Soil Models for Geotechnical Design, Prediction and Problem Solving

Andrew J. Whittle

Massachusetts Institute of Technology

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Introduction

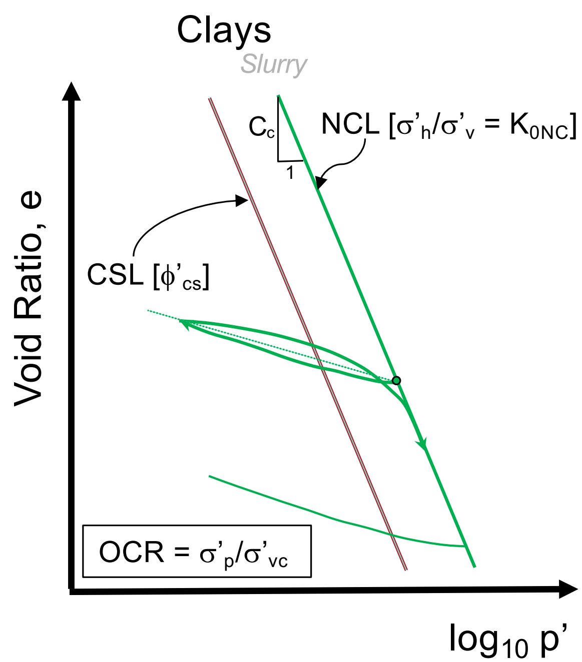
- ***Observations***
  - *Soil models are ubiquitous in geotechnical analyses*
  - *They are essential components in numerical, FE(FD) analyses*
- **My Goal**
  - Share my experience in the development & application of soil models
    - Effective stress-strain-strength properties
  - Predictions of performance
  - Insights for geotechnical problem solving
  - Roles in design
- **The lecture will NOT**
  - Use equations
  - Review the huge literature on this topic

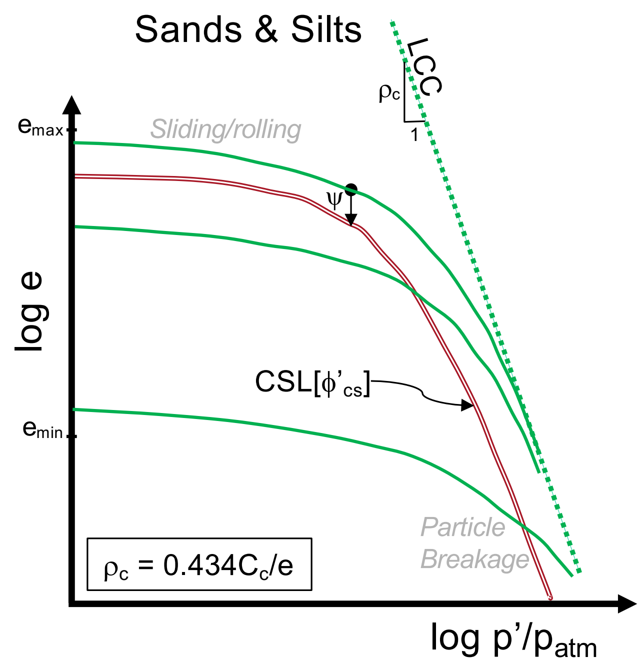
Outline

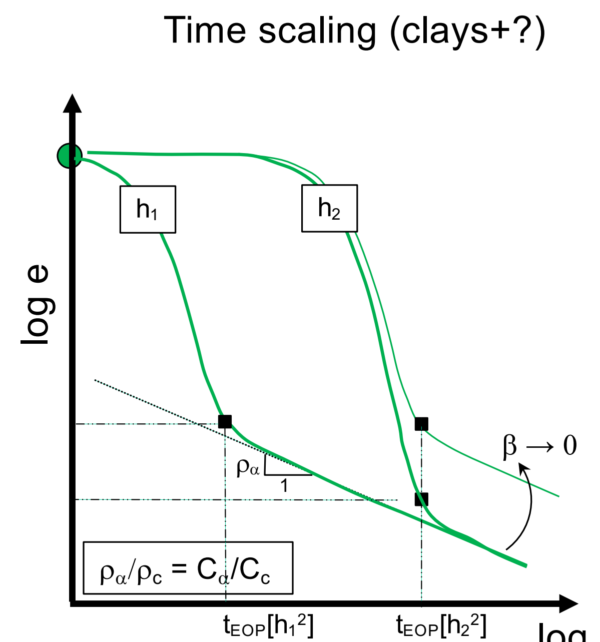
- **Soil Behavior & Generalized Soil Models**
  - Models of 1-D consolidation
  - Shearing: yield, non-linear stiffness, anisotropy
  - Modeling rate effects
    - Unify/accommodate 'Hypothesis A vs B' (Taylor, 1942; Ladd et al. 1977)
- **Applications for Clays**
  - Deep excavations
  - Staged construction & foundations
- **Sands**
  - Effects of confining pressure and density on bearing behavior
  - Latent instability & triggering of static liquefaction
- **Complex Soils & Multiscale Models**
  - 'Destructuring' - effects of changing microstructure on macroscopic behavior

Soil Behavior & Generalized Soil Models

One-Dimensional Consolidation & Three Soil Models





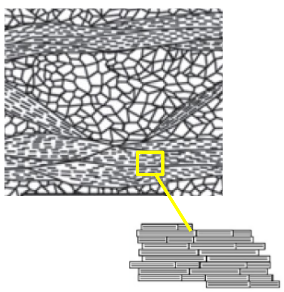


MIT-E3 (1987):
Elasto-plastic
Anisotropy associated with NCL
Load reversal: Elastic behavior
Reload: Bounding surface plasticity

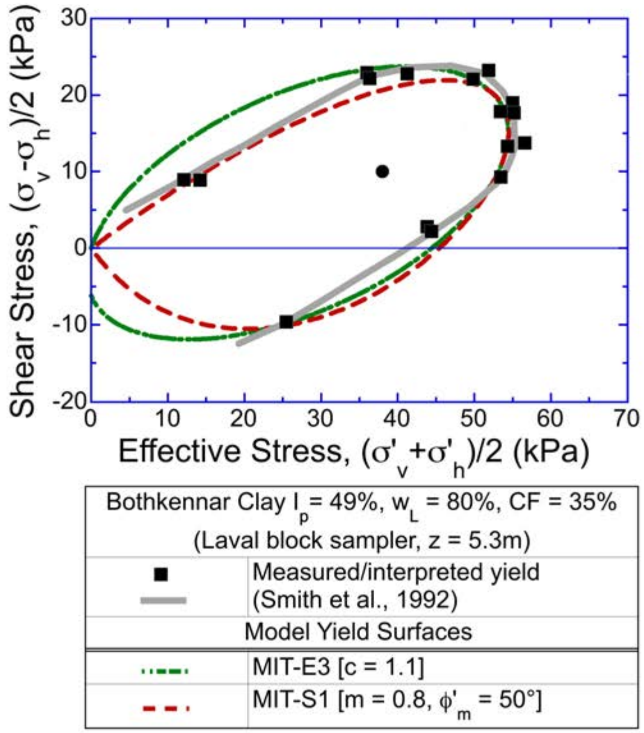
MIT-S1 (1994):
Elasto-plastic
Uses LCC as reference state
Most other models:
Measure CSL use ψ

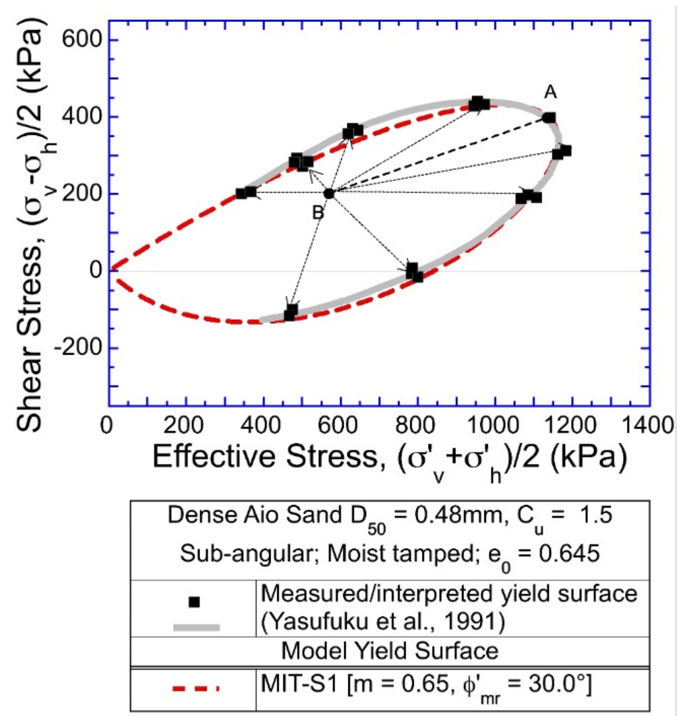
MIT-SR (2016):
Elasto-viscoplastic
Internal strain history state, R_a
Steady state, β
At EOP: NCL unique for $\beta = 0$

