Liquefaction evaluation of gravelly soils: An integrated laboratory testing and numerical modeling approach

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PEER Researchers' Workshop

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Where do we find these soils?

- Fills (Engineered or Reclaimed)
- Natural Deposits
- Mine taili

Gravel Liquefaction in the Literature

Year	M_w	Earthquake	Reference
1891	7.9	Mino-Owari, Japan	Tokimatsu & Yoshimi (1983)
1905	7.1	Messina, Italy	Baratta (1910)
1906	8.2	San Francisco, CA	Youd and Hoose (1978)
1948	7.3	Fukui, Japan	Ishihara (1985)
1964	9.2	Seward, Alaska	McCulloch & Bonilla (1970)
1975	7.3	Haicheng, China	Wang (1984)
1976	7.8	Tangshan, China	Wang (1984)
1976	6.5	Friuli, Italy	Sirovich (1996)
1978	7.4	Miyagiken-Oki, Japan	Tokimatsu & Yoshimi (1983)
1983	6.9	Borah Peak, Idaho	Youd et al (1985), Harder (1986)
1988	6.8	Armenia	Yegian et al (1994)
1992	5.8	Roermond, Netherlands	Maurenbrecher et al (1995)
1993	7.8	Hokkaido, Japan	Kokusho et al (1995)
1995	7.2	Kobe, Japan	Kokusho & Yoshida (1997)
1999	7.6	Chi-Chi, Taiwan	Chu et al (2000)
2008	7.9	Wenchuan, China	Cao et al (2013)
2014	6.1	Cephalonia Island, Greece	Nikolaou et al (2014)
2016	7.8	Muisne, Ecuador	Vera Grunauer et al (2017)
2016	7.8	Kaikoura, New Zealand	Cubrinovsky et al (2017)

2014 Cephalonia EQ

Nikolaou et al. GEER (2014)

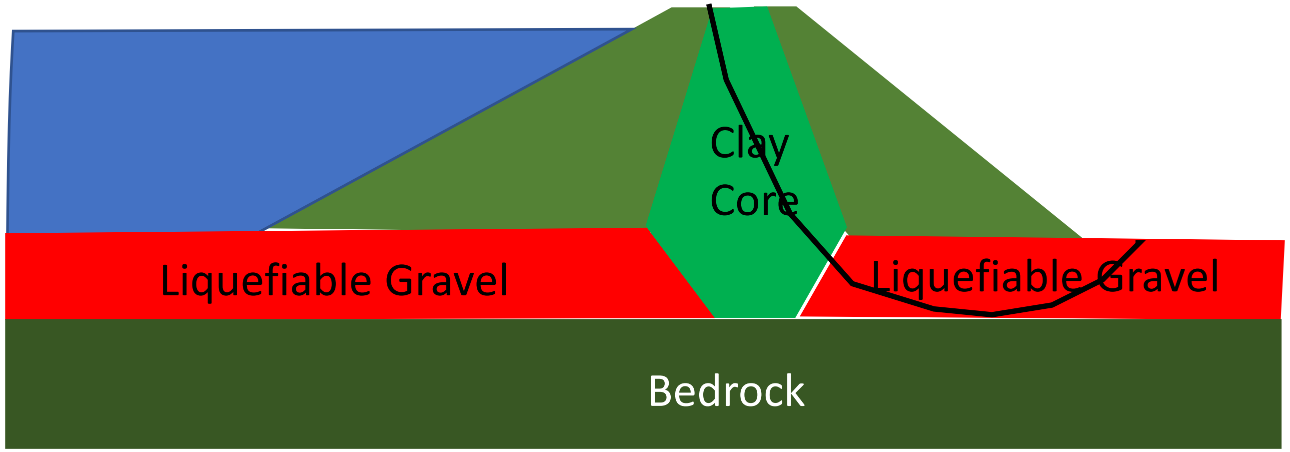
2016 Kaikoura EQ

Cubrinovski et al. (2018)

Gravel Liquefaction Sites in the World

Rollins, 2019

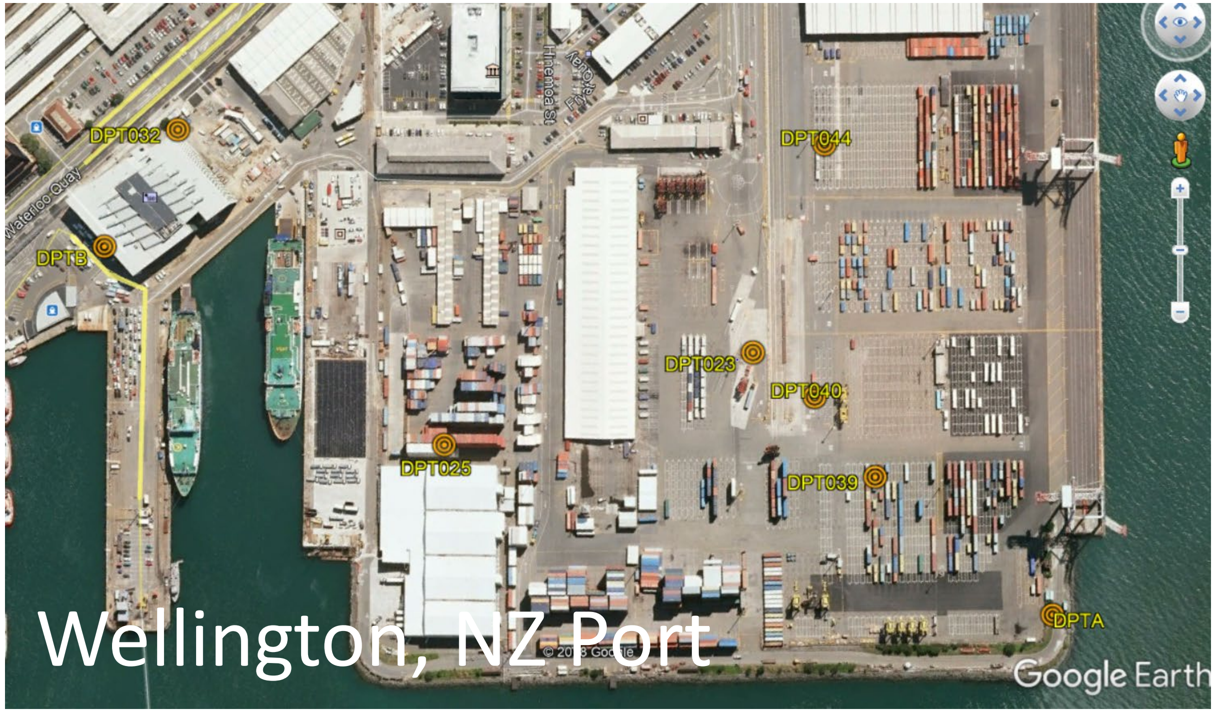
Gravel Liquefaction in Older Dams



- Liquefaction hazard recognized after construction
- Liquefaction evaluation & remediation are often “multi-million dollar” decisions

Gravel Liquefaction at Port Facilities

- Lateral Spread > 1 m
- Settlements > 25cm



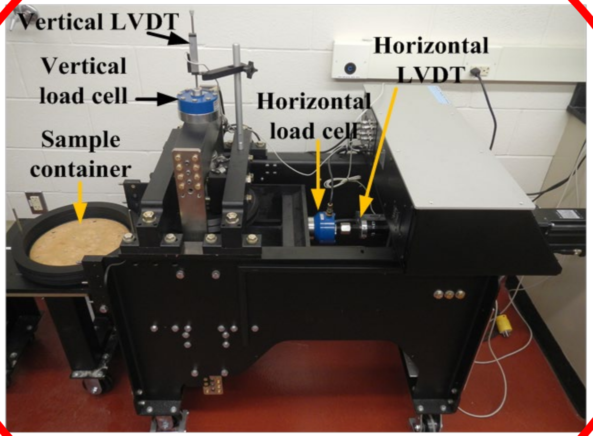
- Lateral Spread > 1.5m
- Gravel ejecta

Integrated approach: Micro to Macro Response

Field Testing

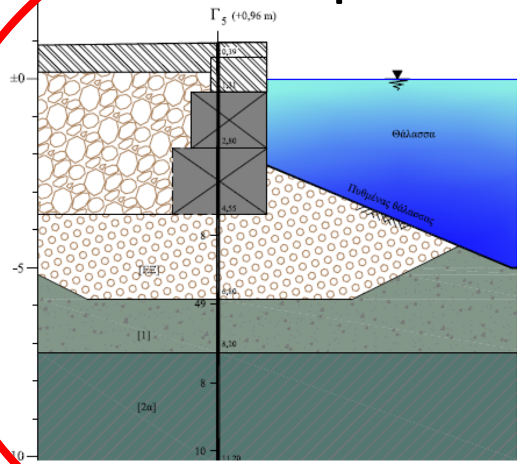
Improved DPT and Vs testing and correlations

Laboratory Testing



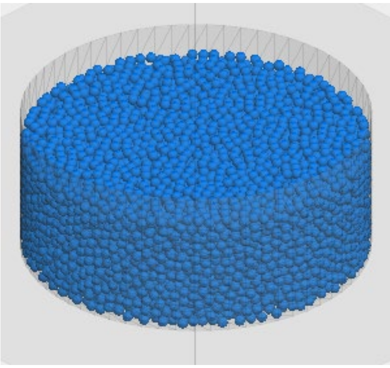
Large-scale CSS used for cyclic, and post-cyclic shear tests with Vs measurements

Field Response



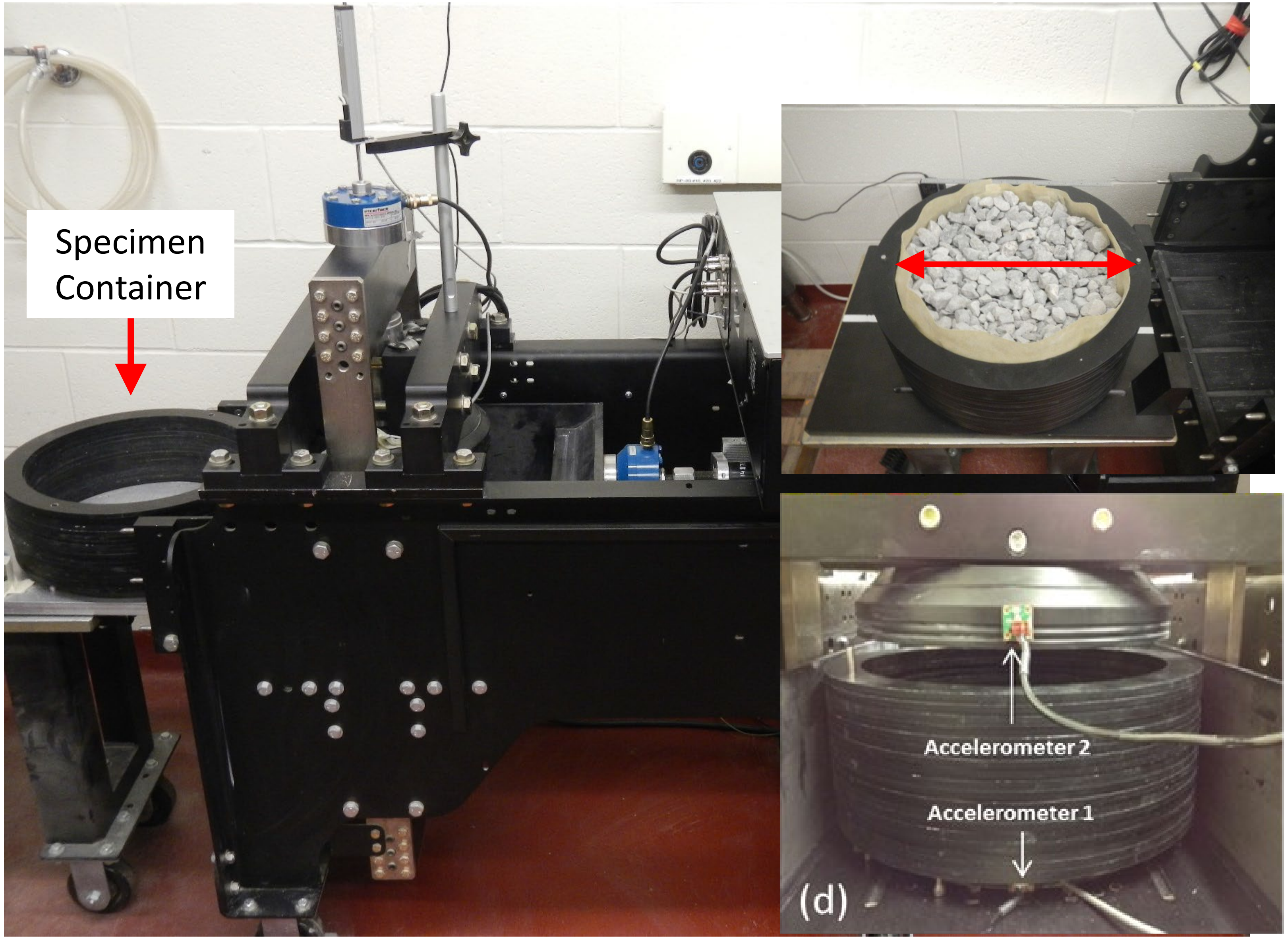
Back-analysis of case histories.

