Effective Stress Analysis to Evaluate Ejecta Severity at Sandy and Silty Soil Sites

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PEER

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lembaga pengelola dana pendidikan

Sediment Ejecta

1. Case Histories: 2010-2011 Canterbury EQs

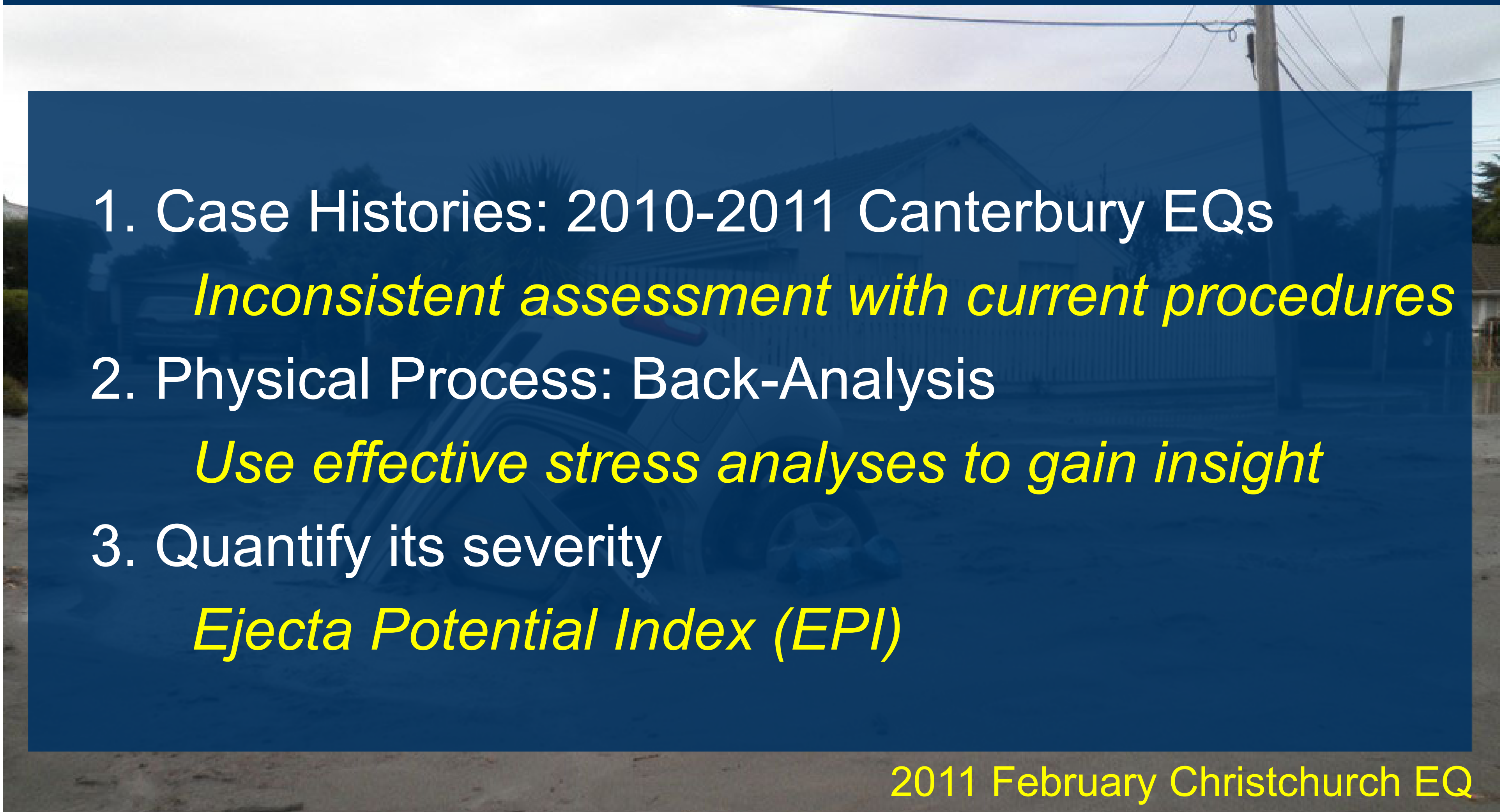
   Inconsistent assessment with current procedures

2. Physical Process: Back-Analysis

   Use effective stress analyses to gain insight

3. Quantify its severity

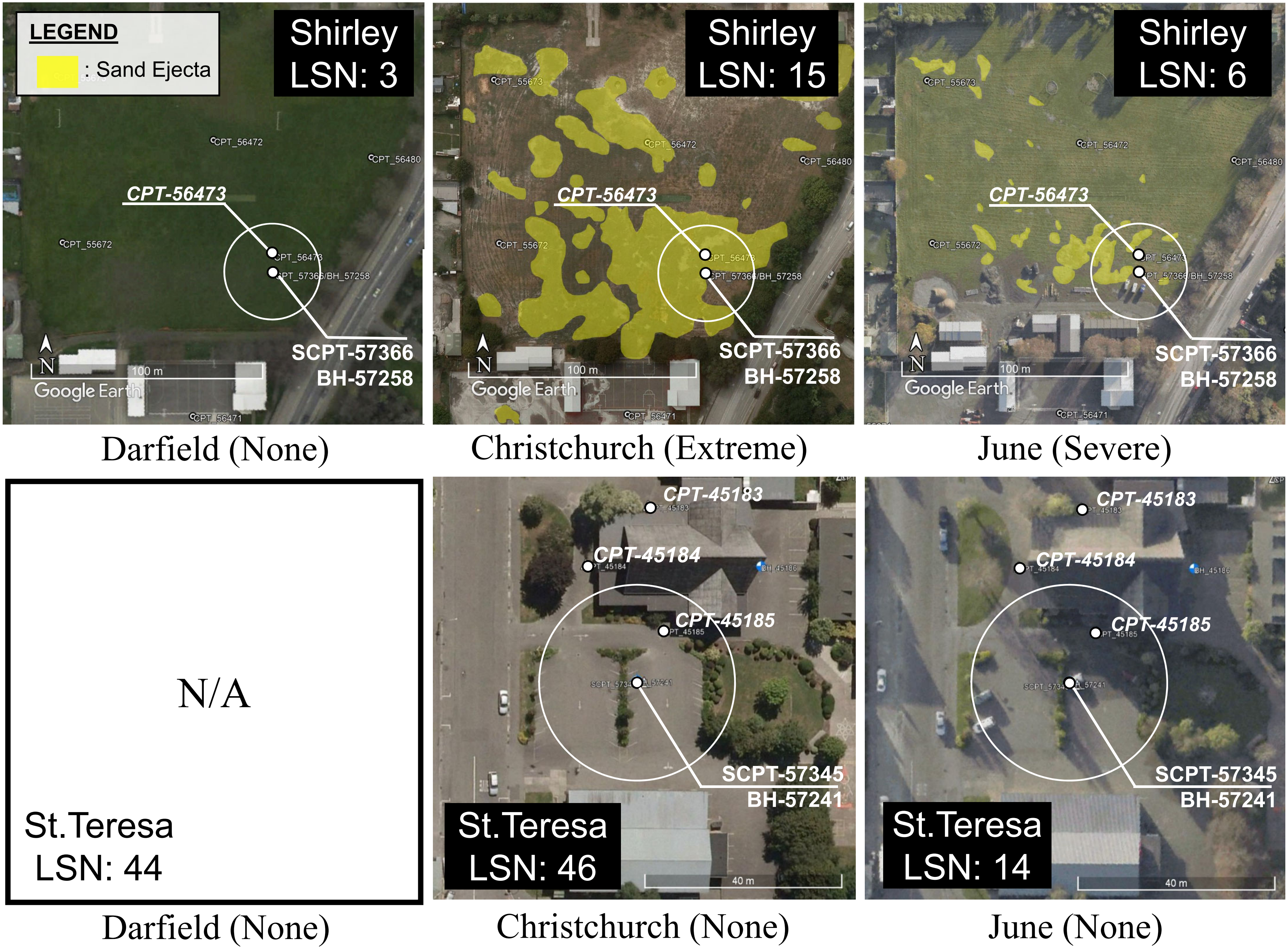
   Ejecta Potential Index (EPI)