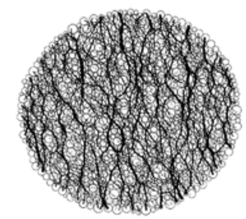
Initial Yield Surfaces of Soils



Clay particle orientation (SEM) (Guglielmi et al., 2021)





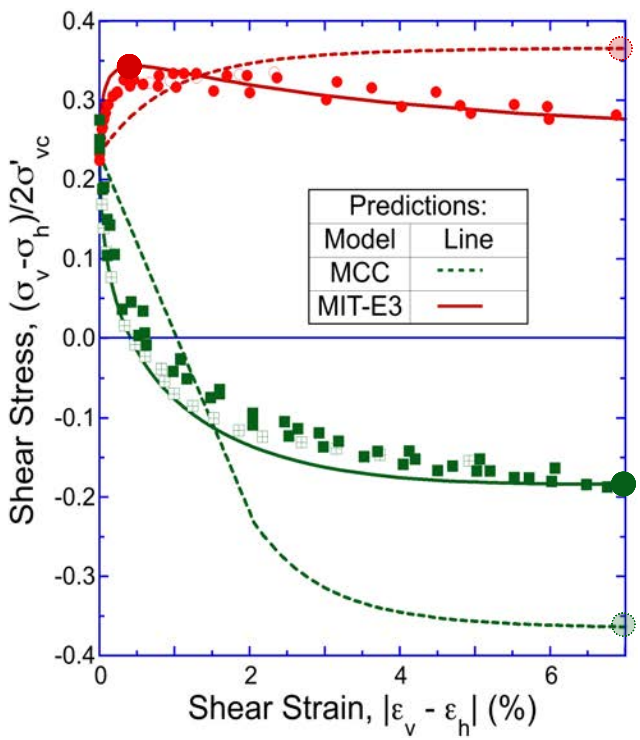


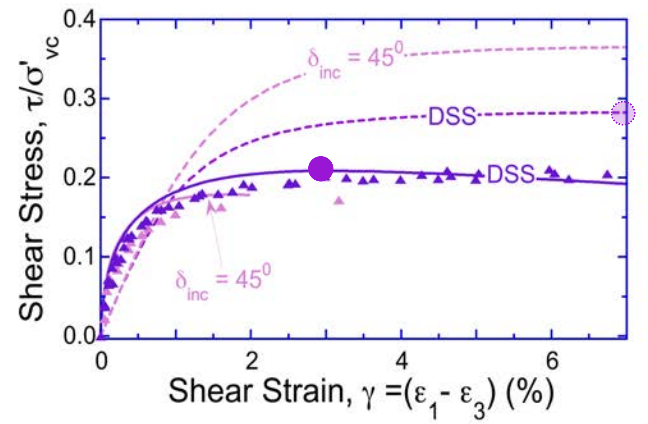
Particle contact fabric (DEM) (Thornton & Barnes, 1986)

Measured data described by elasto-plastic model with single yield function
Inherent anisotropy linked to prior consolidation history
Rotation of yield surface linked to particle fabric

Model Validation: Undrained Plane Strain Shear Tests

[Resedimented BBC, OCR = 1]





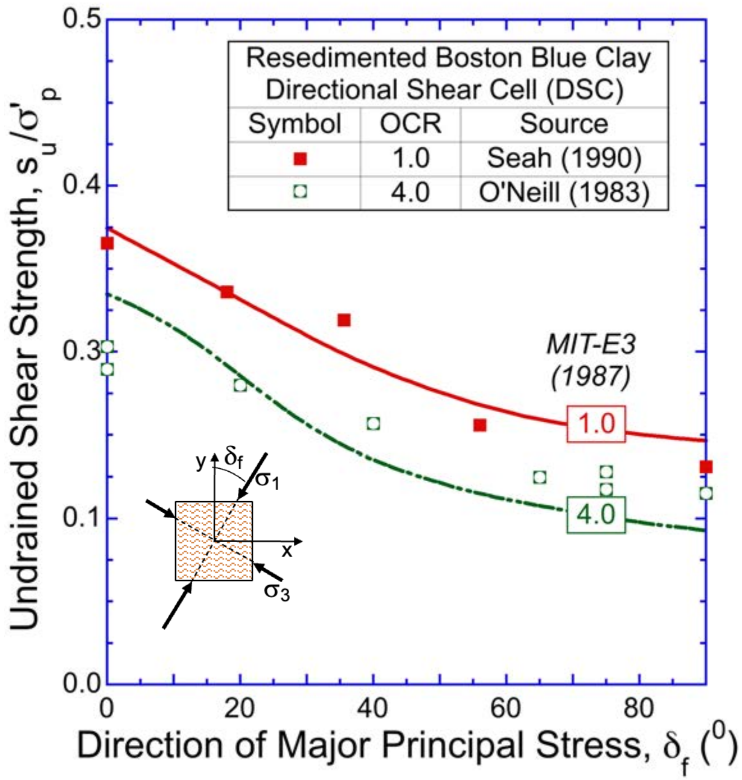
Measured Data:

Symbol	δ_{inc} (^{0})	Device	Source
●	0 (A)	PS	Ladd et al. (1971)
○	0 (A)	DSC	Seah (1990)
▲	45	DSC	Seah (1990)
▲	Varies	DSS	Ladd & Edgers (1972)
⊞	90 (P)	DSC	Seah (1990)
■	90 (P)	PS	Ladd et al. (1971)

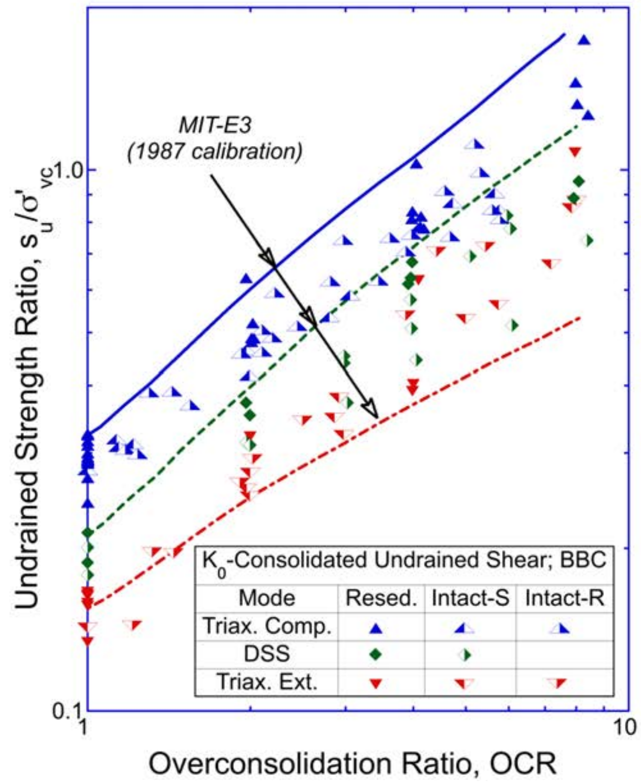
MCC: limitation of isotropic model with unique s_u at critical state

MIT-E3: capability to predict anisotropic stress-strain-strength properties of NC clay