Numerical Modeling



3D DEM analyses

UC Berkeley Large-size Cyclic Simple Shear (CSS)



Monotonic, cyclic and post-cyclic tests were performed on three uniform gravels, and mixtures of gravels and Ottawa Sand C109

Pea Gravel

Rounded to Subrounded

8 mm Crushed Limestone

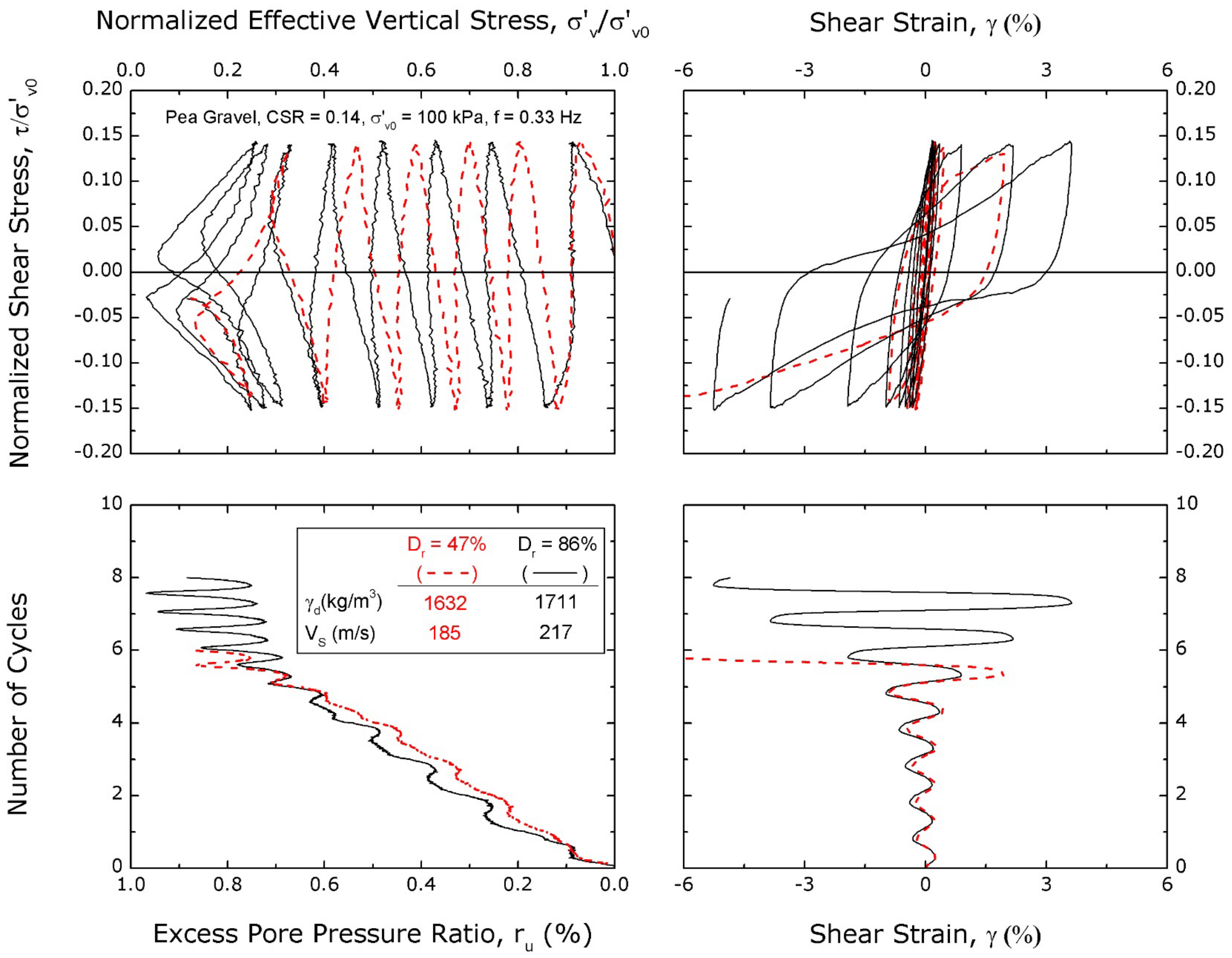
Angular

5 mm Crushed Limestone

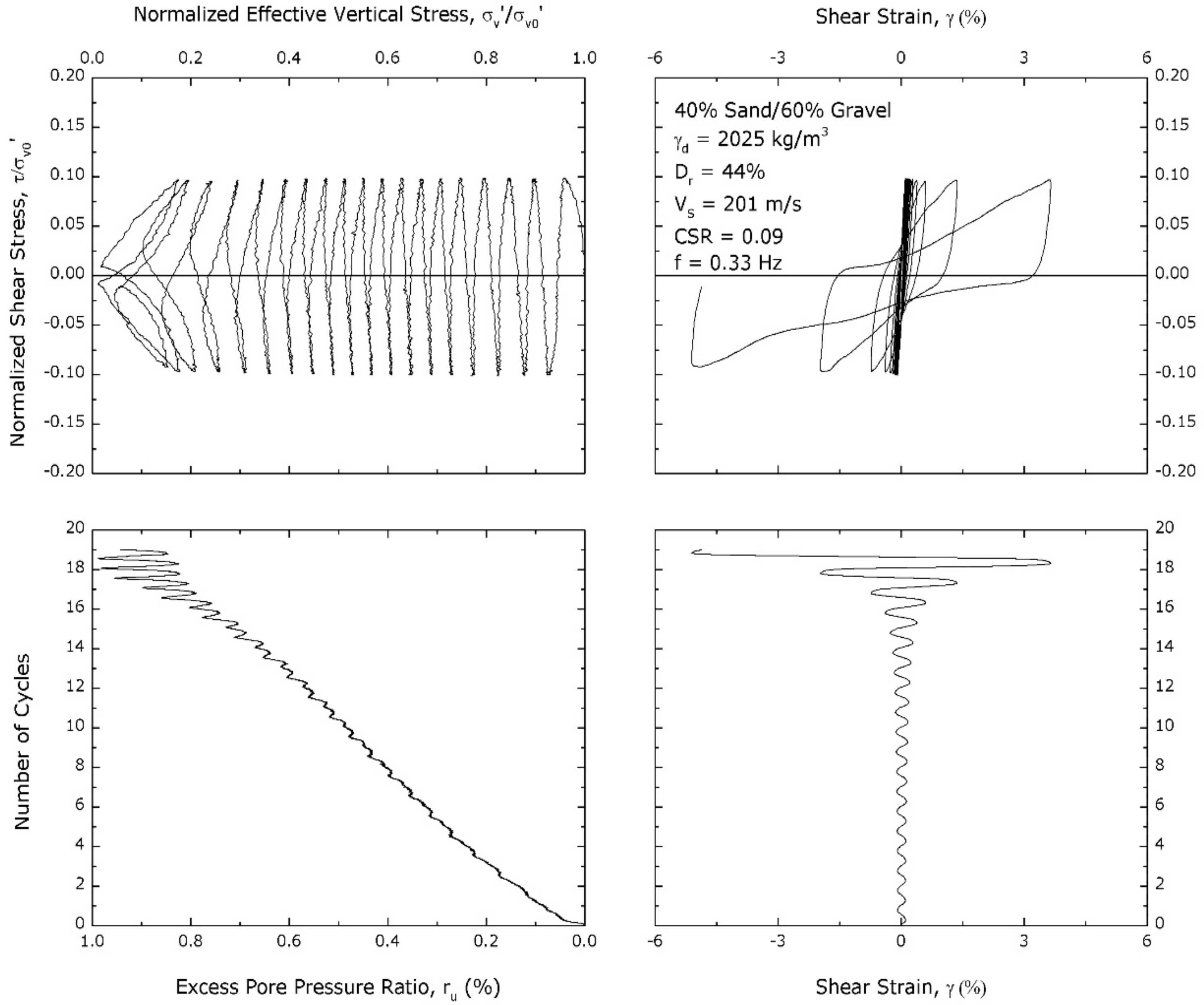
Angular

V_s was measured in every specimen

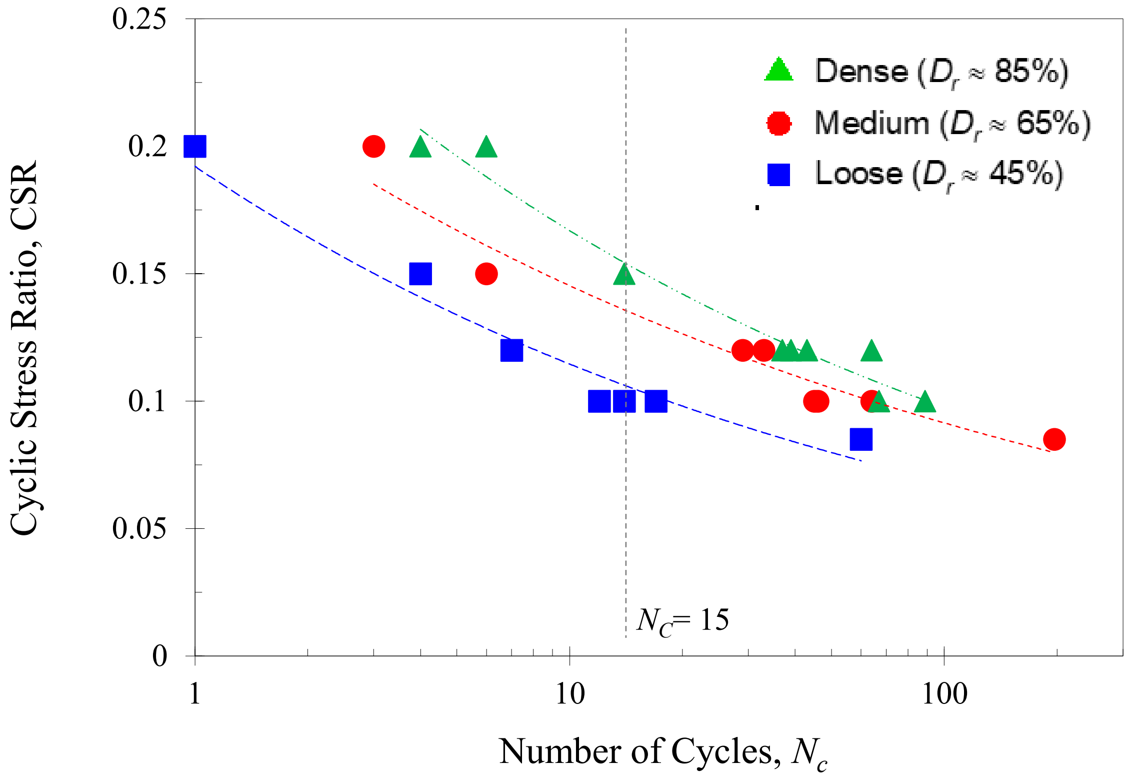
Cyclic Simple Shear Test Results for Pea Gravel