2011 February Christchurch EQ

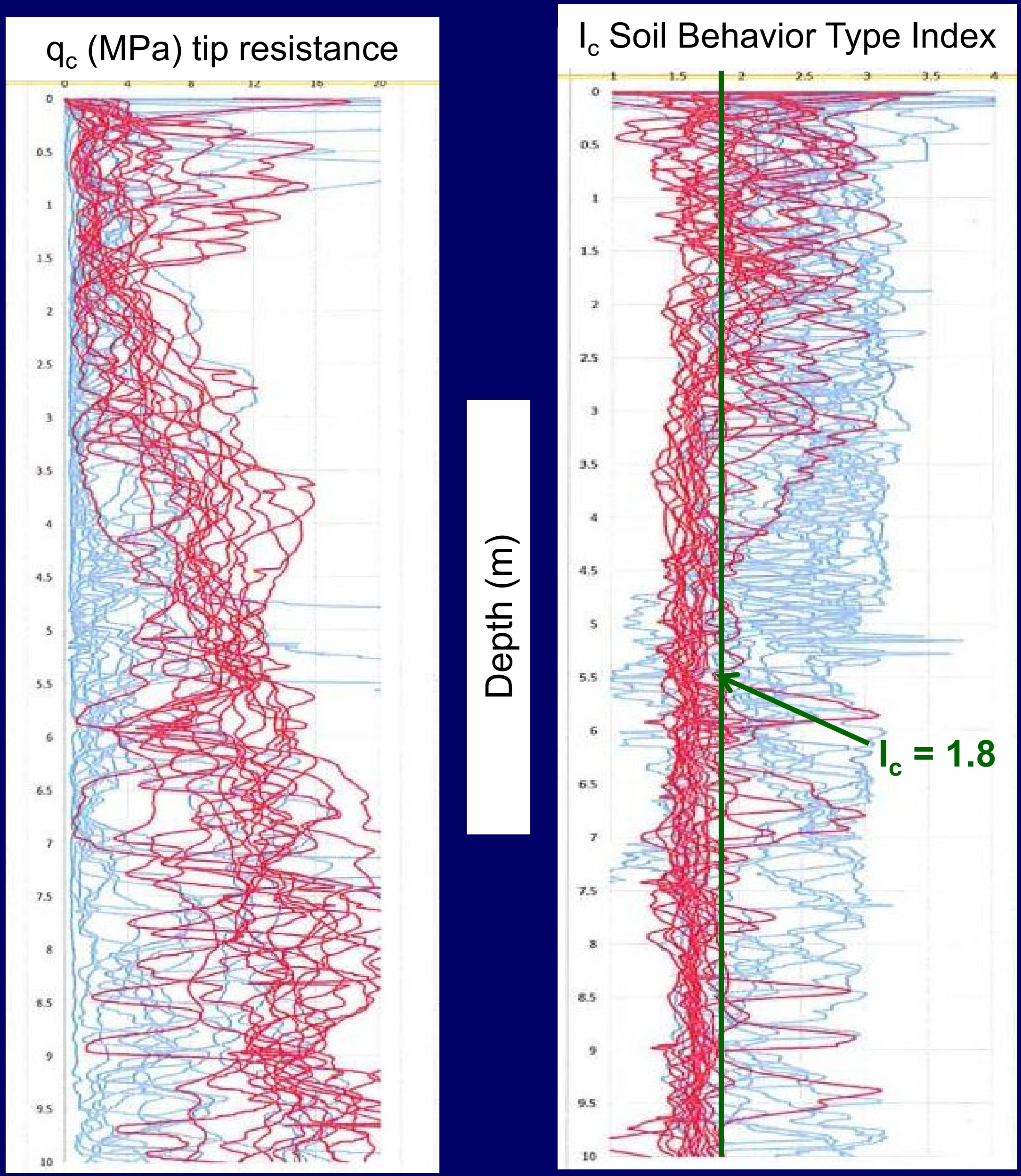
Source: M. Cubrinovski (UC Canterbury)

M_w 6.2 2011 February Christchurch
Why?
Underestimated Case
R_{rup}: 4.7 km
PGA: 0.38 g
Estimation: Moderate
Observation: EXTREME
Shirley
The sunk car
Christchurch CBD
St Teresa
Overestimated Case
R_{rup}: 5.7 km
PGA: 0.34 g
Estimation: Severe
Observation: NONE
2011 Christchurch Rupture
Bradley & Cubrinvoski (2011)
N
9 km



LEGEND
: Sand Ejecta
Shirley
LSN: 3
CPT_56472
CPT_56480
CPT-56473
CPT_55672
SCPT-57366
BH-57258
N
100 m
Google Earth
CPT_56471
Darfield (None)
Shirley
LSN: 15
CPT_55673
CPT_56472
CPT_56480
CPT-56473
CPT_55672
SCPT-57366
BH-57258
N
100 m
Google Earth
CPT_56471
Christchurch (Extreme)
Shirley
LSN: 6
CPT_55673
CPT_56472
CPT_56480
CPT-56473
CPT_55672
SCPT-57366
BH-57258
N
100 m
Google Earth
CPT_56471
June (Severe)
N/A
St.Teresa
LSN: 44
Darfield (None)
CPT-45183
CPT-45184
BH_45186
CPT-45185
SCPT-57345
BH-57241
St.Teresa
LSN: 46
40 m
Christchurch (None)
CPT-45183
CPT-45184
BH_45186
CPT-45185
SCPT-57345
BH-57241
St.Teresa
LSN: 14
40 m
June (None)