Evaluation of Undrained Strength Anisotropy for BBC



Effects of Shear Direction
OCR = 1 vs OCR =4

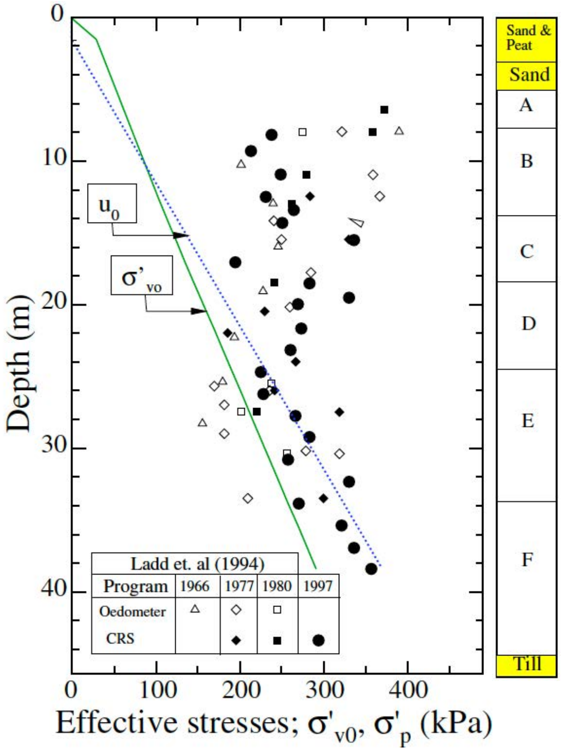


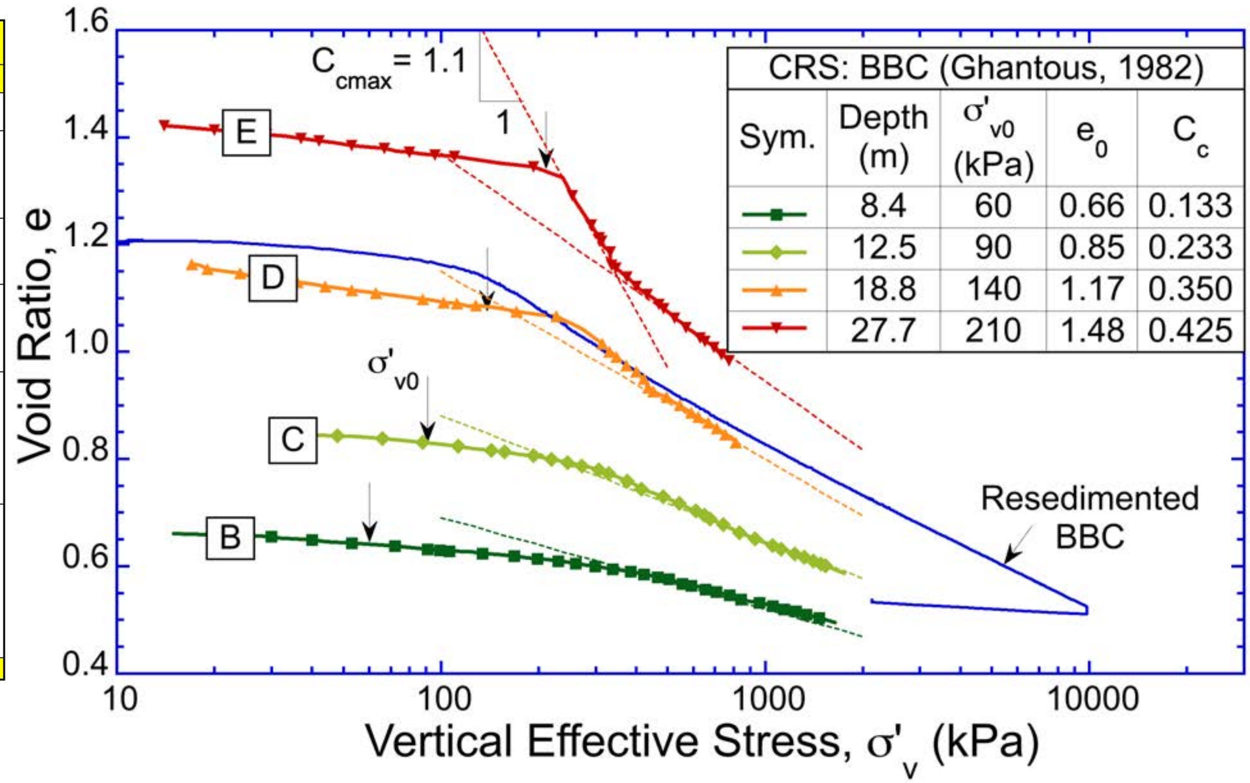
Intact & Resedimented BBC (1992 – 2016)
Model **accuracy reduces** for OCR > 3 - 4

Accept limitations: No edits to model formulation; No adjustments to input parameters

1-D Compression Properties of Natural Clay

Boston Blue Clay [I-95 Saugus site]





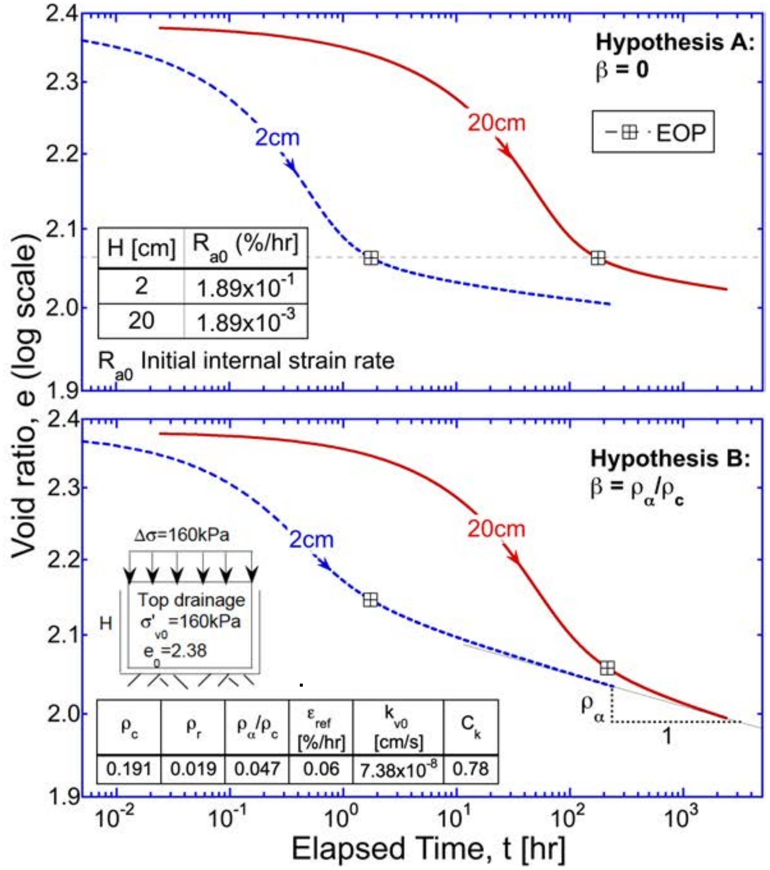
Behavior reflects complex Holocene geology of Boston area

Little physical evidence to explain differences in sub-layer properties

Sub-layers: Selection of compression index (C_c) will reflect stress range of interest

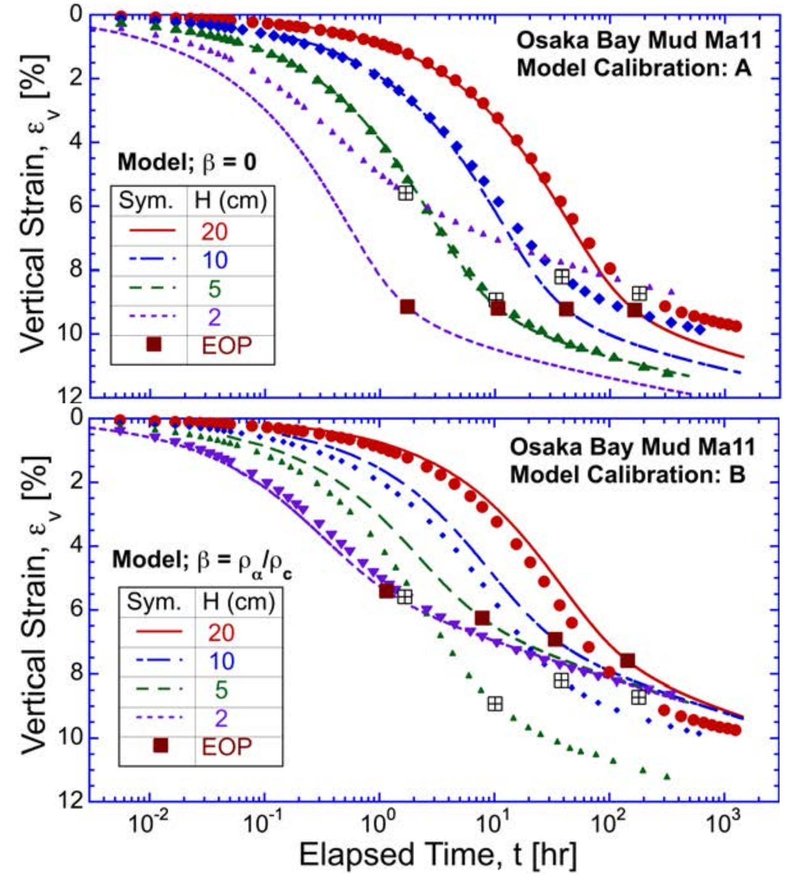
Scale Effects: Primary & Secondary Compression

MIT-SR Simulations (Yuan & Whittle, 2018)