Cyclic Simple Shear Test Results for Sand/Gravel Mix



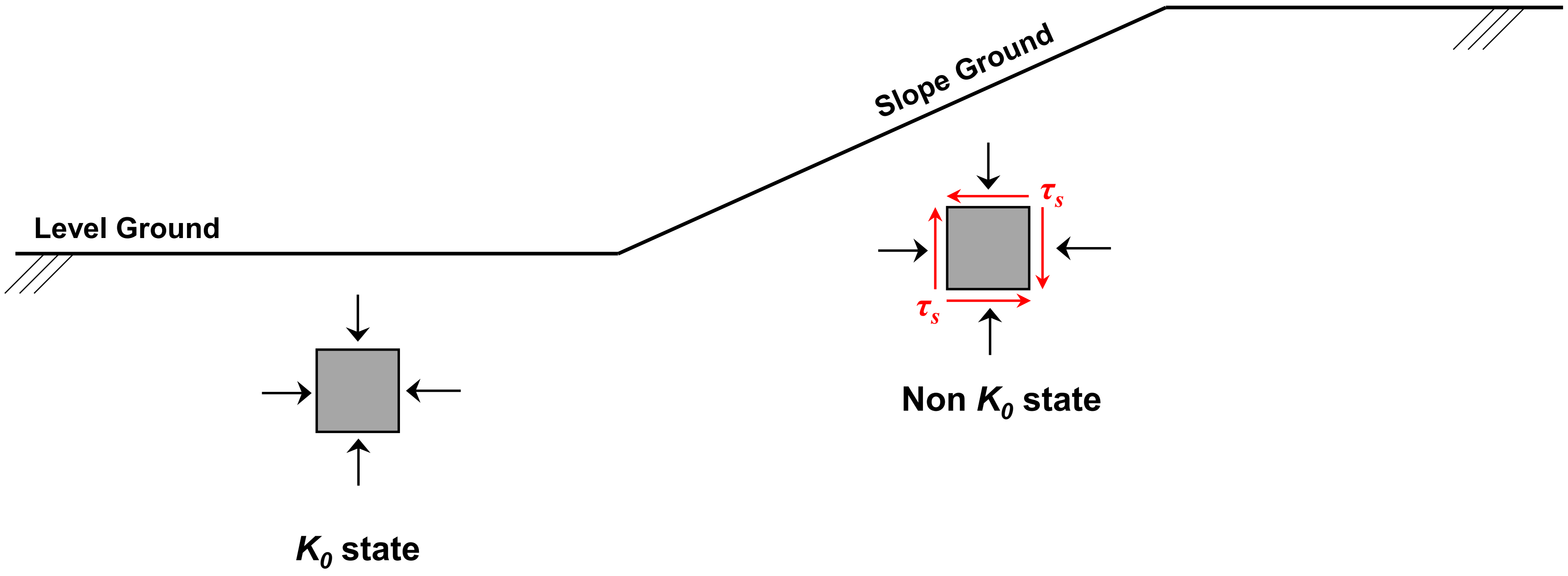
Liquefaction Resistance



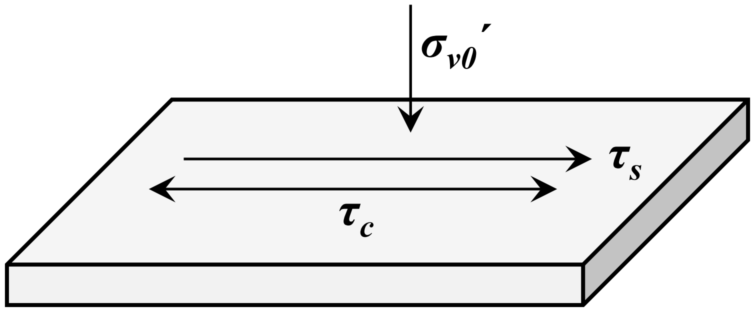
- ***CRR*$_{15}$ = 0.104 (loose), 0.134 (medium), 0.152 (dense)**
- Higher N_c required for denser specimens (less contractive)

Kim et al. 2023 ASCE JGGE

Initial Shear Stress (α) Conditions



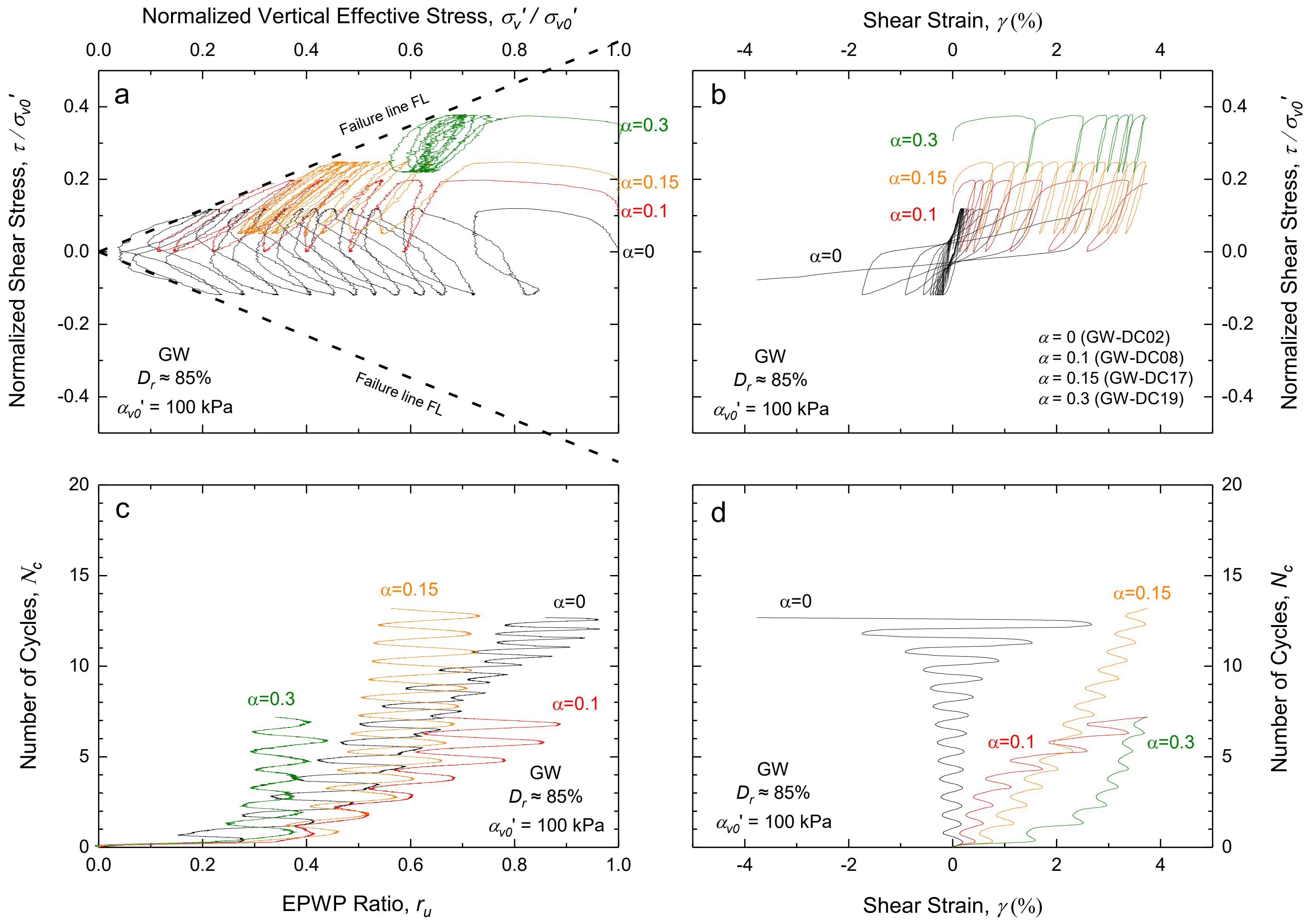
$$\alpha = \frac{\tau_s}{\sigma_{v0}'}$$



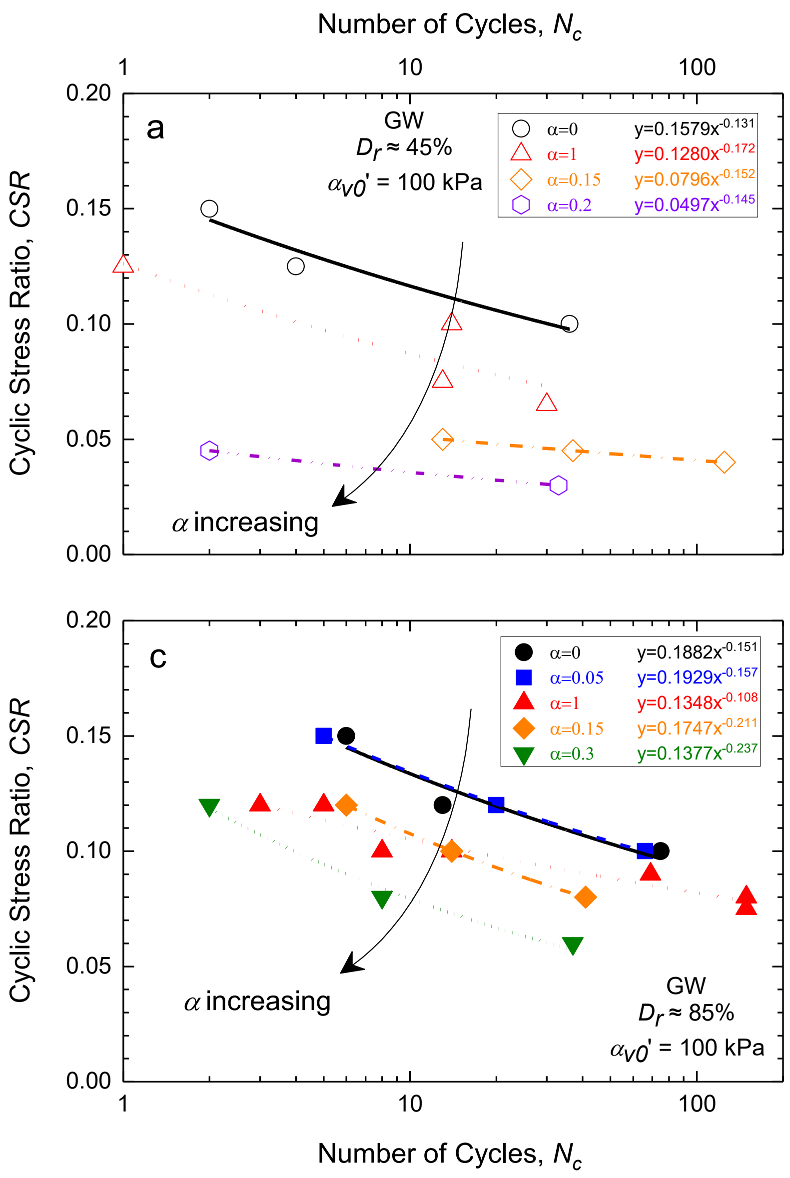
Parallel cyclic loading

- Various initial static shear stress is applied before cyclic loading to simulate the slope ground conditions
- Parallel direction shear stress.

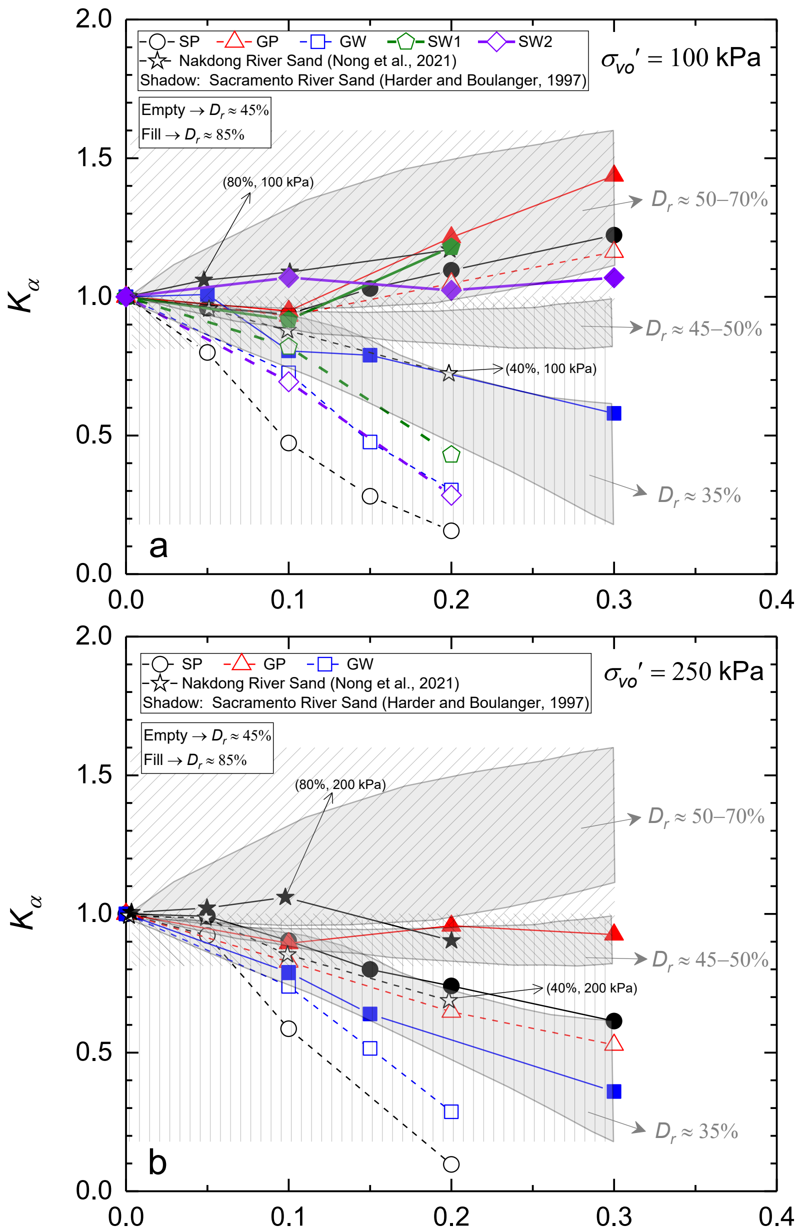
Initial Shear Stress (α) Conditions



Liquefaction Resistance (Alpha conditions)