Occurrence of Liquefaction Ejecta Related to CPT Profile

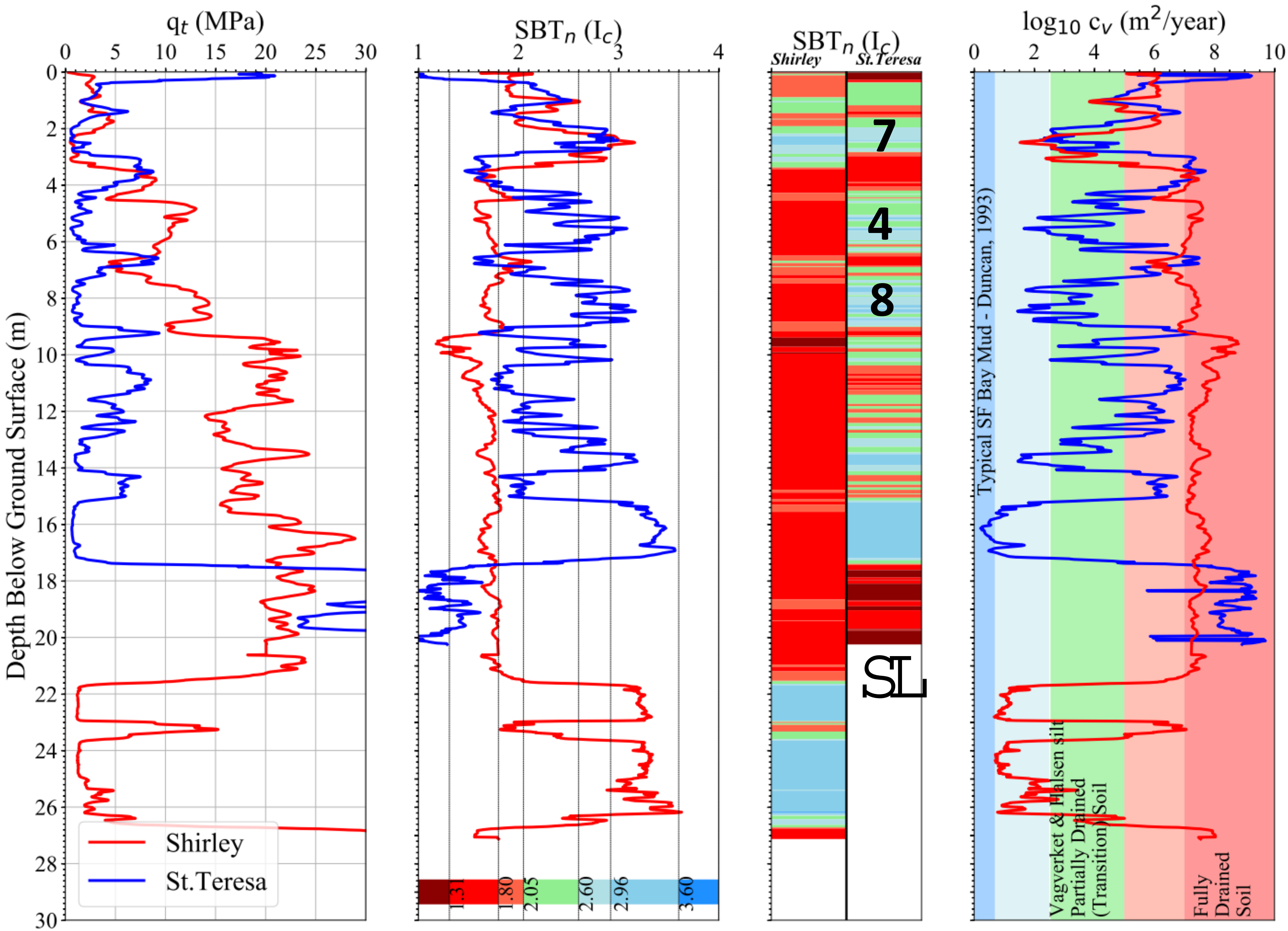


2010 Darfield EQ

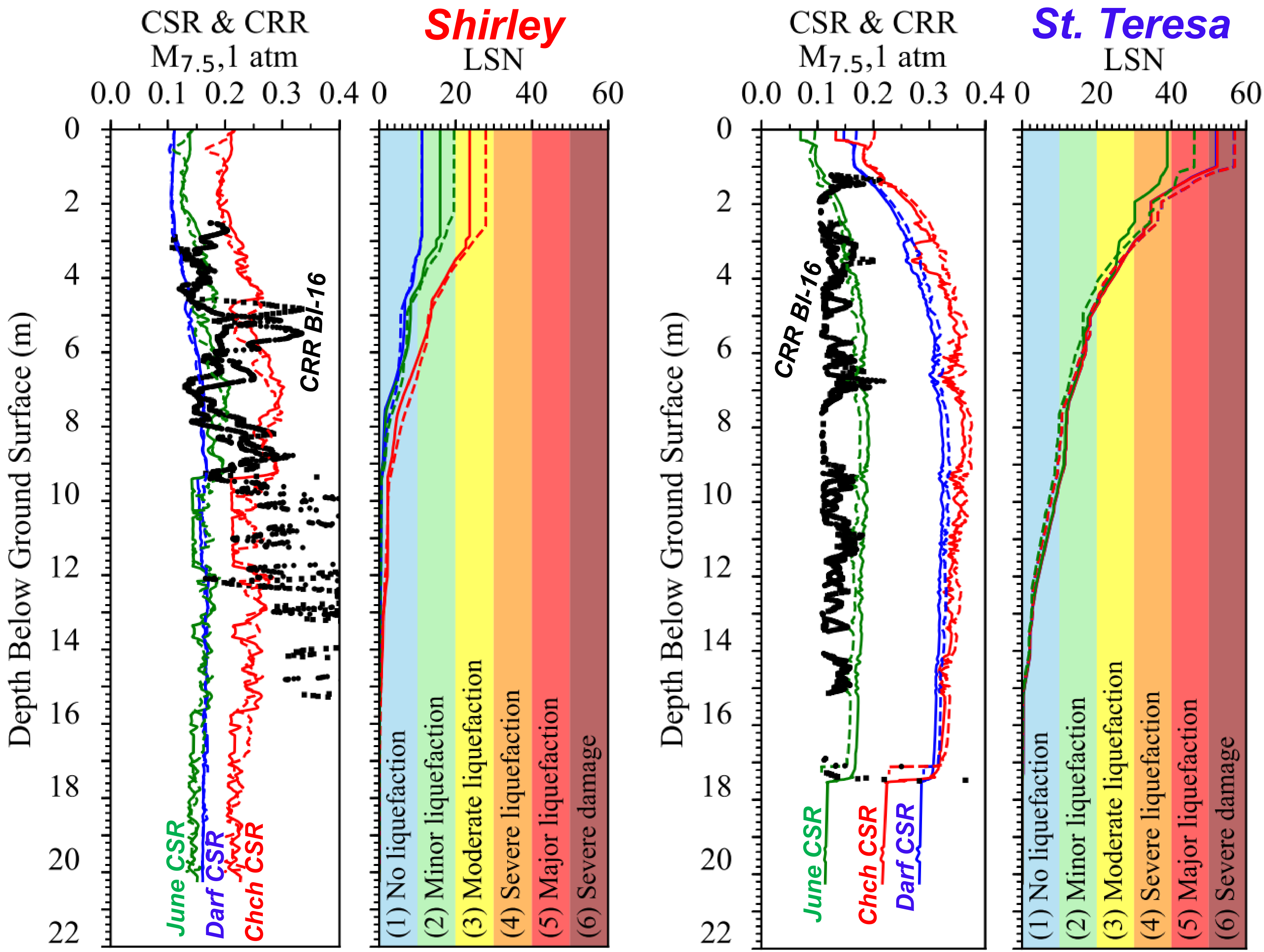
Ejecta Observed

No Ejecta

van Ballegooy et al.
Tonkin & Taylor
for the EQC



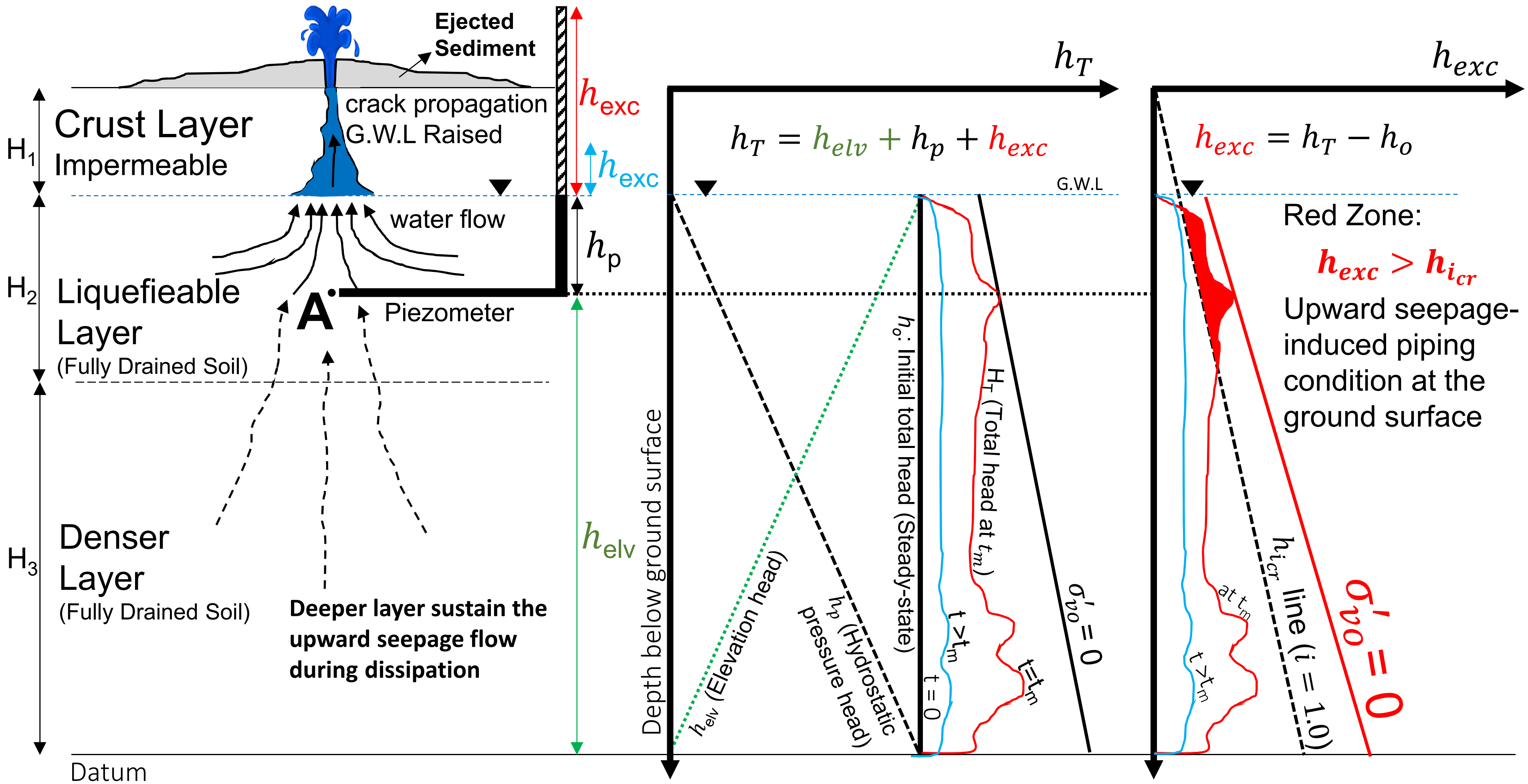
q_t (MPa)
SBT_n (I_c)
SBT_n (I_c)
Shirley
St.Teresa
$\log_{10} c_v$ (m^2/year)
Depth Below Ground Surface (m)
Shirley
St.Teresa
7
4
8
SL
1.31
1.80
2.05
2.60
2.96
3.60
Typical SF Bay Mud - Duncan, 1993)
Vagverket & Halsen silt
Partially Drained
(Transition) Soil
Fully
Drained
Soil



CSR & CRR
$M_{7.5}$,1 atm
Shirley
LSN
St. Teresa
Depth Below Ground Surface (m)
CRR BI-16
June CSR
Darf CSR
Chch CSR
(1) No liquefaction
(2) Minor liquefaction
(3) Moderate liquefaction
(4) Severe liquefaction
(5) Major liquefaction
(6) Severe damage


M_w 6.0 June 13 , 2011 Christchurch Earthquake
Original Video Duration: 3 mins 27 sec
Location: Christchurch Suburb
https://youtu.be/rRVK5NJE2qE