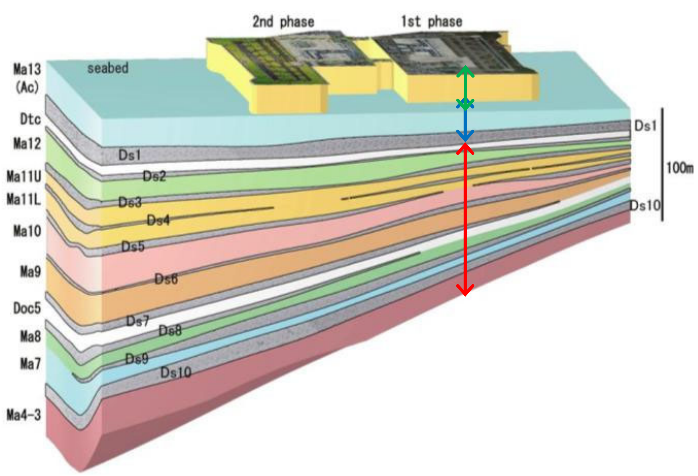
Unique capability of MIT-SR model:
Can simulate both Hypothesis A & B

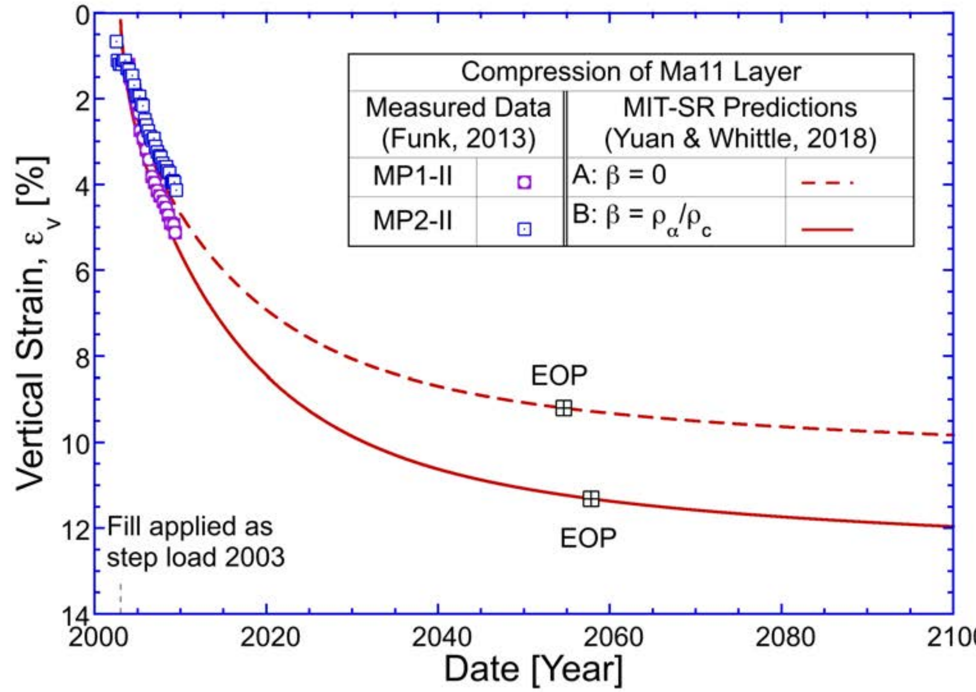
Model vs Measured Data: Osaka Bay Mud (Ma11)



Inconsistent results
Two calibrations: MIT-SR bounds the data

Validation Using Available Monitoring Data





2[nd] Phase fill constructed 1999-2007

Ma11 layer: 20m thick (2-way drained)

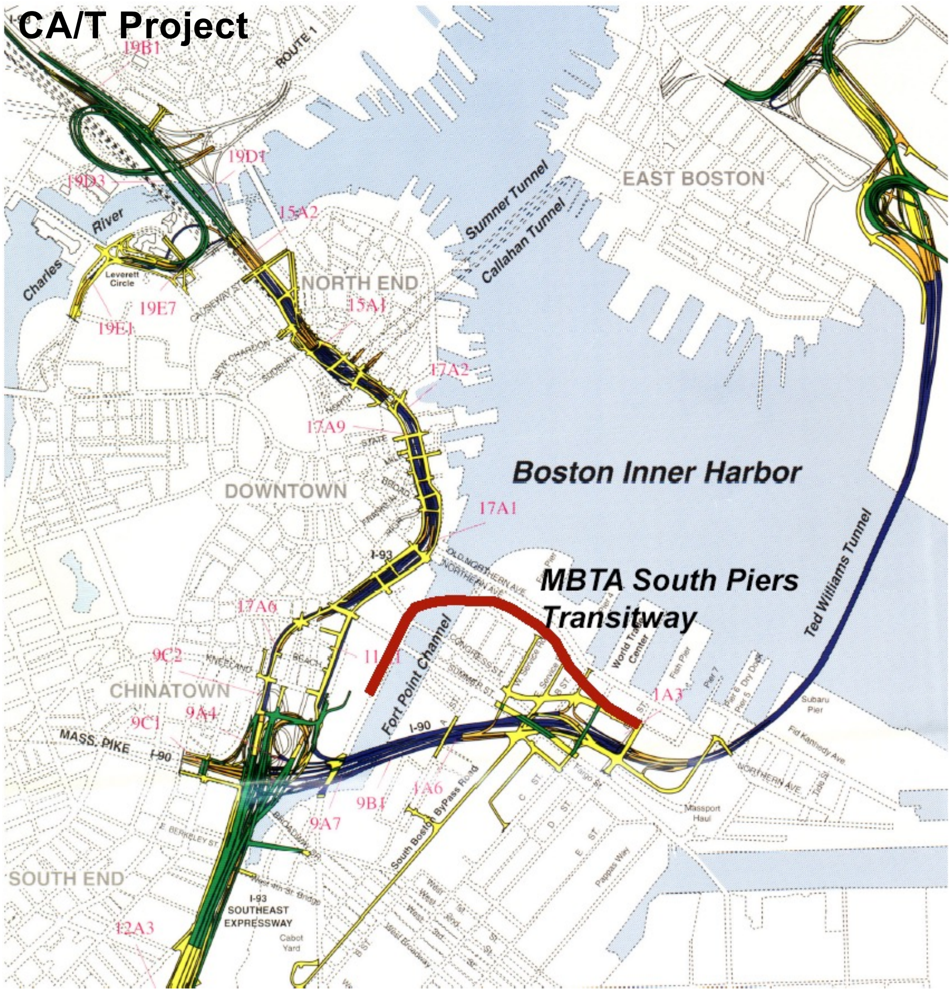
Ave. σ'_{v0} = 489kPa; σ'_p = 700kPa; $\Delta\sigma_v$ = 590 kPa

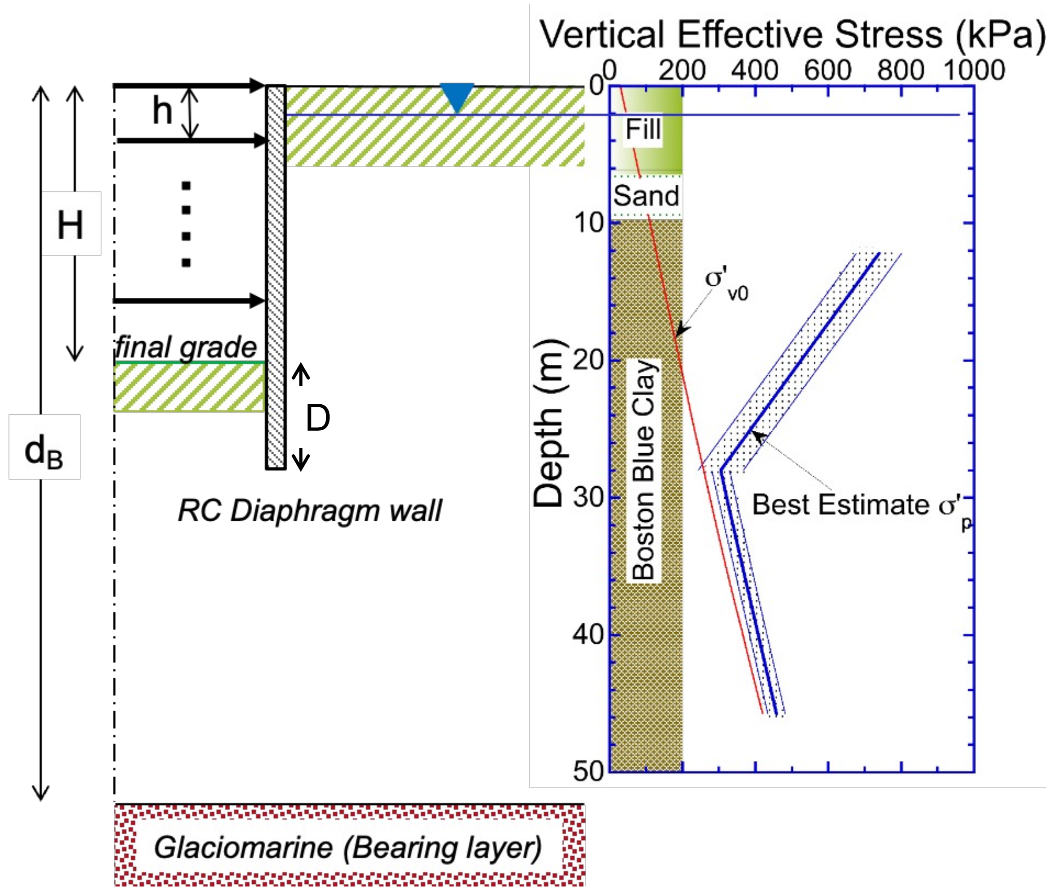
MIT-SR: bounds predictions of long-term settlement