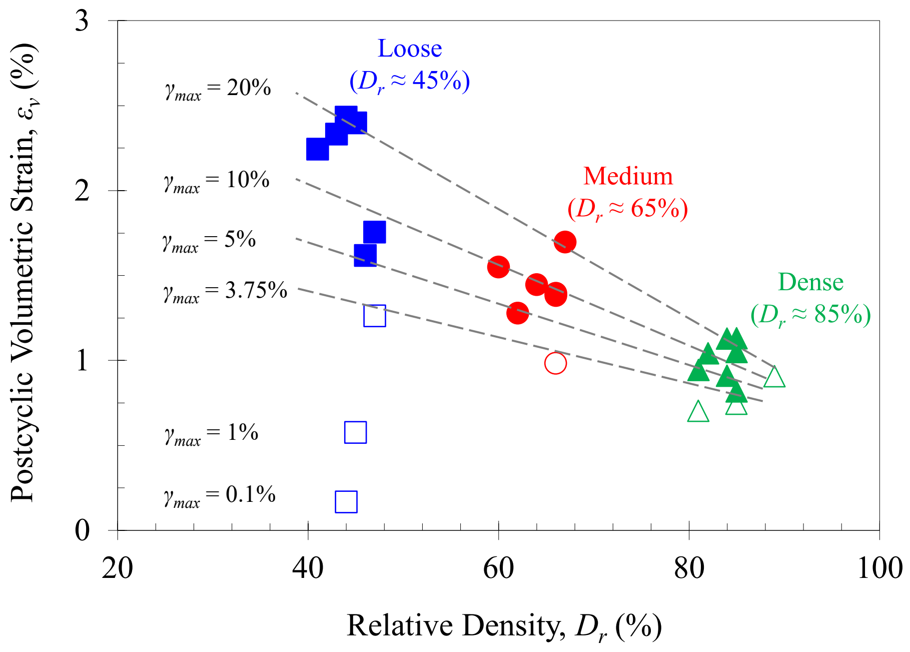
$$K_\alpha = \frac{CRR_{15,\alpha}}{CRR_{15,\alpha=0}}$$

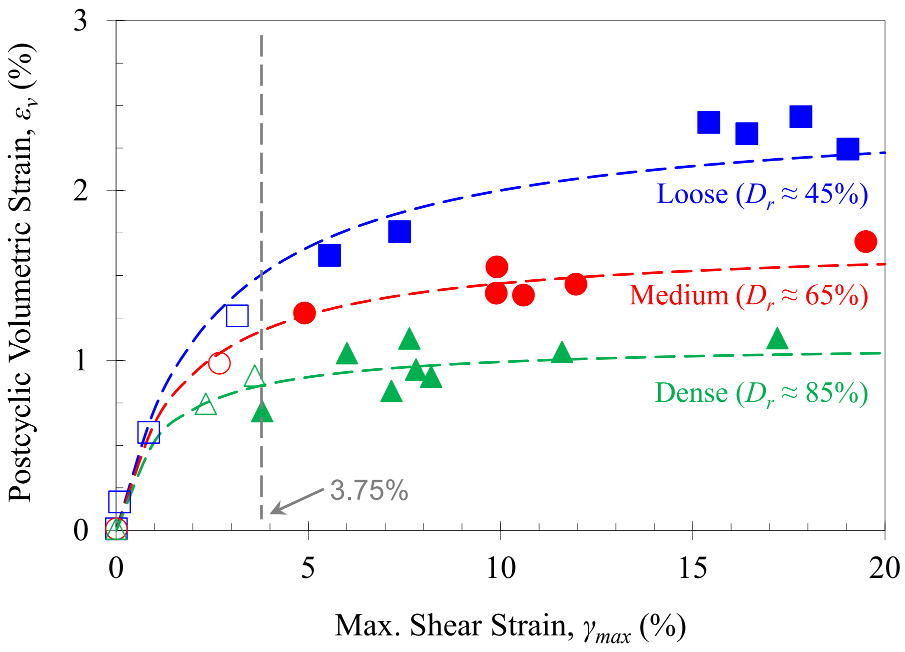


Postcyclic Volumetric Strain

Dissipation of excess pore water pressure

→ Recovery of vertical effective stress 100 kPa (reconsolidation)





- Loose packing → higher postcyclic volumetric strain
- Higher Max. Cyclic shear strain → higher postcyclic volumetric strain

Hyperbolic $\varepsilon_v = \dfrac{\gamma_{max}}{a + b \cdot \gamma_{max}}$

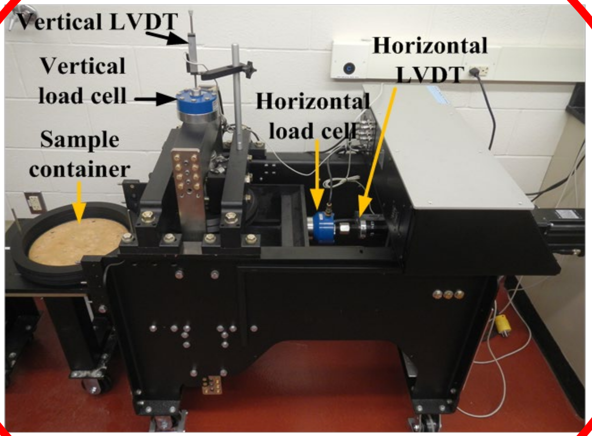
1/a = initial slope
1/b = max. volumetric strain

Integrated approach: Micro to Macro Response

Field Testing

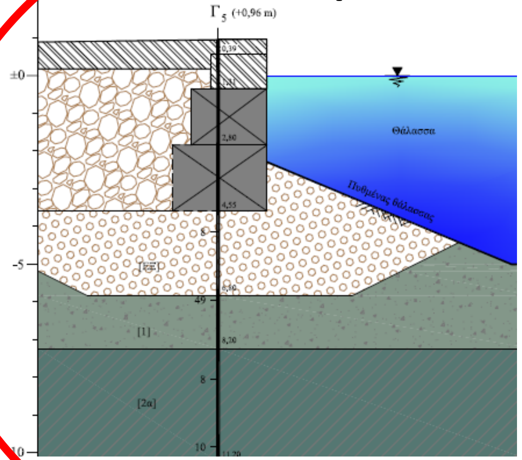
Improved DPT and Vs testing and correlations

Laboratory Testing



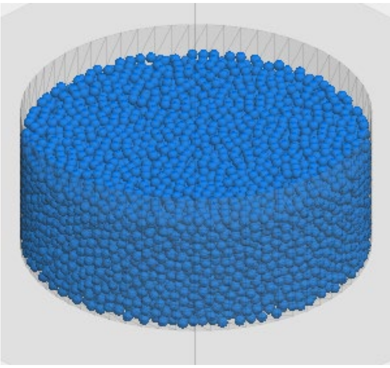
Large-scale CSS used for cyclic, and post-cyclic shear tests with Vs measurements

Field Response



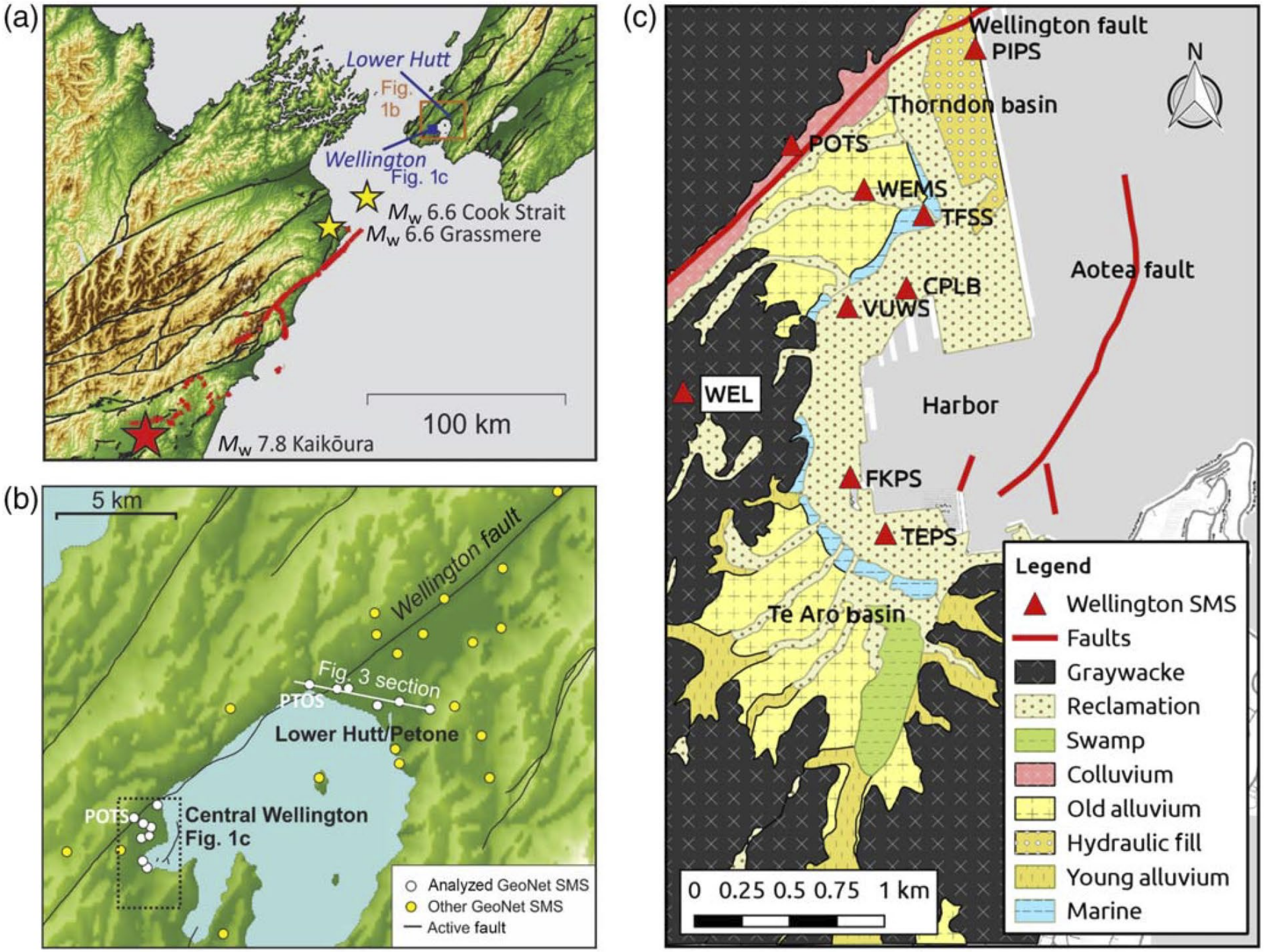
Back-analysis of case histories.