Physical Process of Sediment Ejecta

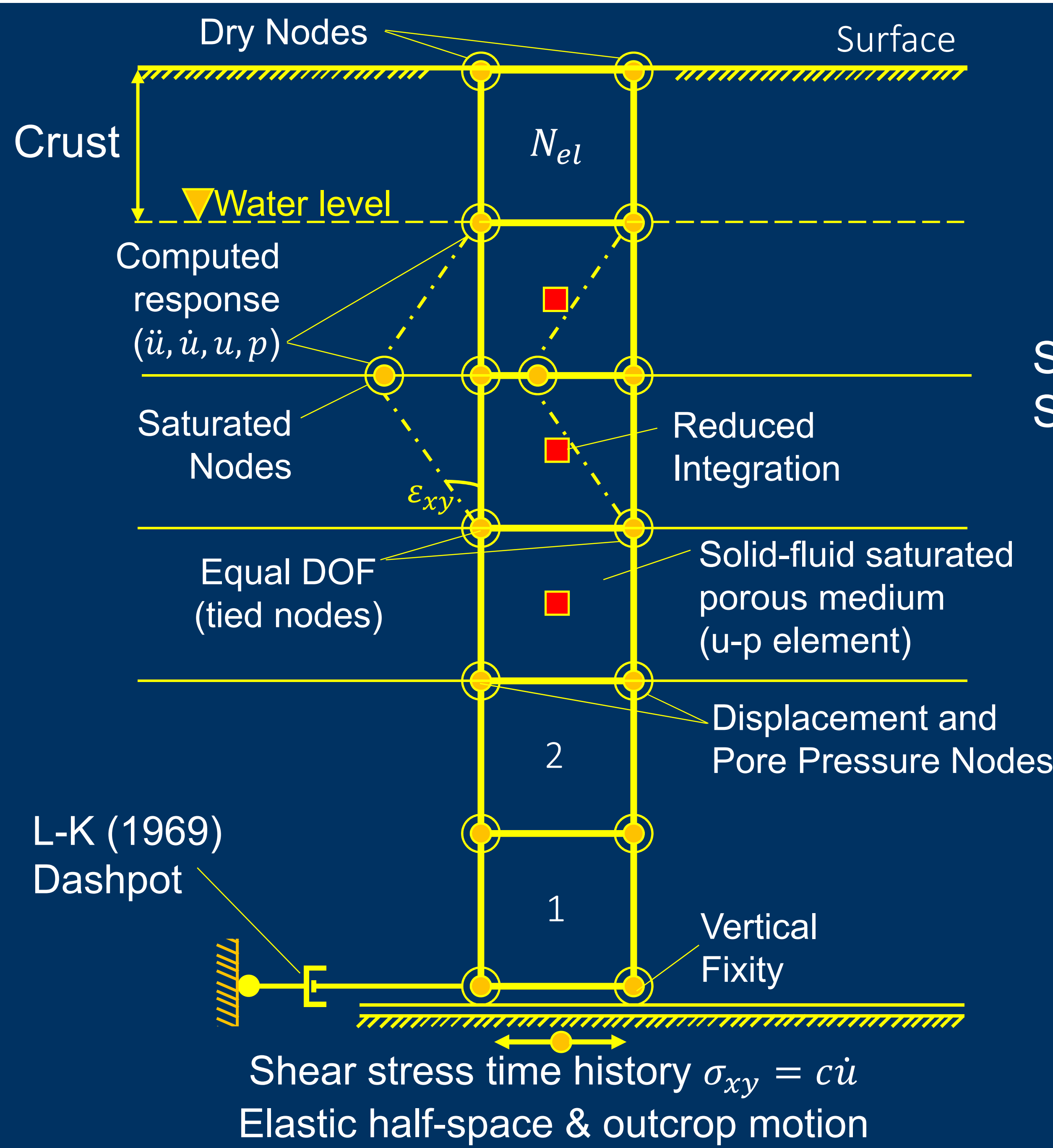


(a) Typical Soil Profile (b) h_T, Total Head (m) (c) h_{exc}, Excess Head (m)

h_{exc}: Excess pressure head (m)

$h_{i_{cr}}$: Critical head to cause piping condition ($i > i_{cr}$) at ground surface

Effective Stress Analysis (ESA) OpenSees v3.0



Stack of quad elements
Solve for

At Corner:

- $displacement\ (u)$
- $velocity\ (\dot{u})$
- $acceleration\ (\ddot{u})$
- $pore\ pressure\ (p)$

At Center:

- $\frac{\tau_{xy}}{\sigma'_{vo}}\ (CSR)$
- γ_{xy}

Constitutive Models

PM4Sand & PM4Silt
(Boulanger & Ziotopoulou 2017,2018)

Based primarily on CPT data

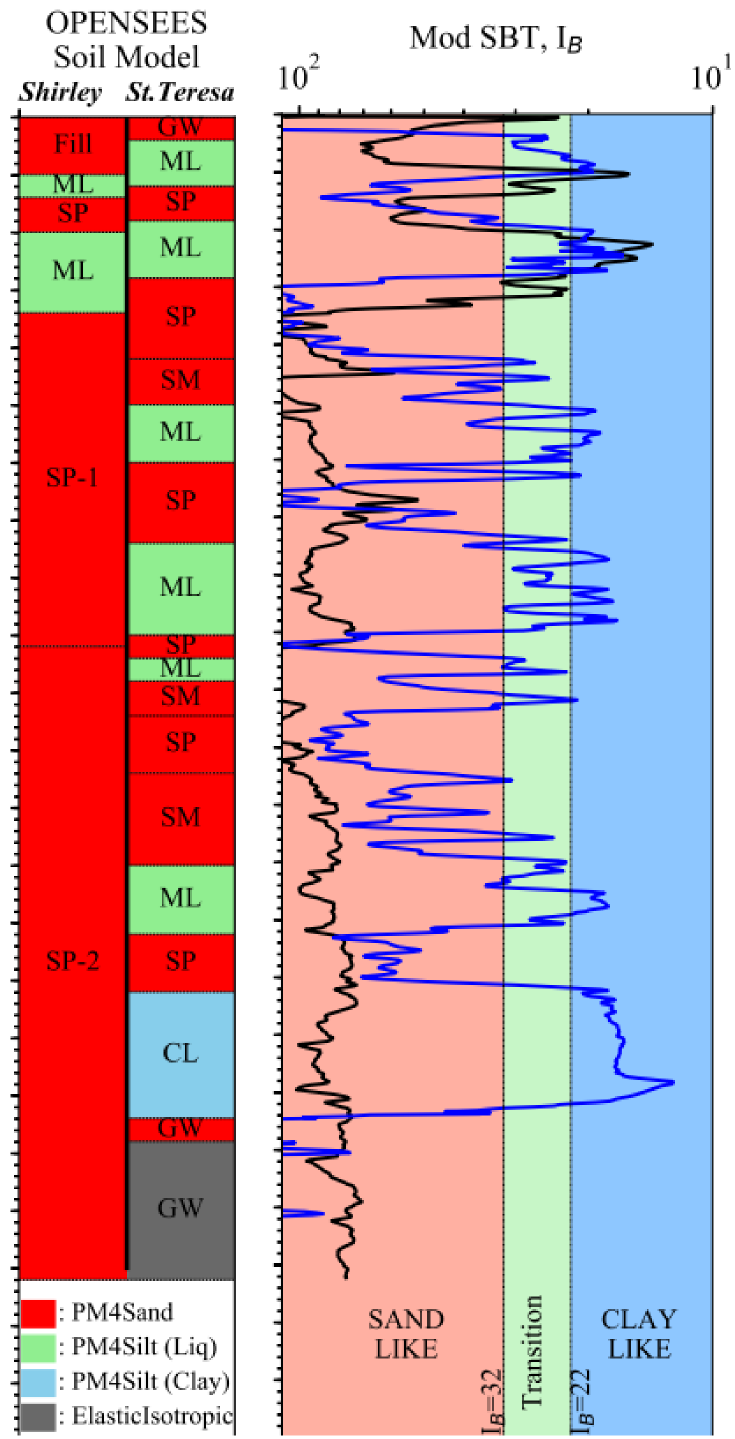
For:

$I_B > 32$: PM4Sand (Sand-Like)

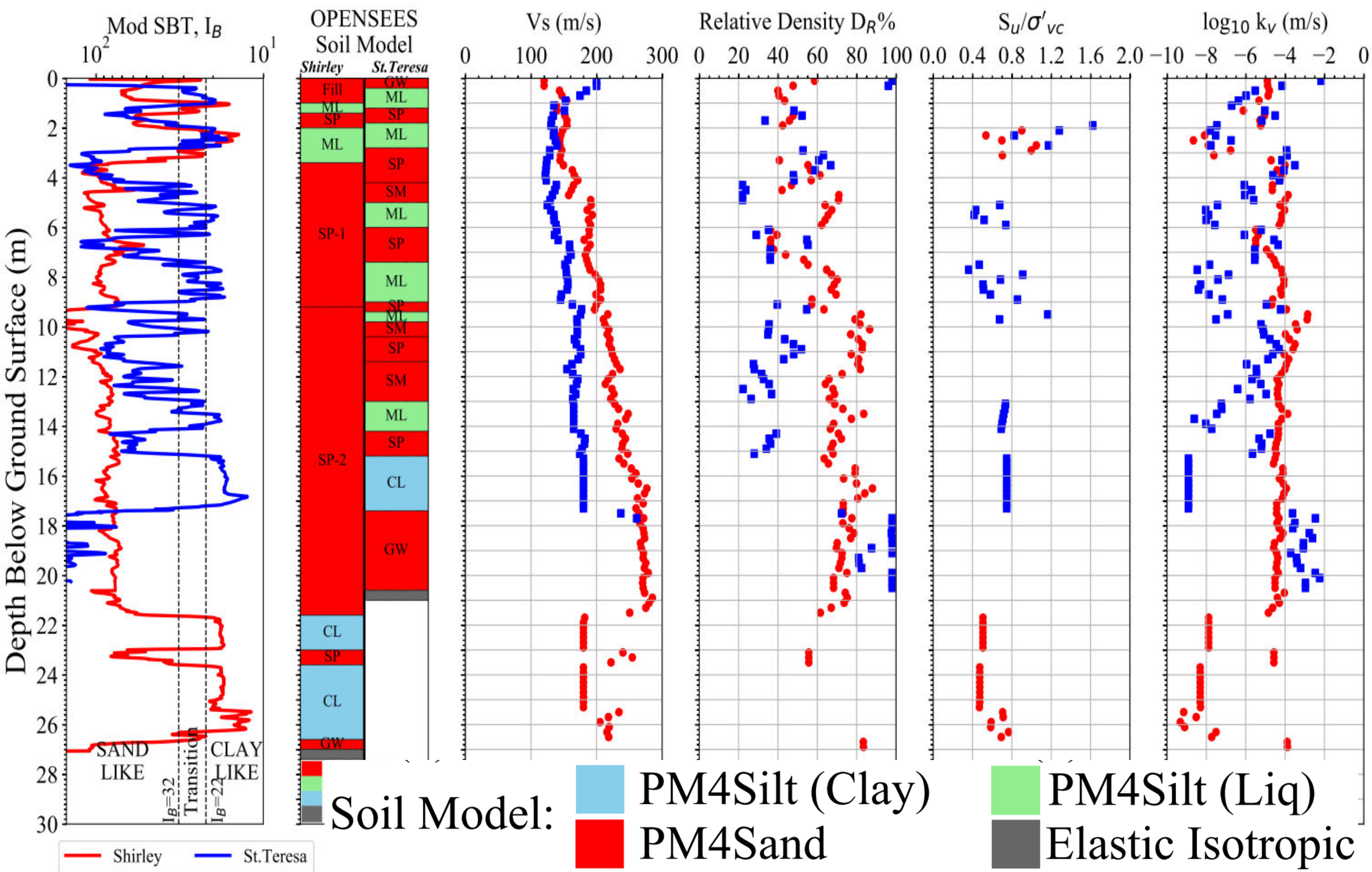
$22 < I_B < 32$: PM4Silt ($r_{u-max} = 0.99$)

$I_B < 22$: PM4Silt (Clay-Like)

** Hutabarat & Bray PEER Report for more detail on PM4Sand & PM4Silt parameters*

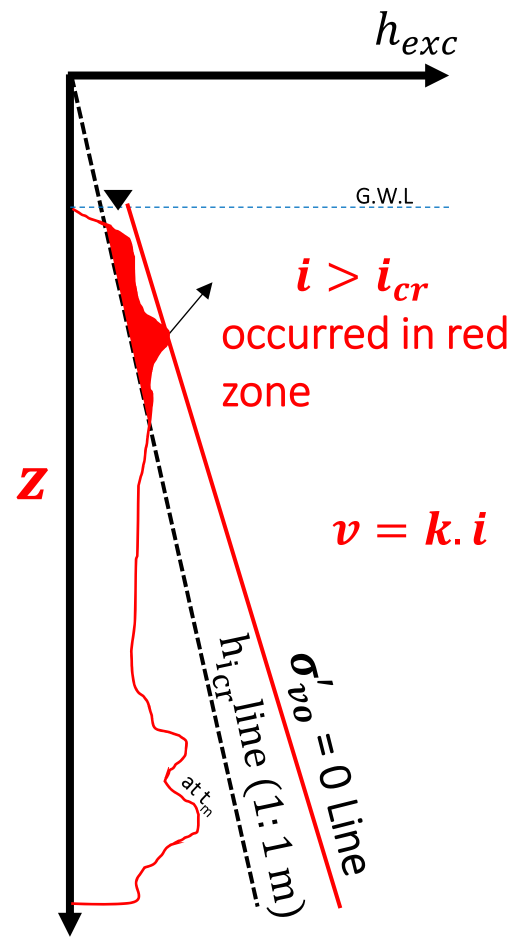


CPT Sounding | Soil Model | 4 Key Parameters: V_s | D_r | S_u | k_v



At each time step when $h_{exc} > h_{i_{cr}}$, the area is given by:

$$\text{Artesian Flow Potential } (\text{m}^3) = \int_{Datum}^{GWL} \left(h_{exc} - h_{i_{cr}}\right)^2 dz$$