Yuan & Whittle (2018)

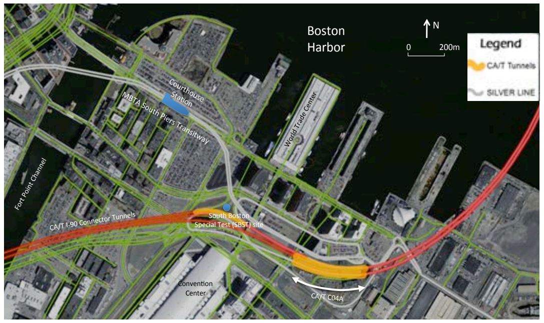
Applications for Clays

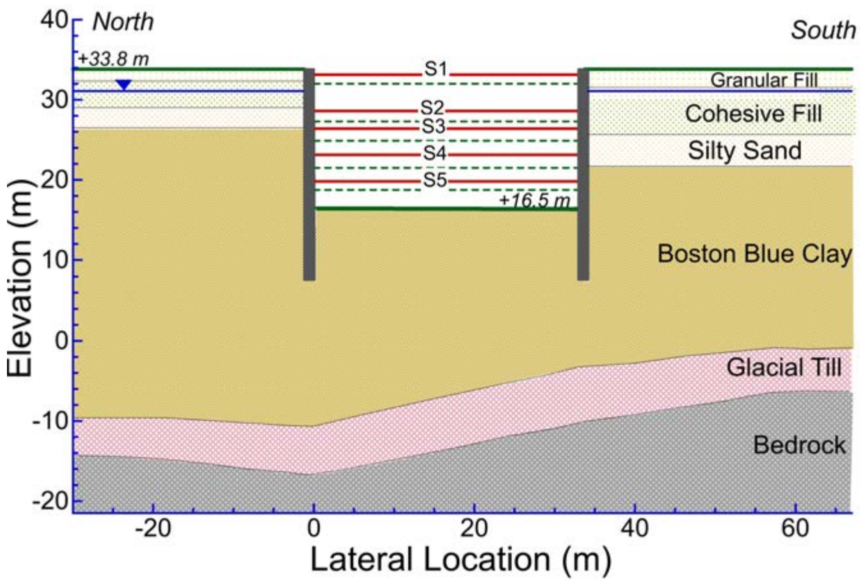
Deep Excavations in Boston





Courthouse Station Project

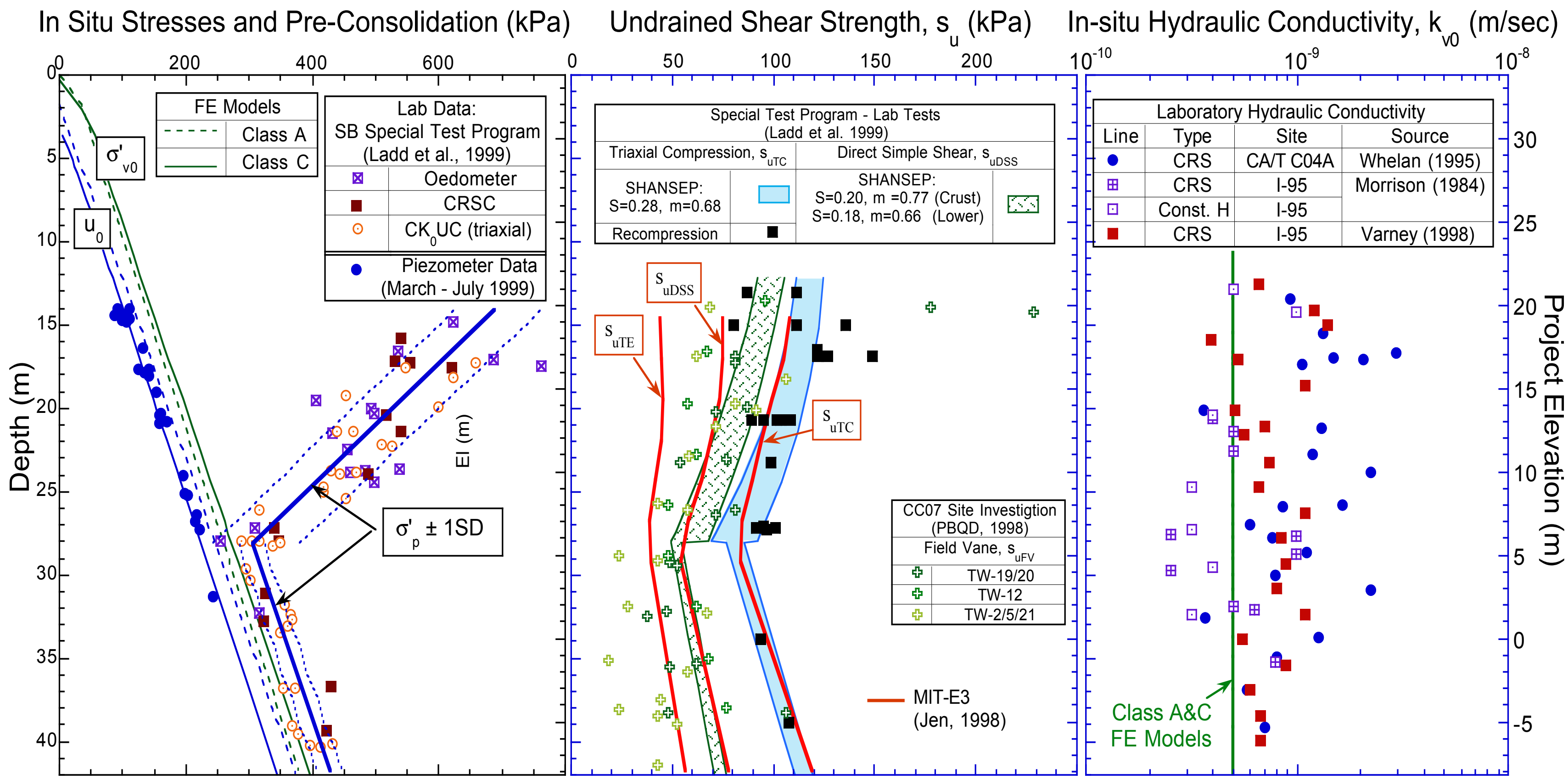




Class A predictions: Included in construction bid package
Class C predictions: Updated excavation timeline, strut preloads

[Whittle et al., 2015]