Numerical Modeling



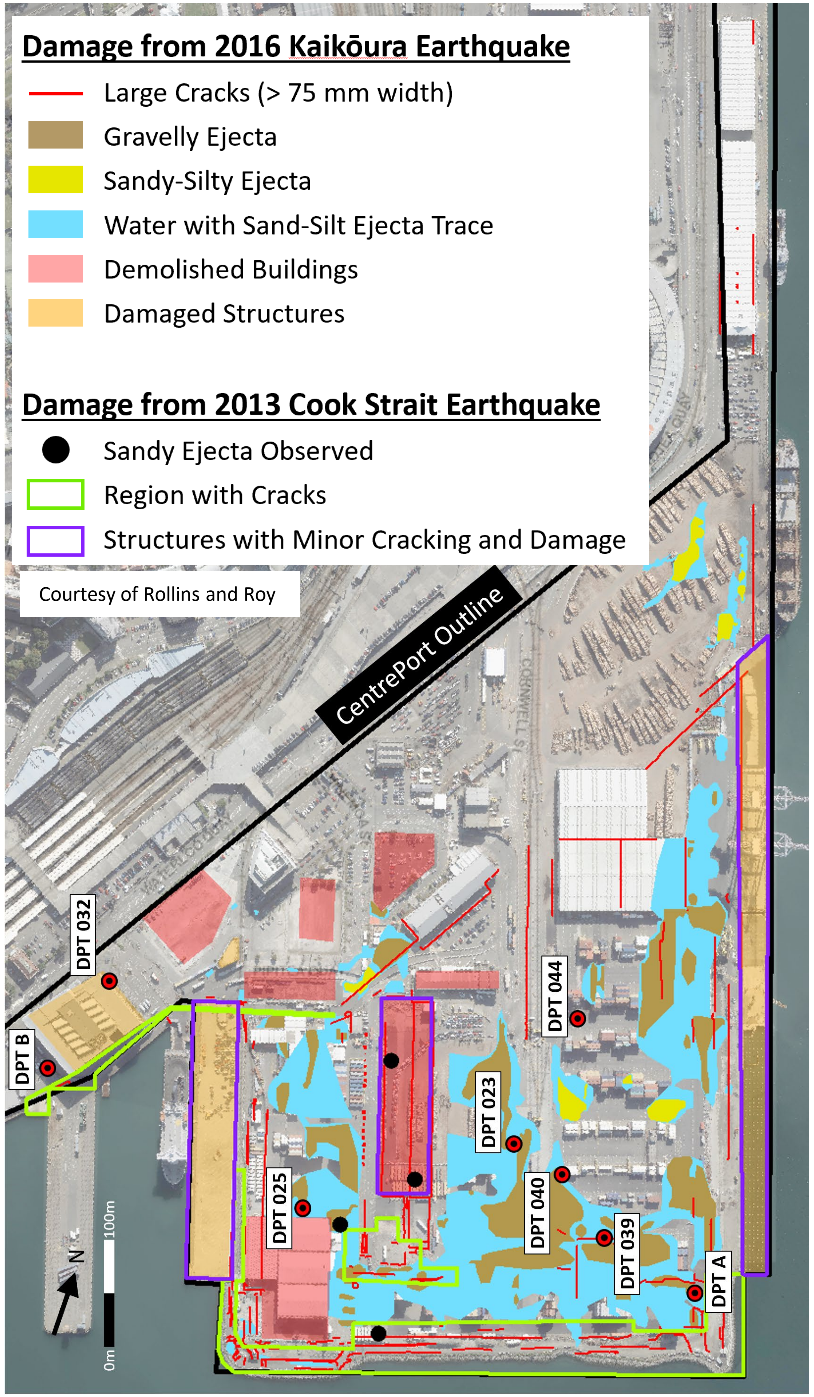
3D DEM analyses

Regional Map and Seismicity

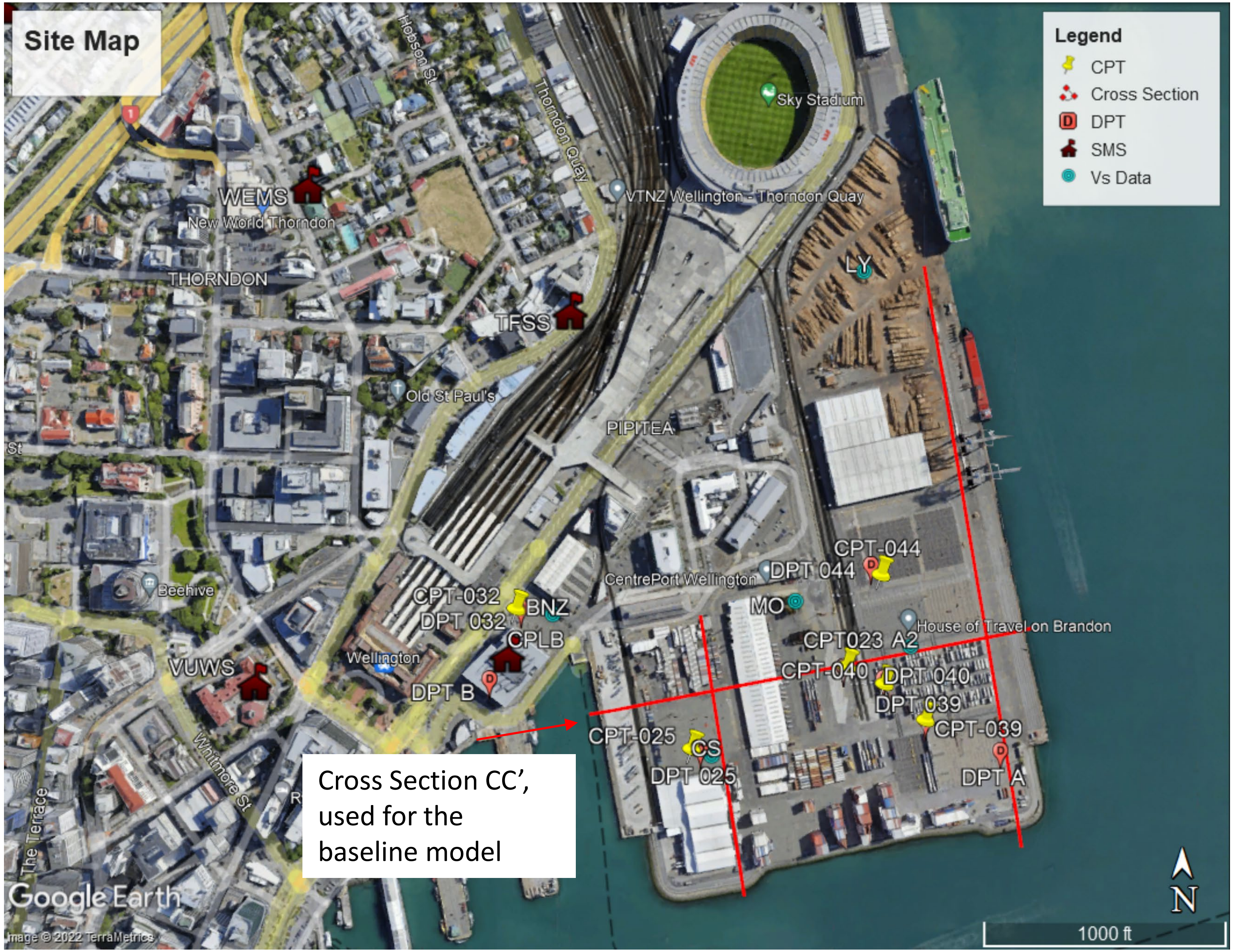


Bradley et al 2017

Site Map



Damage from 2016 Kaikōura Earthquake
Large Cracks (> 75 mm width)
Gravelly Ejecta
Sandy-Silty Ejecta
Water with Sand-Silt Ejecta Trace
Demolished Buildings
Damaged Structures
Damage from 2013 Cook Strait Earthquake
Sandy Ejecta Observed
Region with Cracks
Structures with Minor Cracking and Damage
Courtesy of Rollins and Roy
CentrePort Outline
DPT 032
DPT B
DPT 044
DPT 023
DPT 025
DPT 040
DPT 039
DPT A
N
100m
0m



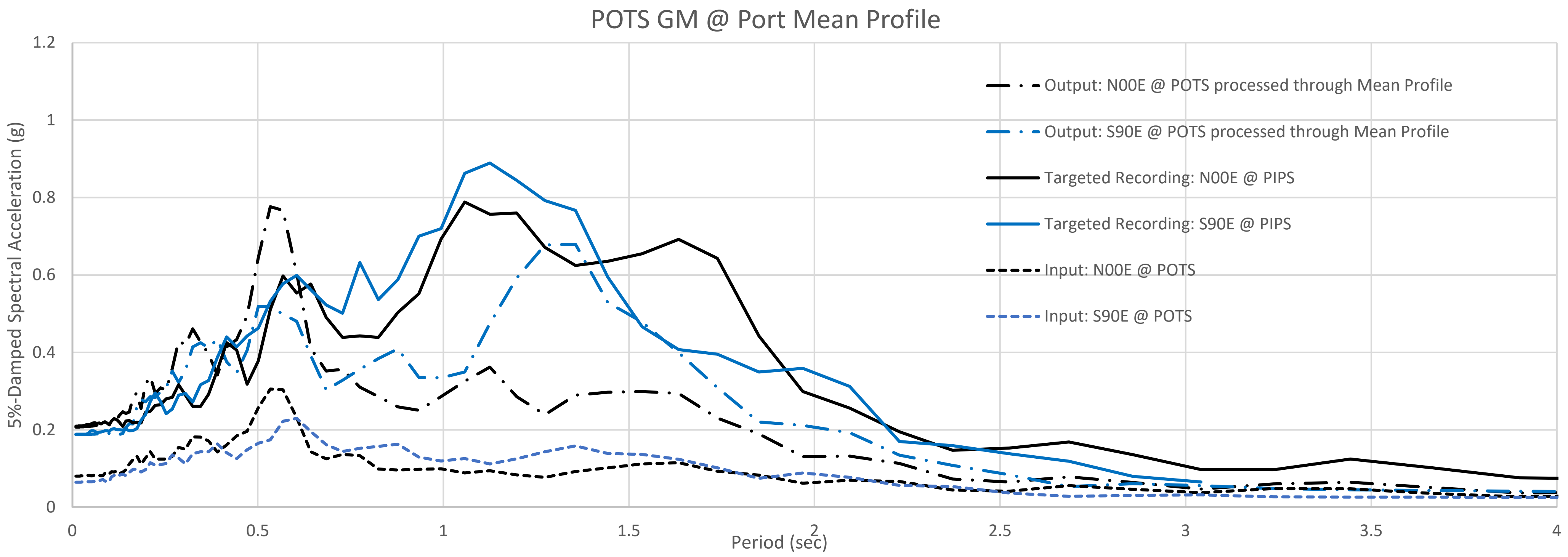
Site Map
Legend
CPT
Cross Section
DPT
SMS
Vs Data
Sky Stadium
WEMS
New World Thorndon
THORNDON
TFSS
VTNZ Wellington - Thorndon Quay
LY
Old St Paul's
PIPITEA
Beehive
CPT-032
DPT 032
BNZ
CPLB
CentrePort Wellington
DPT 044
CPT-044
MO
House of Travel on Brandon
CPT023
A2
CPT-040
DPT 040
DPT 039
CPT-039
VUWS
Wellington
DPT B
CPT-025
CS
DPT 025
DPT A
Cross Section CC', used for the baseline model
Google Earth
Image © 2022 TerraMetrics
1000 ft
N

