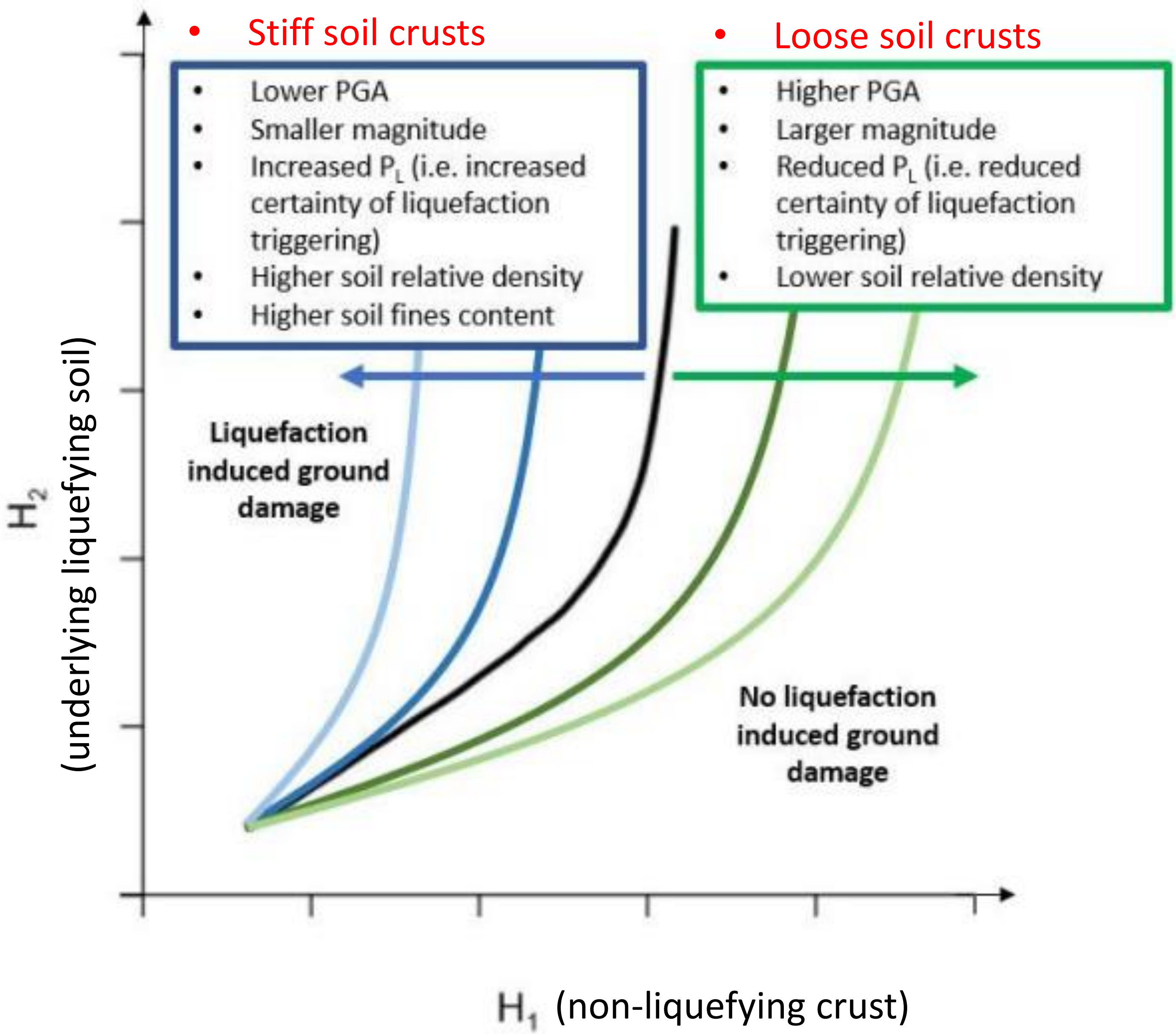
Blast-induced Liquefaction Summary
(flexural distortion vs total settlement)



Stiff crusts perform better compared to less stiff crusts and help reduce flexural distortion

Blast-induced Liquefaction Testing of HSM Beam Ground Improvement Methods Beneath Existing Houses - Video

Conclusions – Shallow Ground Improvements are effective in Reducing Liquefaction Vulnerability



Conclusions

- **The CPT has proven to be a great screening tool for assessing liquefaction triggering in ChCh. However, in some natural soils with higher fines content it tends to over-estimate triggering.**
- **Vs/Vp have proven to be a good indicators of liquefaction resistance in ChCh soils that were predicted to liquefy via CPT, yet did not manifest liquefaction damage in the earthquakes.**
- **When sites are clearly predicted as susceptible to liquefaction triggering via CPT and/or Vs, ground improvement may be considered as an option to mitigate liquefaction damage.**

Conclusions cont…

- **The presence of a thick/stiff enough non-liquefying crust is effective at mitigating liquefaction damage in residential areas:**
  - Proposed by Ishihara (1985)
  - Demonstrated by the Canterbury earthquakes in areas without observed damage
  - Demonstrated by the blast trials performed in this study
- **Shallow ground improvement (GI) can be affordable and effective at creating a non-liquefying crusts.**
- **While some GI methods may be "better" than others, there are a number of methods that can be effective.**
- **GI effectiveness must be verified, because even "good" methods may not work well in unfavorable soil conditions or with poor installation.**