In Situ Properties: South Boston

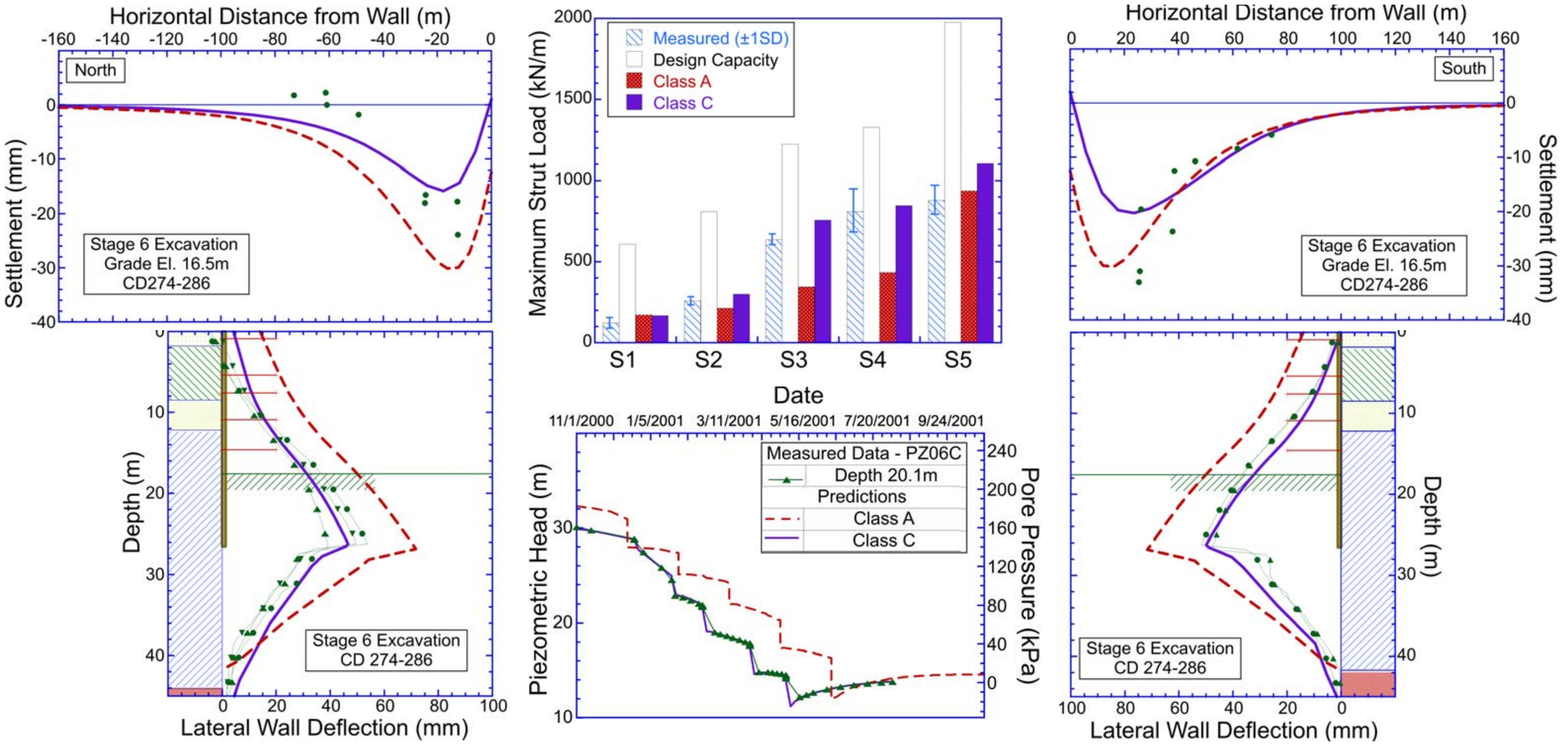


Data from nearby Special Test Site – Ladd et al. (1999)
Extensive test program: In situ tests & laboratory tests
Very low margin of safety against basal instability; FS = 1.18 – 1.23 (original design)

[Whittle et al., 2015]

Performance of Excavation Support Systems

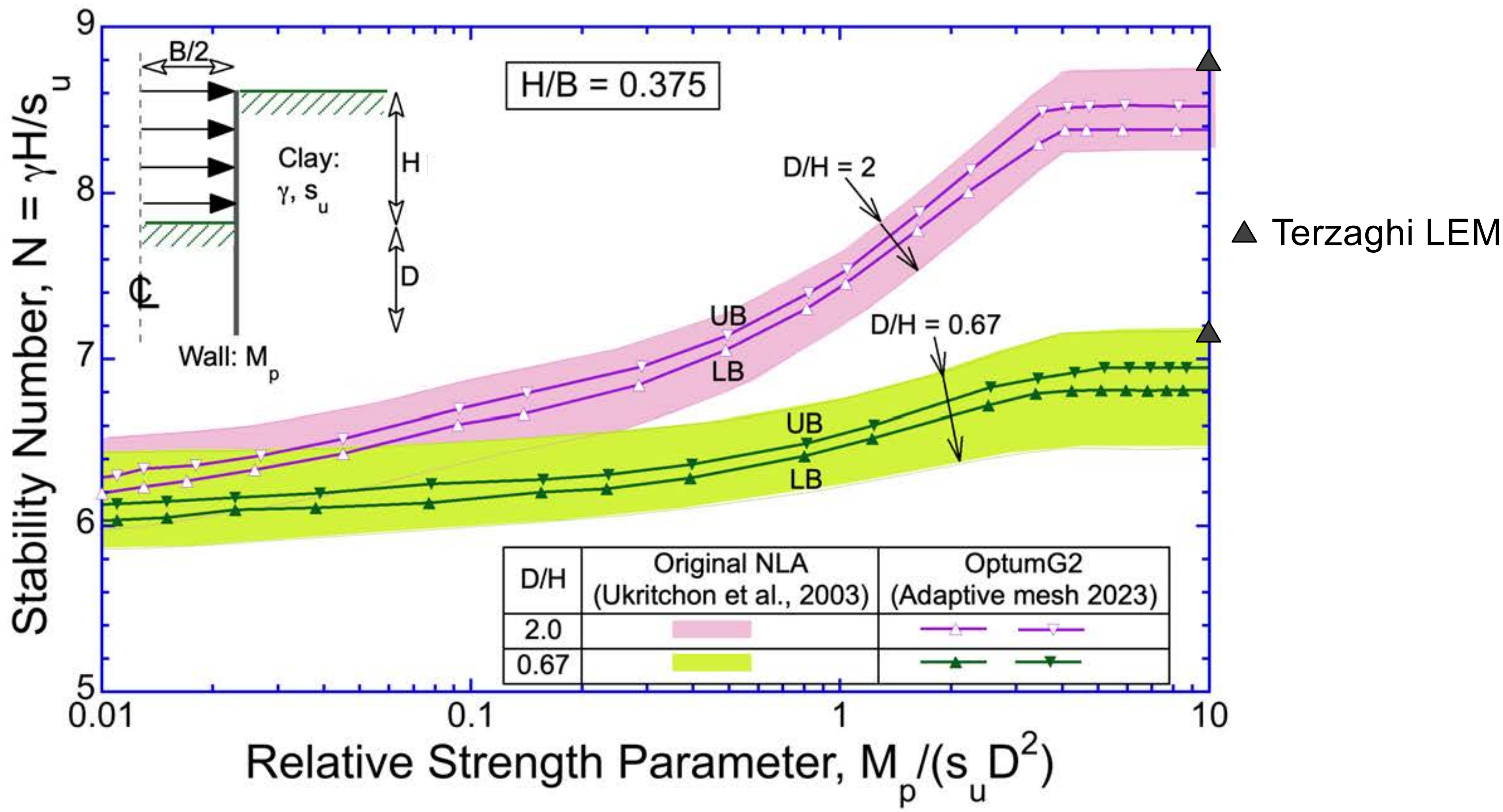
Class A vs Class C Predictions: Courthouse Station



[Whittle et al., 2015]

Stability Using Numerical Limit Analyses (NLA)

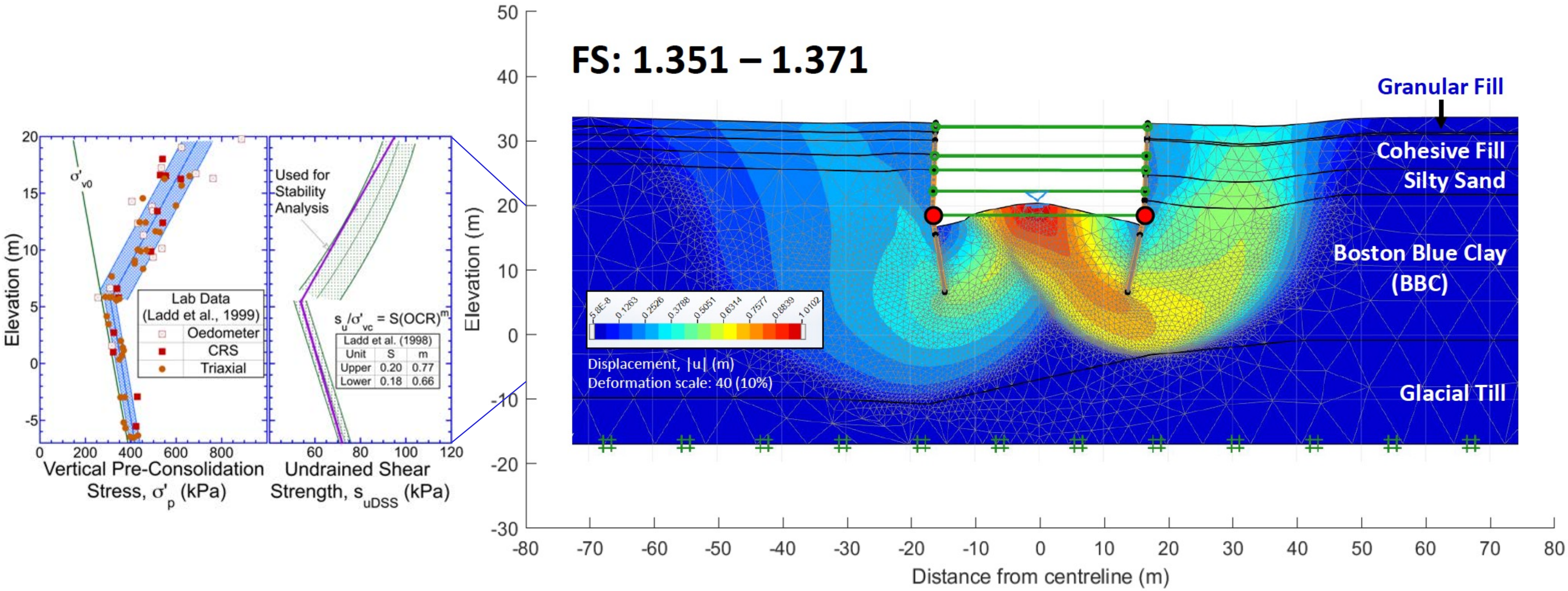
Upper & Lower Bounds solved using FE spatial discretization (after Sloan, 2013)