Data synthesized for this analysis

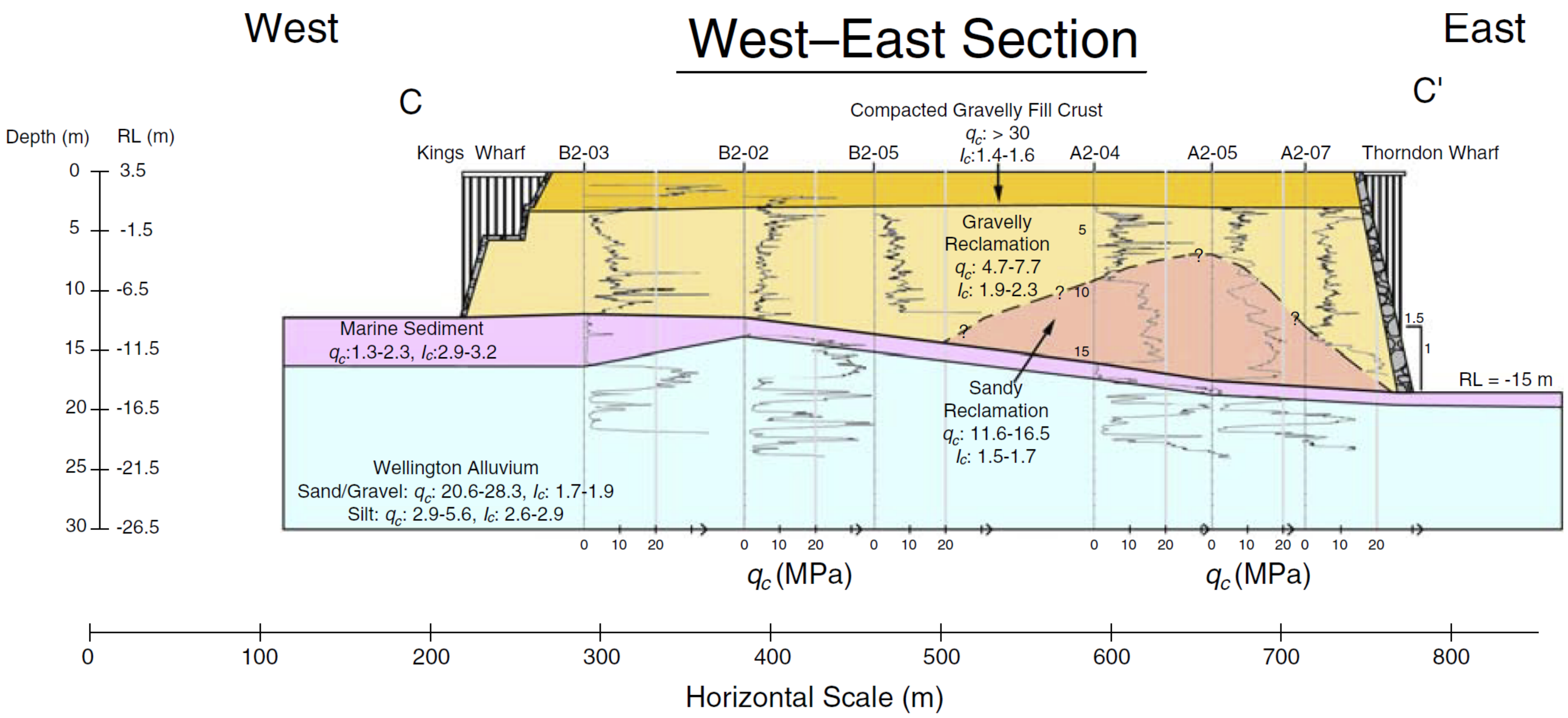
- Onsite Vs Profile
  - Roy and Rollins , Vantassel et al 2018
- CPT (six onsite data points)
  - Provided by Roy and Rollins
- Lab Data – providing CRR Curve and Residual Strength of the gravelly fill
  - Cyclic Simple Shear (CSS), Monotonic Simple Shear (MSS) on Gravelly Fill Sampled collected from the site, **Kim et al 2022 (UCB)**
- Observed Deformations
  - GEER Report, Kaikoura 2016
- Cross Sections
  - Cubrinovski et al 2018

Input Ground Motion Selection and Pre-Processing

- Recording from POTS (the Rock Site recording) used directly as the outcrop motion.
- Equivalent Linear 1-D Site Response Analysis performed in *DEEPSOIL* with the CPLB, PIPS, and Mean Vs Profile
- Compared with the CPLB, and PIPS Recordings



Underground Stratigraphy



- Used subsurface conditions from Cubrinovski et al 2018, combined with rock depth determined using the forementioned Vs Profiles, as the basis of baseline model development.

Constitutive Models and Soil Parameters

Liquefiable Soil

- Gravelly Reclamation Fill
  - PM4Sand model used, with CRR curve developed from the lab.
  - Sr used from the lab data
- Sandy Reclamation Fill
  - PM4Sand model used, with CRR curve developed using the liquefaction triggering relationship (LTR) Boulanger and Idriss (2014), from the CPT data.
  - Sr, Boulanger and Idriss (2015), using the CPT data.

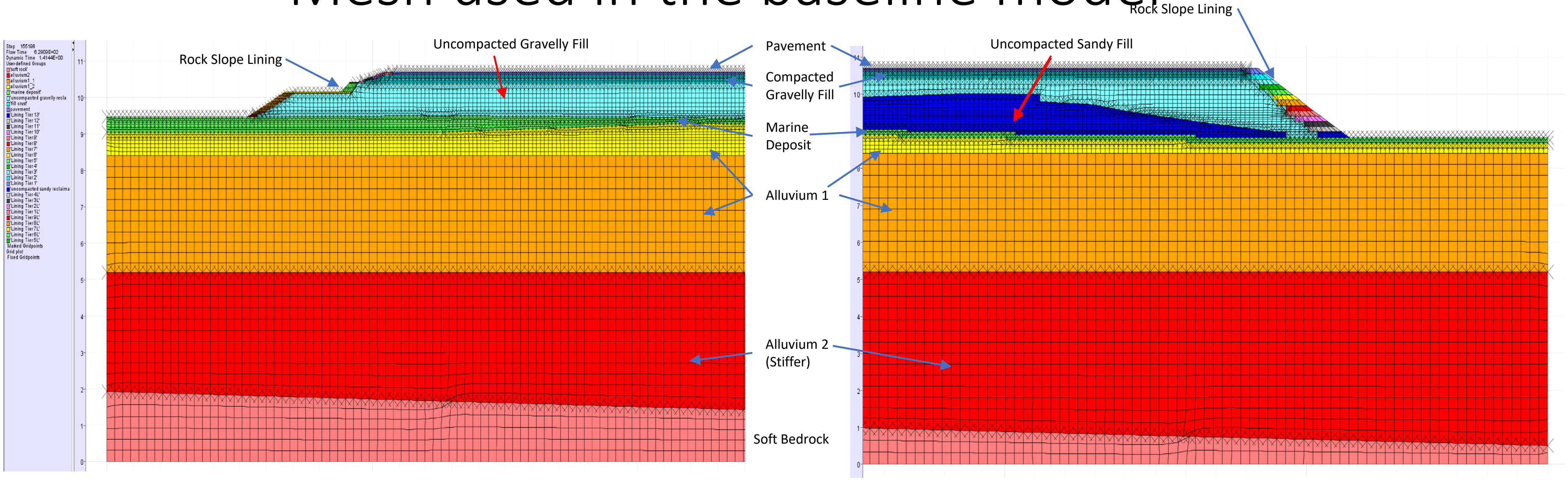
Non-Liquefiable Soil

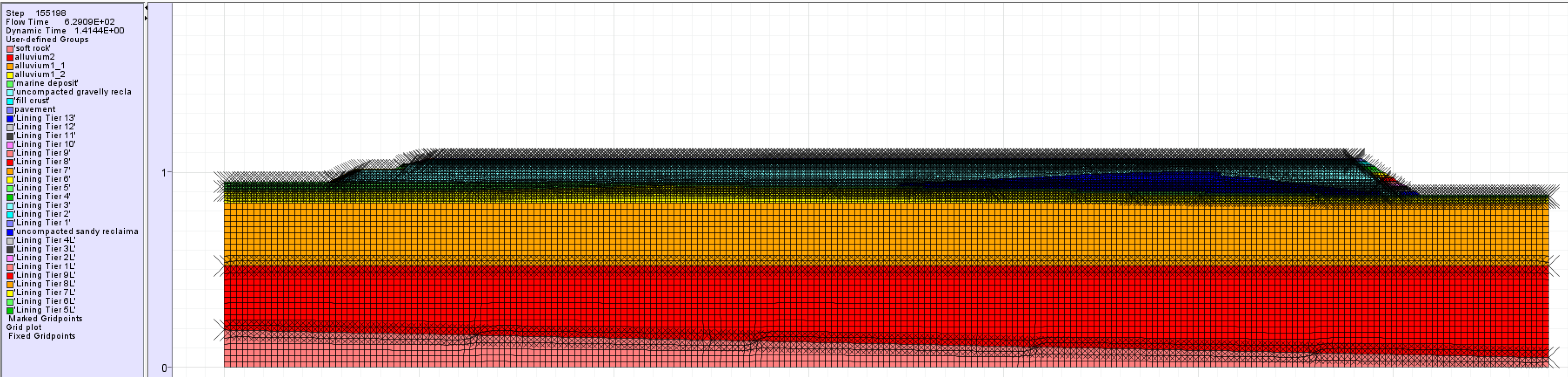
- MC Model used with soil parameters developed from the limited CPT data points we have.
- Generic values are used in the baseline model, for secondary parameters, e.g. porosity, hydraulic conductivity, etc.
- Linear Elastic material is used for bedrock

Soil Parameters used in the baseline model

Phase	Soil Unit Name	Model Type	Bulk Modulus (Pa) 3D formulae	Shear Modulus (Pa)	Density (kg/m^3)	Cohesion (pa)	Phi_cv (Degrees)	Vp (m/s inherent)	Vs (m/s inherent)	Data Based on
Static Phase	Compacted Gravelly Fill Crust	MC	260000000	120000000	1800	2000	37	453	258	Generic
	Marine Sediment	MC	195000000	90000000	1600	15000	29	416	237	CPT
	Wellington Alluvium 1 (approx. 18 to 55 meters deep)	MC	390000000	180000000	2050	2000	38	520	296	Vs/Generic
	Wellington Alluvium 2 (approx. 55 to 98 meters deep)	MC	498333333	230000000	2100	2000	40	581	331	Vs/Generic
	Soft Bedrock	Linear Elastic	8666666667	4000000000	2300			2300	1320	CPT
	Rock Lining	MC	346666667	160000000	1800	2000	37	523	298	Generic
	Uncompacted Gravelly Reclamation Fill	MC	195000000	90000000	1750	2000	36	398	227	CPT
	Sandy Reclamation Fill	MC	216666667	100000000	1850	2000	38	408	232	CPT
	Soil Unit Name	Model Type	G_o	h_po	D_r	e_min (secondary)	e_max (secondary)	h_o (secondary)	Data Based on	
Dynamic Phase	Uncompacted Gravelly Reclamation Fill	PM4Sand	1000	0.20	0.55	0.258	0.568	0.4	Kim et al 2022 (UCB), and CPT	
	Sandy Reclamation Fill	PM4Sand	930	1.1	0.6	default			CPT	