$i > i_{cr}$, cause piping

Progressive cracks at crust

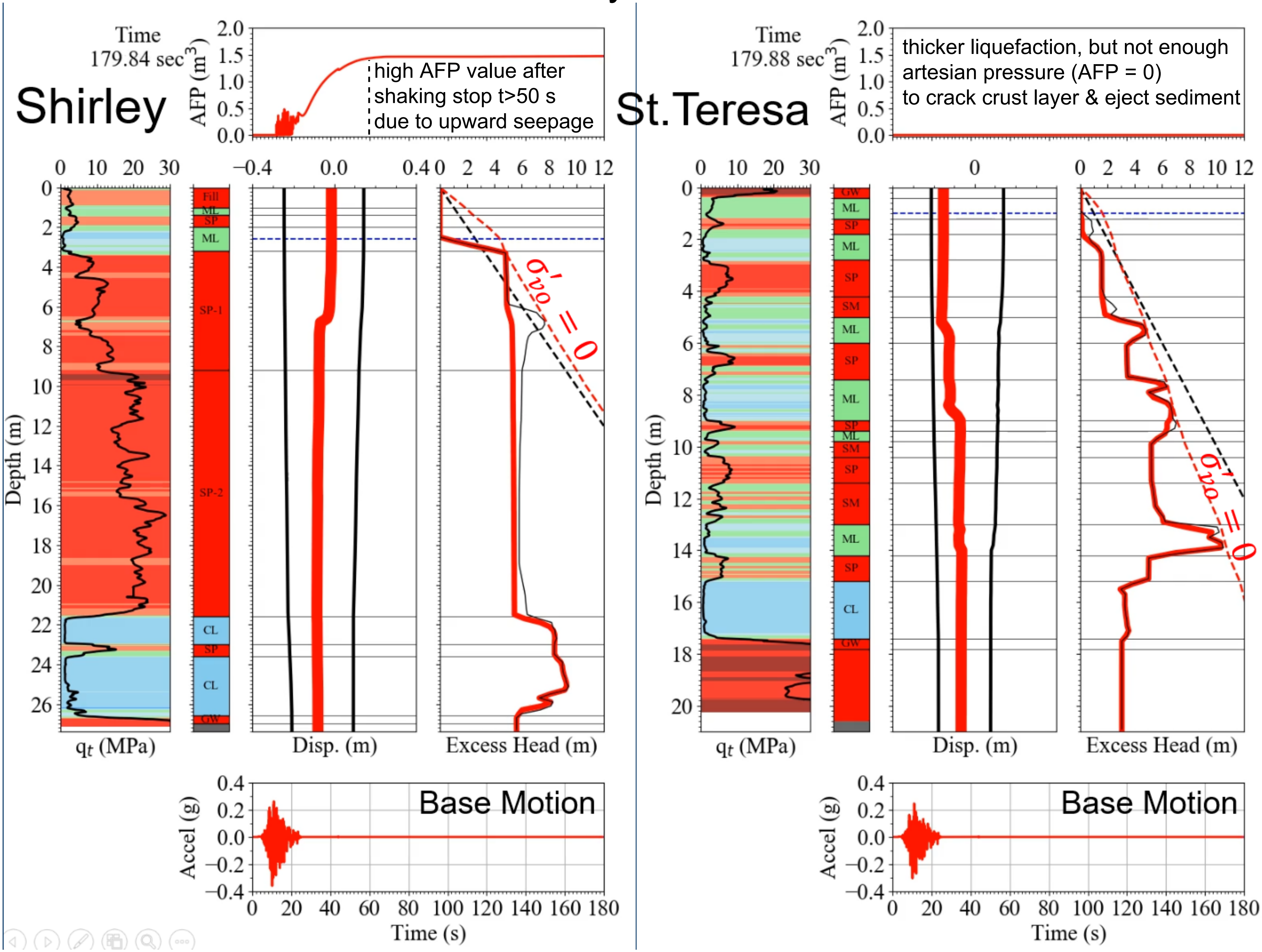
For thicker liquefaction,

More RED Shaded Area

Greater Artesian Pressure

More Water Volume

180 Seconds of Dynamic ESA simulation



Ejecta Potential Index (EPI)

Artesian Flow Potential integrated over time

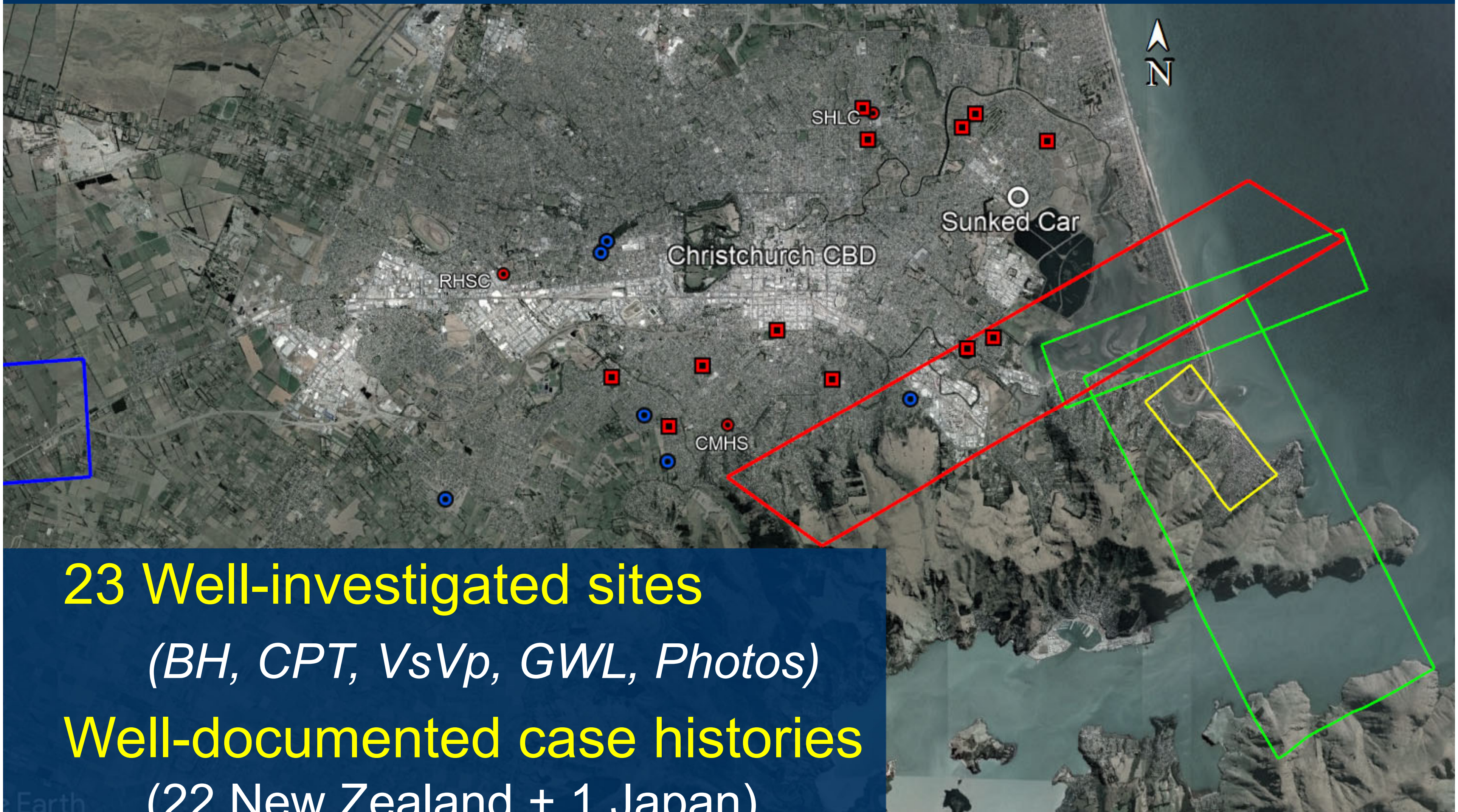
$$EPI(m^3.s) = \int_{0}^{t_d} \int_{Datum}^{GWL} \left(h_{exc} - h_{i_{cr}}\right)^2 dz\, dt$$