Rigid plastic soil behavior [γ, s_u or (c', ϕ')]

Combined failure of soil mass and bending failure of wall

Undrained Stability of Courthouse Excavation, South Boston



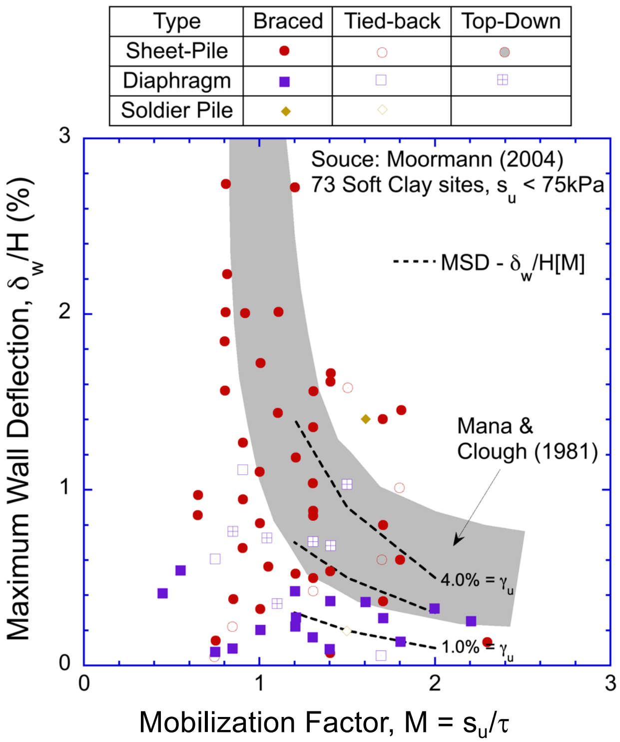
Upper Bound Failure Mechanism

Rigid plastic soil behavior

FS solved by strength reduction

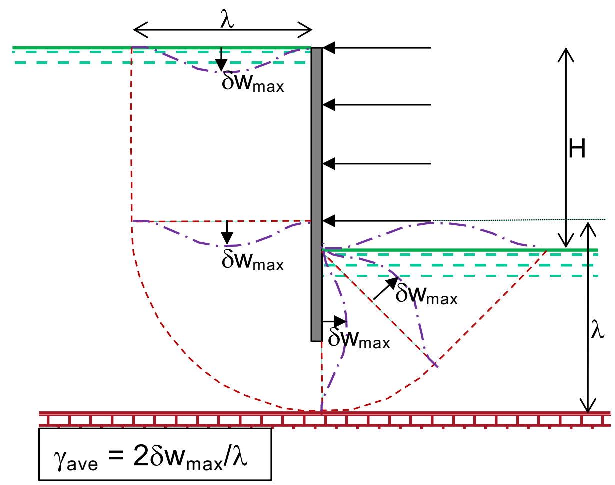
[John, pers. comm., 2024]

Wall Deflection and Control of Construction

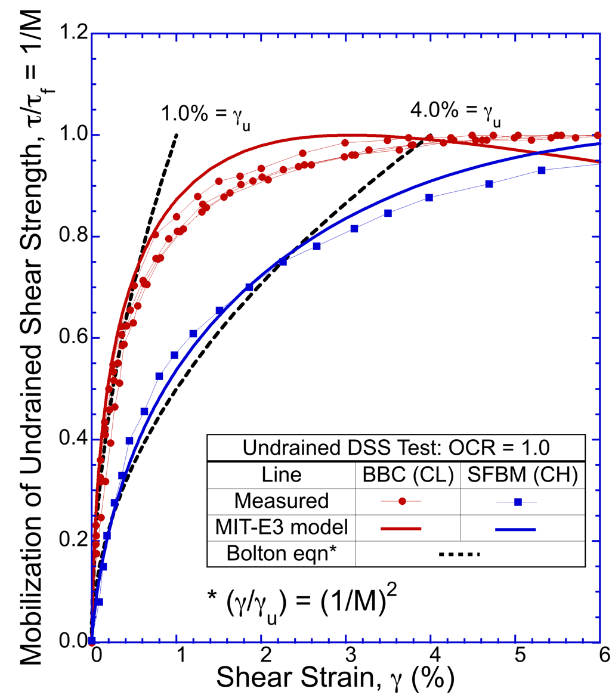


Empirical data exhibit large scatter
LEM – not accurate for FS

Mobilizable Strength Design (MSD)
(after Osman & Bolton, 2006)

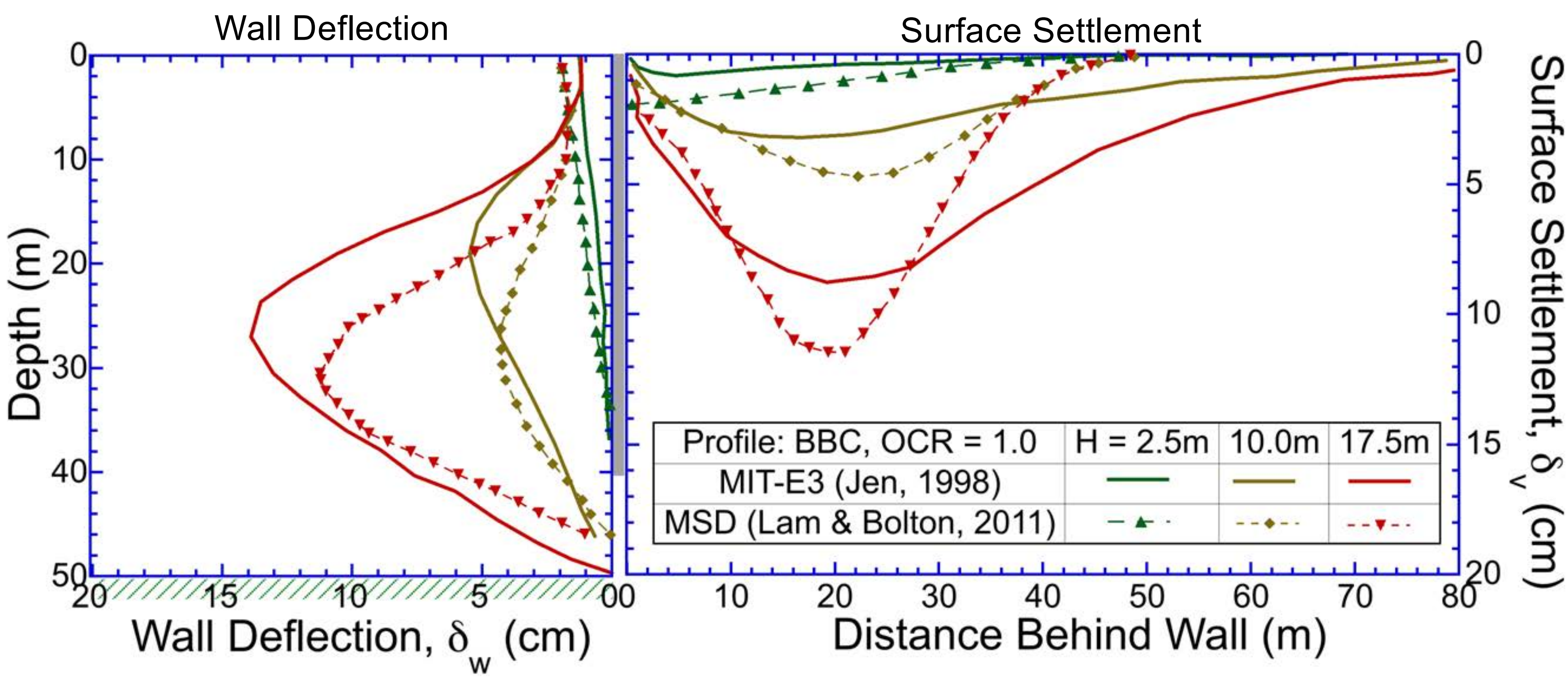


Estimates average soil shear strain from assumed plastic flow mechanism



Shear stress from DSS mode
Mobilization factor, M ~ FS
(shear strength reduction)