Mesh used in the baseline model





Lab CSS Testing and CRR Curves

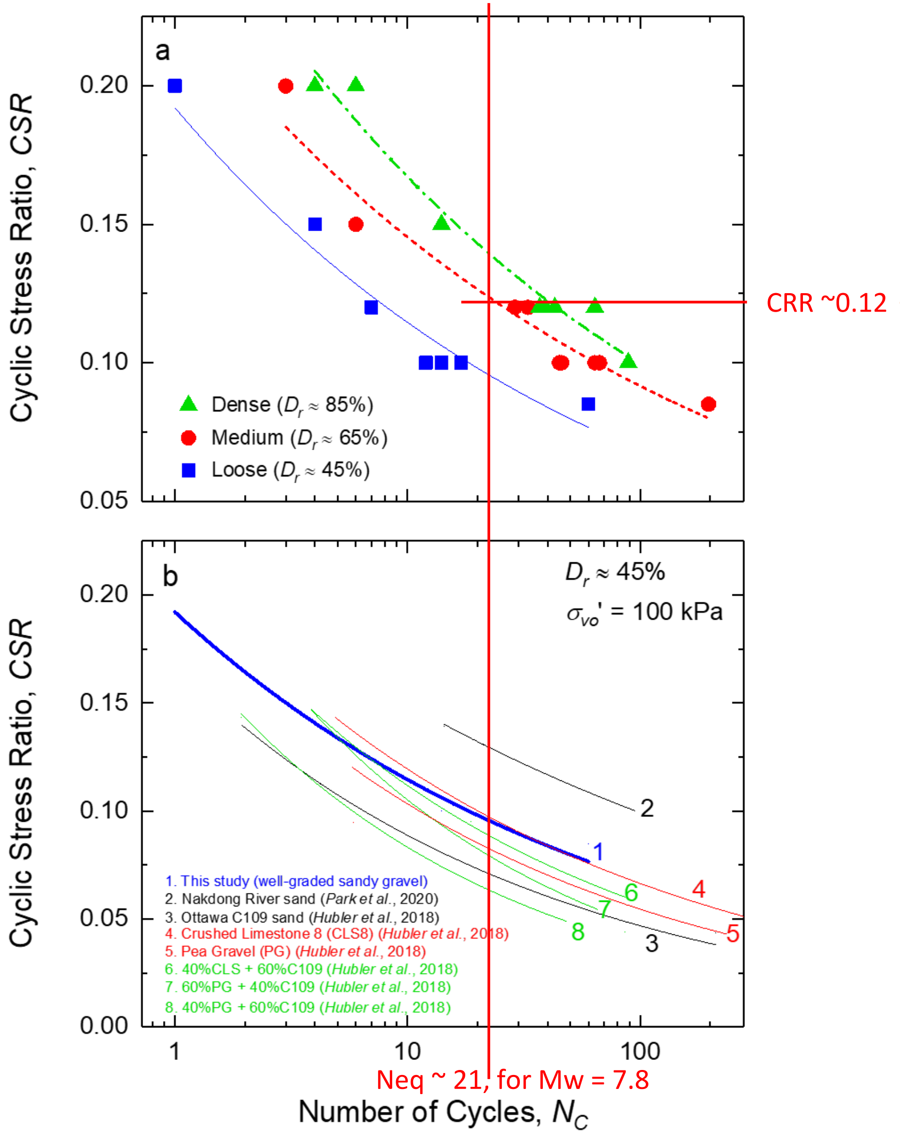
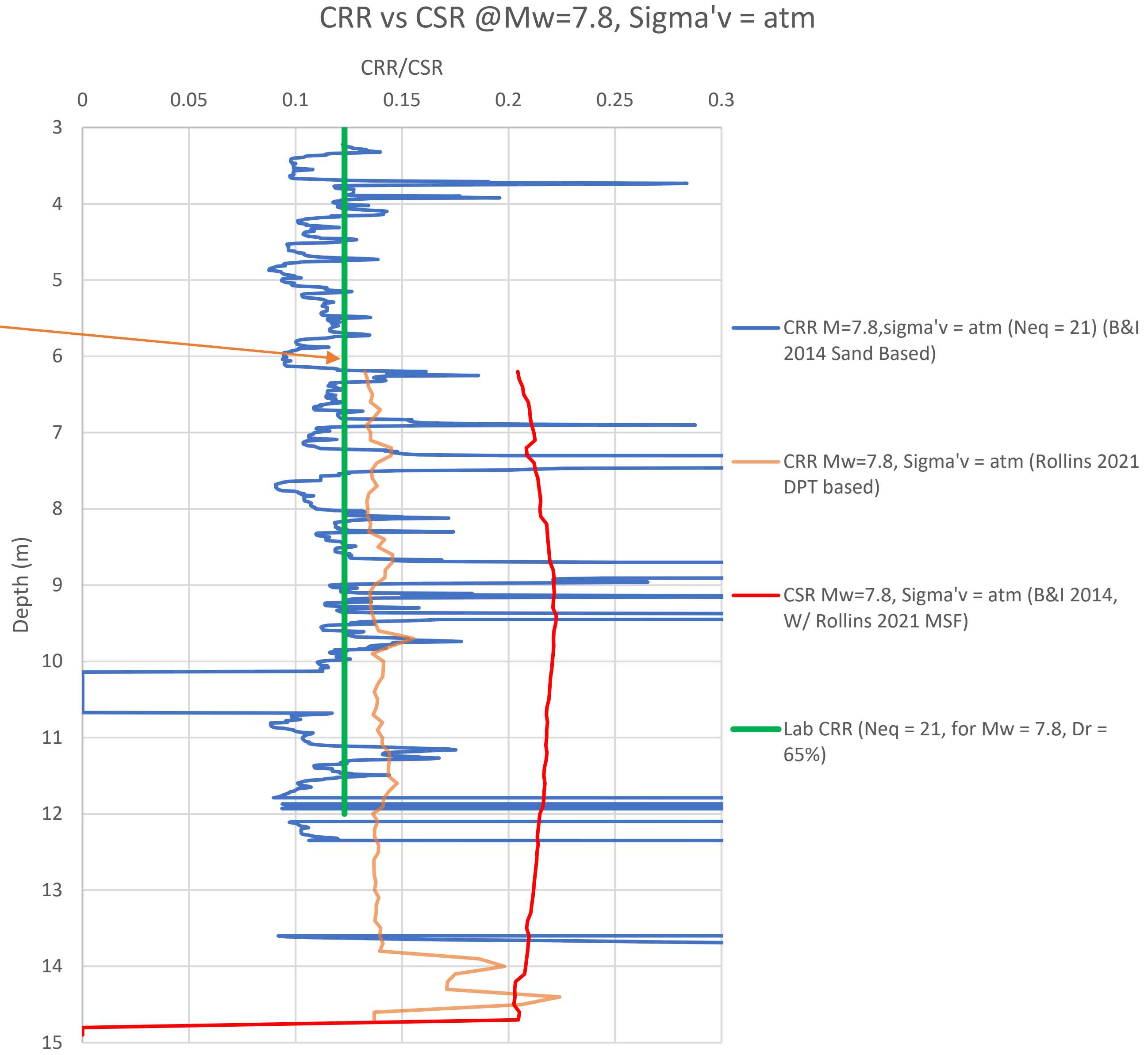
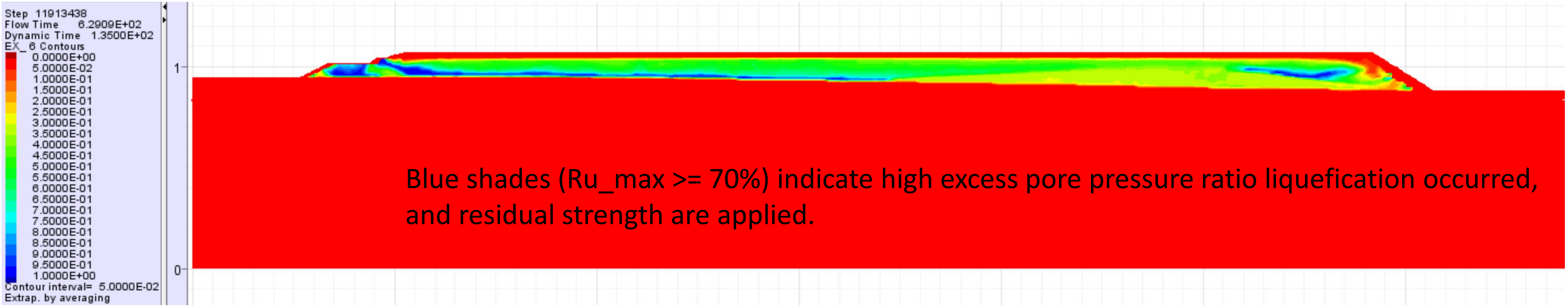
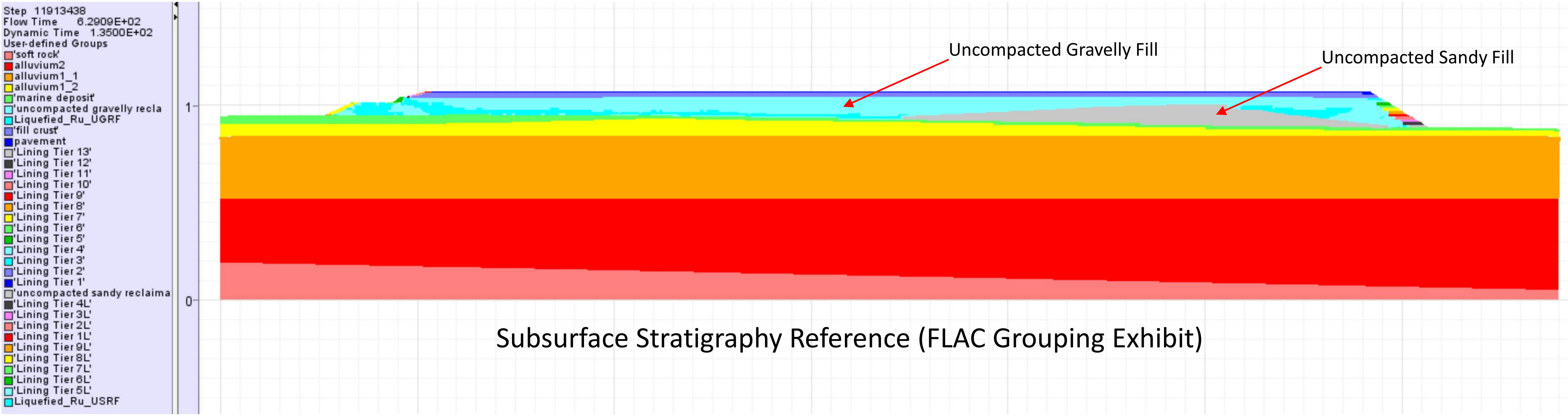


Figure 7, Kim et al 2022 (UCB)



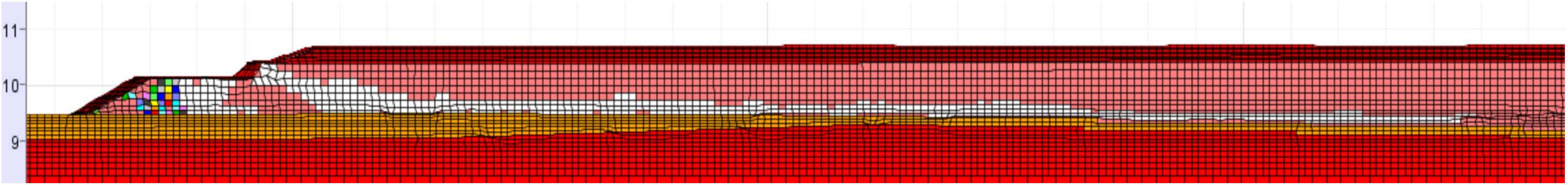
Maximum Excess Pore Pressure Ratio (pp_ex/sigma'v_ini)



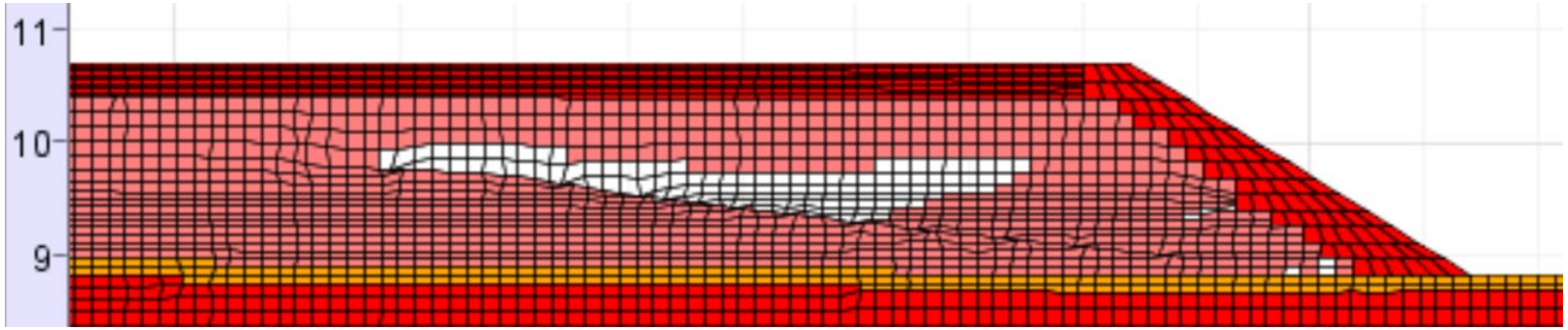


Subsurface Stratigraphy Reference (FLAC Grouping Exhibit)

Post-Liquefaction response



Soil Unit Name	Sr (defined as ratio to the initial vertical stress)	Data Based on
Uncompacted Gravelly Reclamation Fill	0.02	Kim et al 2022 (UCB)
Sandy Reclamation Fill	0.28	CPT (Idriss and Boulanger (2015))