Conclusions cont…

- **Four main mechanisms of effective GI were identified in this study:**
  - Increase in soil density/strength to improve the liquefaction triggering resistance
  - Increase in "composite"/effective shear stiffness to improve the liquefaction triggering resistance
  - Increase the crust thickness to reduce the ground surface differential settlement and flexural distortion
  - Increase the crust stiffness to reduce the ground surface flexural distortion
- **In this study, GI effectiveness was verified using a combination of:**
  - CPT (density/strength) and Crosshole Vs/Vp (composite stiffness)
  - Full scale shaking tests with T-Rex & Blast induced liquefaction tests
  - 2D Dynamic and 3D deformation numerical simulation

Conclusions cont…

- **A link between composite soil-GI stiffness from crosshole Vs tests and T-Rex shaking tests has been established in ChCh. Now, crosshole composite Vs tests can be used to infer effectiveness of full-scale GI in ChCh without the need to perform additional T-Rex testing.**

Conclusions cont…

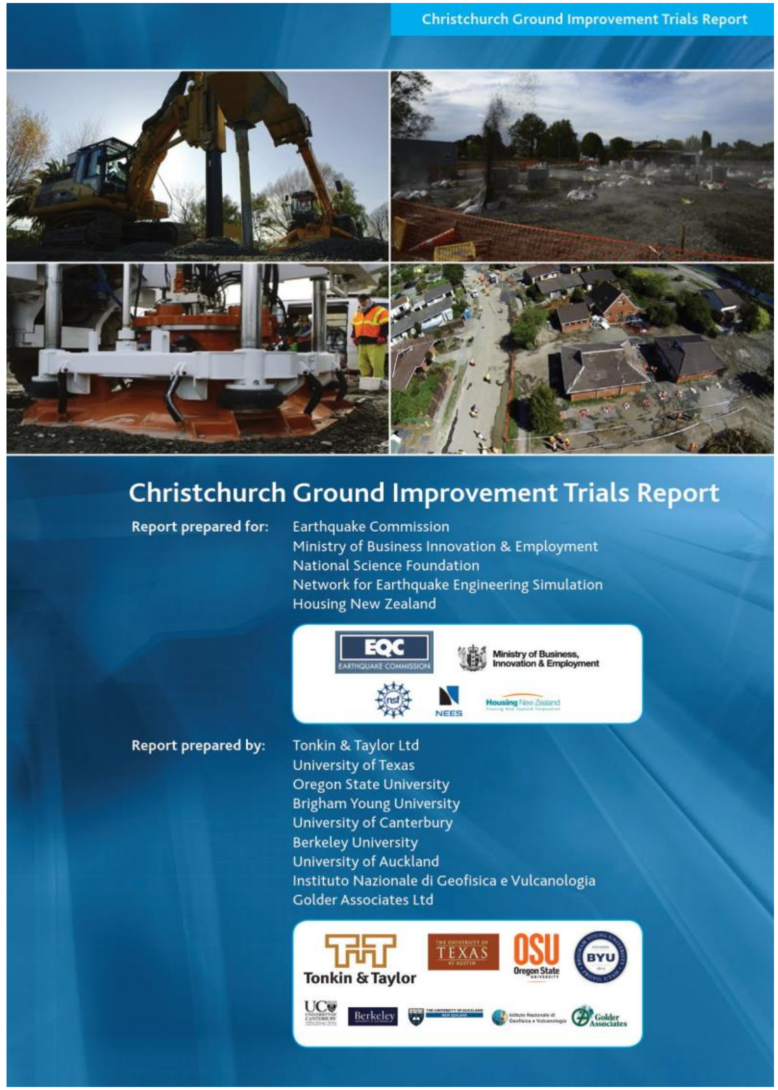
Shallow, Residential Ground Improvement Methods Studied

Ground Improvement Method	Soil Type	Mechanism and effectiveness for increasing the thickness of the non-liquefying crust		Mechanism and effectiveness for reducing the differential settlement caused by liquefaction of the underlying soils		Relative overall effectiveness
		Mechanism	Effectiveness	Mechanism	Effectiveness	
Rapid Impact Compaction	Sandy	Densification	Good	Thicker crust	Good	Good
	Silty	Densification	Poor	Thicker crust	N/A	Poor
4m deep Rammed Aggregate Piers	Sandy	Densification & Stiffness	Very good	Stiffer and thicker crust	Very good	Very good
	Silty	Stiffness	Good	Stiffer and thicker crust	Good	Good
4m deep Low Mobility Grout	Sandy	Densification	Poor*	Thicker crust	Poor*	Poor*
	Silty	Densification	Poor*	Thicker crust	Poor*	Poor*
4m deep Driven Timber Poles	Sandy	Densification & Stiffness	Moderate	Stress redistribution	Moderate	Moderate
	Silty	Densification & Stiffness	Poor	Stress redistribution	Moderate	Moderate
1.2m Reinforced Cement Stabilised Raft	Sandy	Cementation	Very good**	Stiffer crust	Very good	Very good
	Silty	Cementation	Very good**	Stiffer crust	Very good	Very good
1.2m Reinforced Gravel Raft	Sandy	Replacement with non-liquefying material	Very good**	Stiffer crust	Good	Good
	Silty	Replacement with non-liquefying material	Very good**	Stiffer crust	Good	Good
Horizontal Soil Mixed beams	Sandy	Stiffness	Good	Stiffer and thicker crust	Good in one direction marginal in another	Good
	Silty	Stiffness	Good	Stiffer and thicker crust	Good in one direction marginal in another	Good

*Poor for shallow/low confined applications.

** Where the groundwater level is >1.2m below the ground surface these methods do not increase the crust thickness, but do increase the crust stiffness.

Availability of this research work



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Questions