Measure of hydraulic gradient, critical layer thickness, and volume of water over time

Site	Event	LSN	Observation	EPI ($m^3.s$)
Shirley	Darfield	3	NONE	0
St.Teresa		44	NONE	0
Shirley	Christchurch	15	**EXTREME**	211
St.Teresa		46	NONE	0
Shirley	June	6	SEVERE	83
St.Teresa		14	NONE	0

Extending the analysis duration is important to understand the full story

Evaluation of EPI



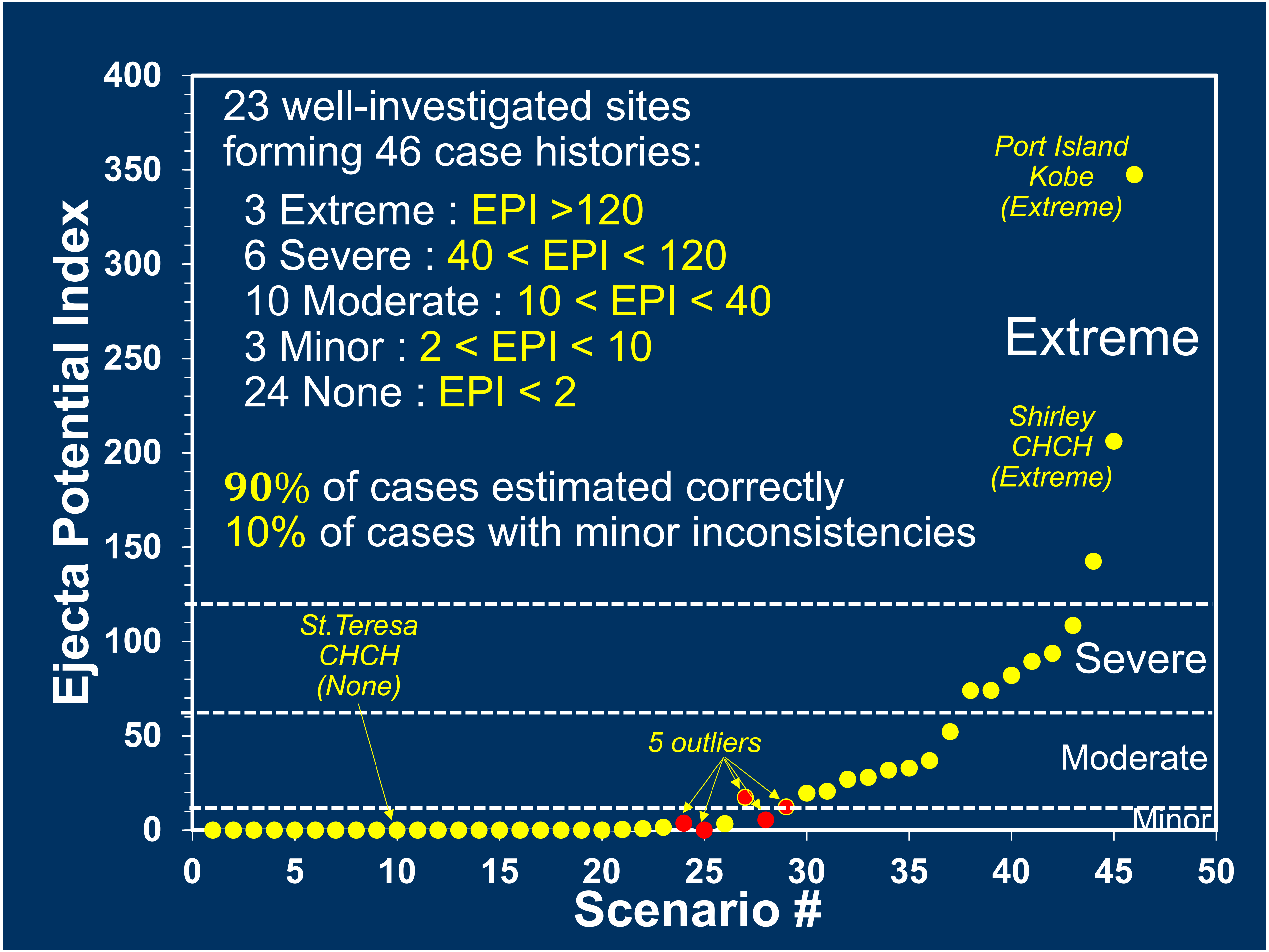
23 Well-investigated sites

(BH, CPT, VsVp, GWL, Photos)

Well-documented case histories

(22 New Zealand + 1 Japan)

4 Shallow-crustal earthquakes



23 well-investigated sites
forming 46 case histories:
3 Extreme : EPI >120
6 Severe : 40 < EPI < 120
10 Moderate : 10 < EPI < 40
3 Minor : 2 < EPI < 10
24 None : EPI < 2
90% of cases estimated correctly
10% of cases with minor inconsistencies
Port Island
Kobe
(Extreme)
Extreme
Shirley
CHCH
(Extreme)
St.Teresa
CHCH
(None)
Severe
5 outliers
Moderate
Minor
Ejecta Potential Index
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
35
40
45
50
Scenario #

Conclusions

Post-shaking water flow is important, because the primary driving mechanism is *upward seepage-induced piping*

Severity of sediment ejecta influenced by:

- Drainage contrast ($\boldsymbol{c_v}$ profile)
- Excess head (pressure)
- Duration (piping)

Ejecta Potential Index (EPI):

46 case histories (23 sites & 4 earthquakes)
90% well-estimated

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