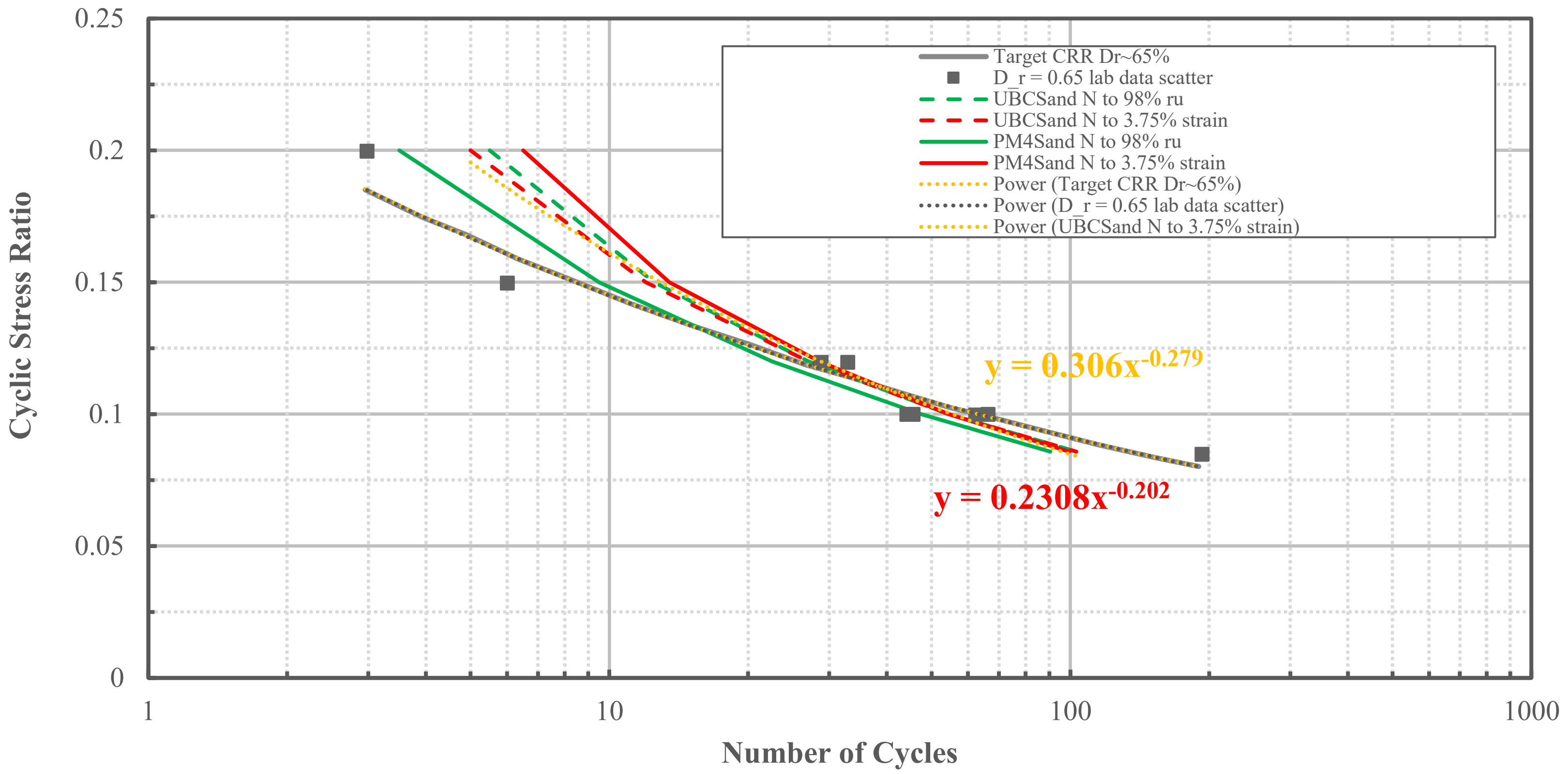
Muti-colored and void cells are zones with Residual Strength applied, which correspond to the liquefied zones shown in the previous slide. Voids are due to FLAC running out of legend space.

URS/Roth model

- No calibration needed; the key input is CRR_15 (set to 0.134).
- Gravelly fill soil parameters
  - Density 1750, consistent with PM4sand
  - Vs 194, consistent with G0 of 1000 in PM4Sand
  - Friction Angle, 38 degrees
  - CRR15 – 0.134 constrained by lab data
  - For K sigma - Idriss and Boulanger (2008) (N160CS = 14.6)
  - For K alpha - Idriss and Boulanger (2008) (N160CS = 14.6)
  - residual shear strength ratio = 0.125 – **back analyzed to achieve a reasonable match in the displacement field**

UBCSand model

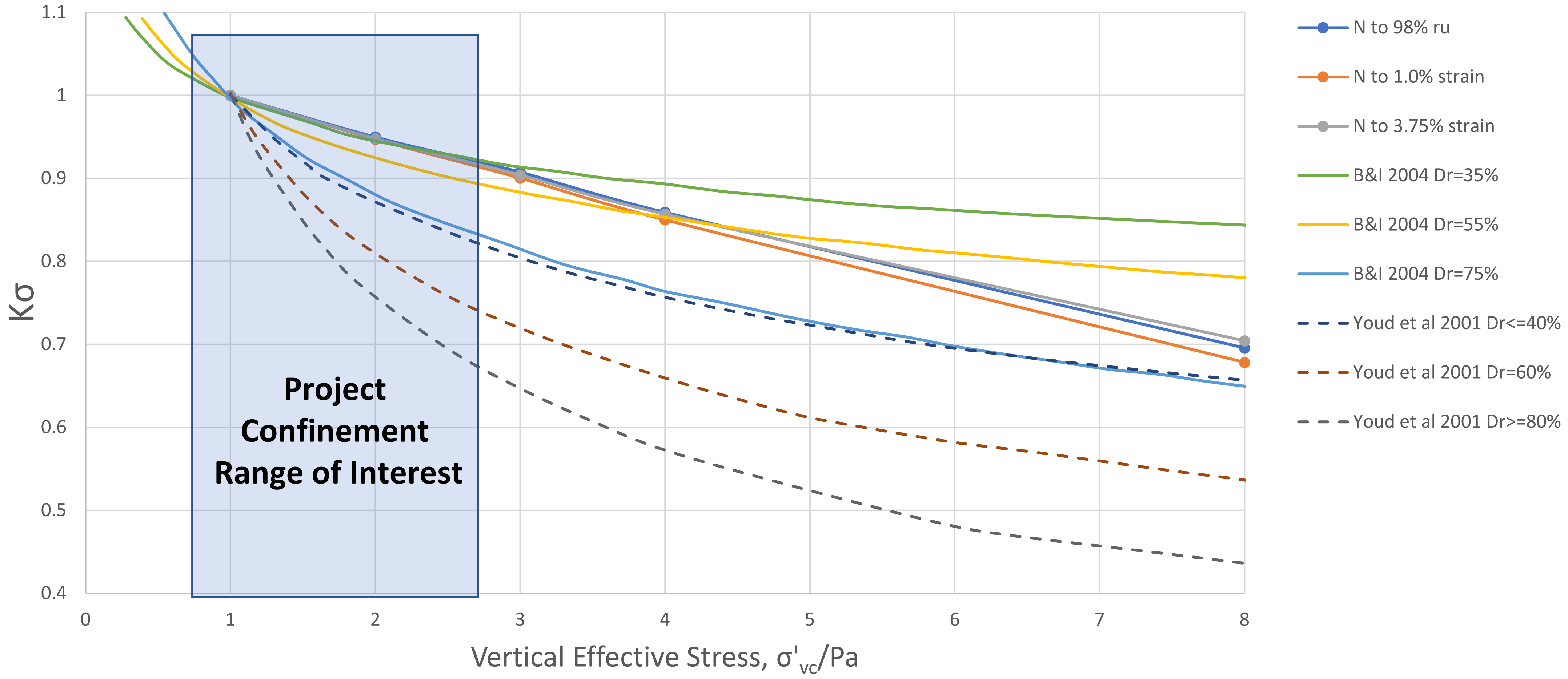
- Calibrated to match the lab derived CRR curve
- Key parameters adjusted for calibration include the failure ratio m_rf (set to 0.8), and the shear modulus number m_kge (set to 400).



Displacement field obtained compared to the PM4Sand and URS/Roth cases

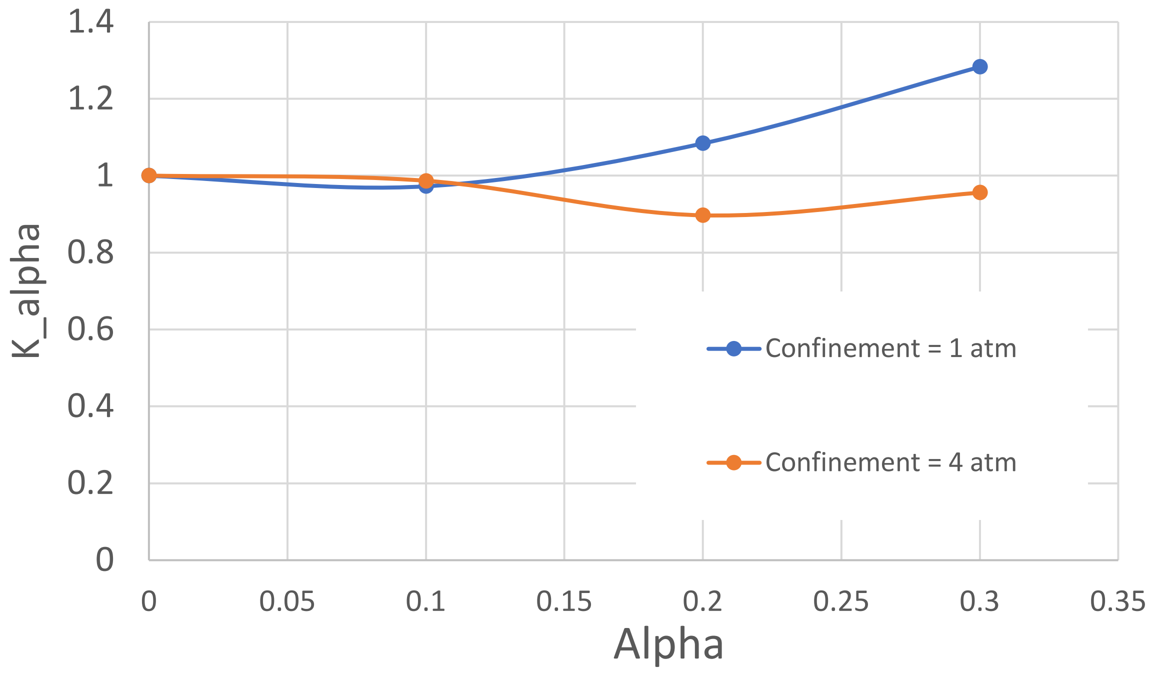
K_σ effect

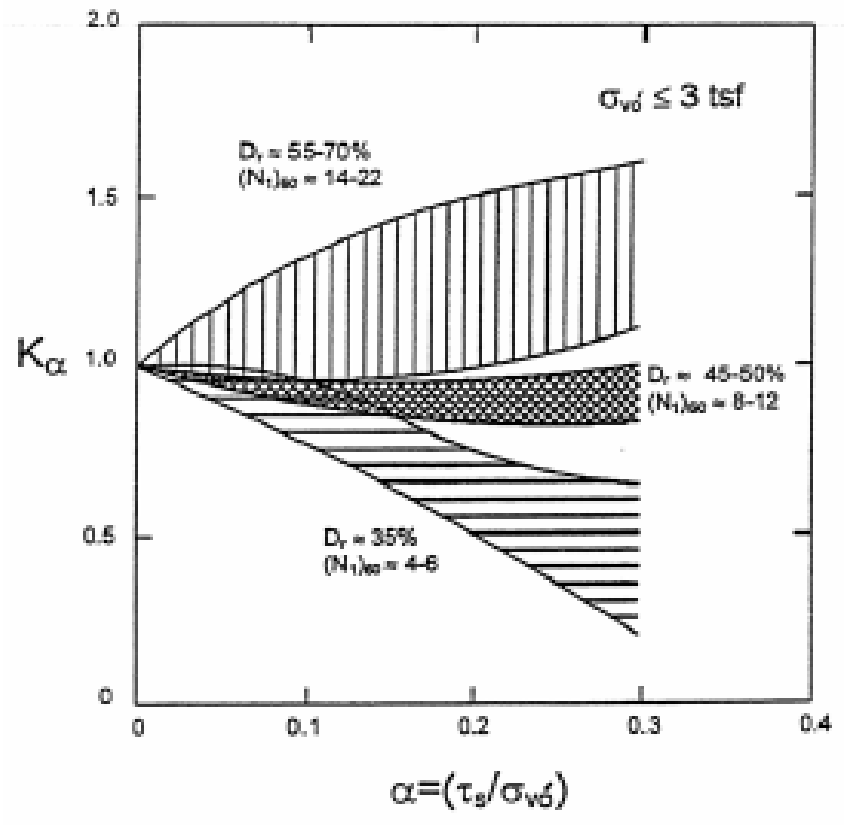
- K sigma, the overburden stress correction factor, was not explicitly an input for PM4Sand and UBCSand, as opposed to the direct assignment in URS/Roth model.
- For illustration purposes, the analytical details for PM4Sand are presented here.



Kα effect

- Similarly, K alpha, the overburden stress correction factor were studied for PM4Sand and UBCSand. For illustration purposes, the analytical details for PM4Sand are presented here.





Harder and Boulanger (1997)

Next Steps

- Assess the performance of all three implemented constitutive models: further evaluate and summarize the differences in their development and calibration processes, and how they lead to varying levels of post-event displacements.
- Study the sub-layering effects within the reclamation fills.
- Quantitatively study the SSI effects from the wharfs

Acknowledgements

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Prof. Kyle Rollins

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Dr. Jongchan Kim

Thank You!