Evaluation of MSD Using FE Numerical Simulations

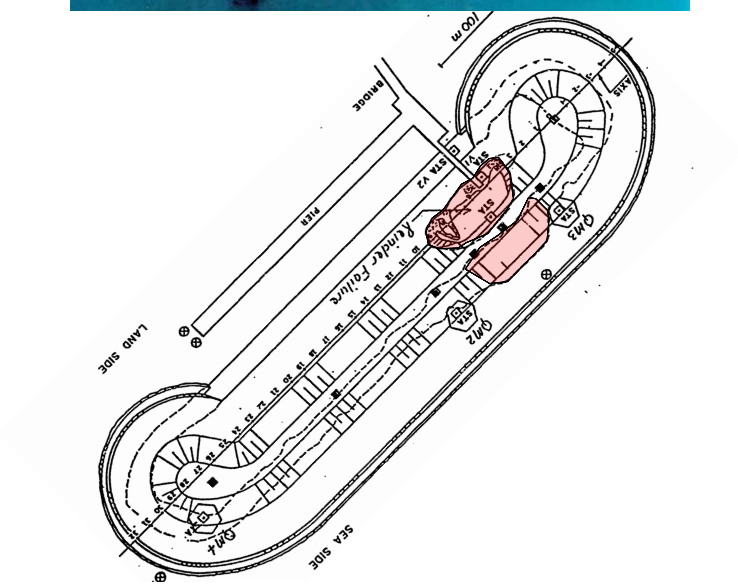


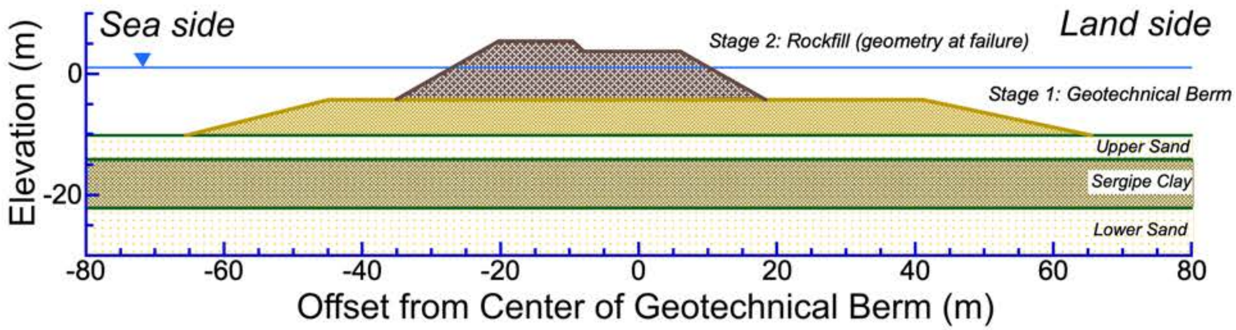
MSD: Computed incrementally using M from MIT-E3 (DSS shear mode)

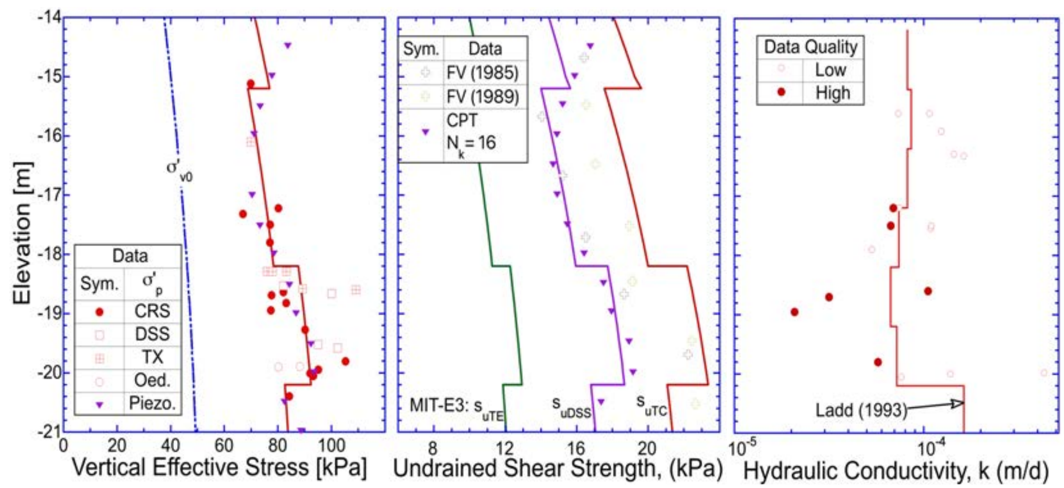
- MSD Underestimates δ_w: Passive shear mode controls below excavated grade
- MSD Overestimates δ_v: Flow mechanism too simplified

MIT-E3/FE simulations – rich data source for training machine learning algorithms

Failure of Offshore Rockfill Breakwater, Sergipe





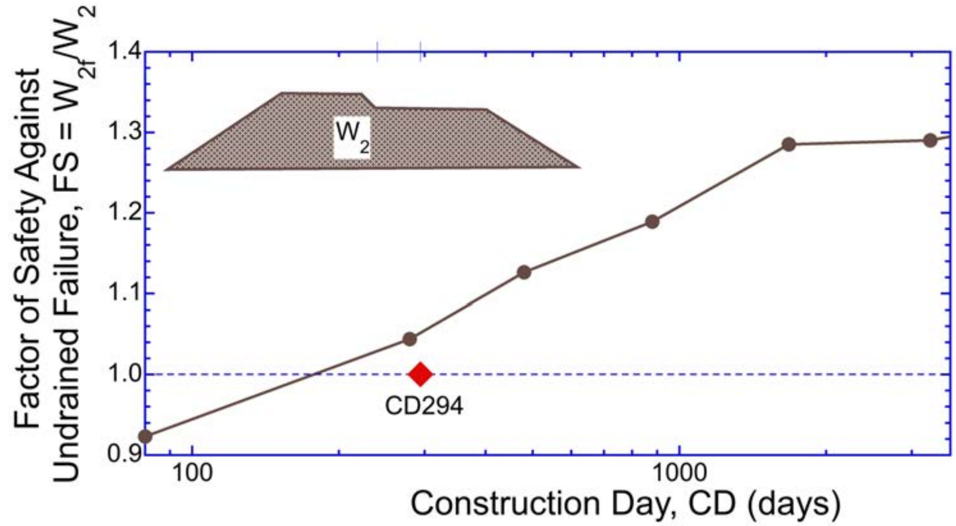


Forensic study: Ladd & Lee (1993)

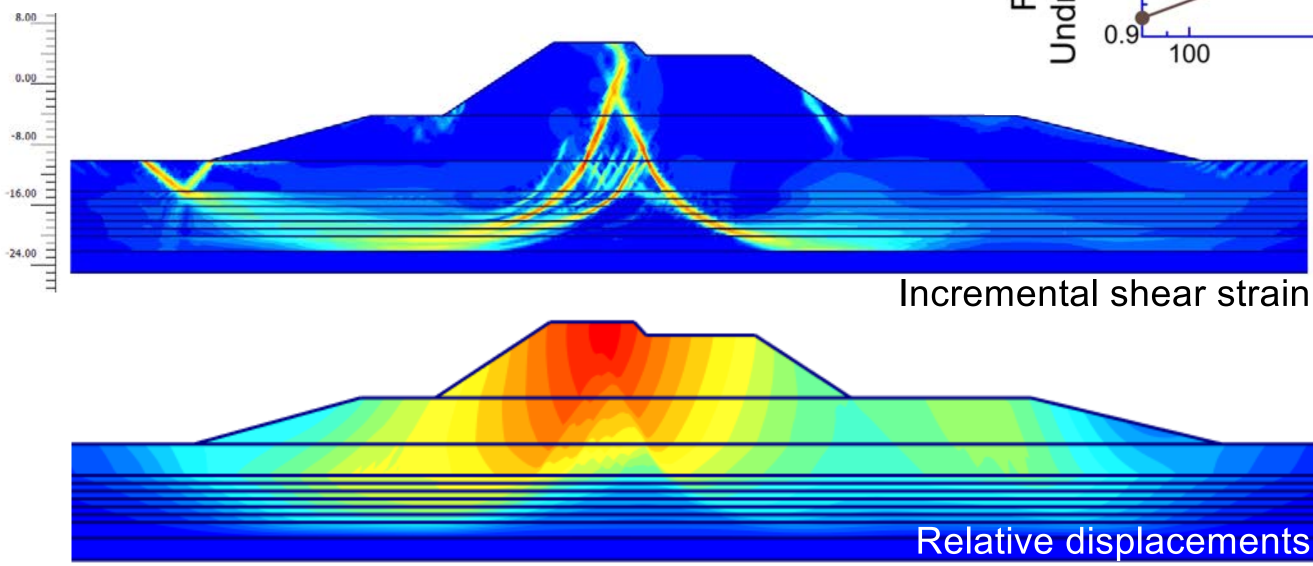
Included lab tests, calibration of MCC & MIT-E3 models

Undrained Stability Analyses

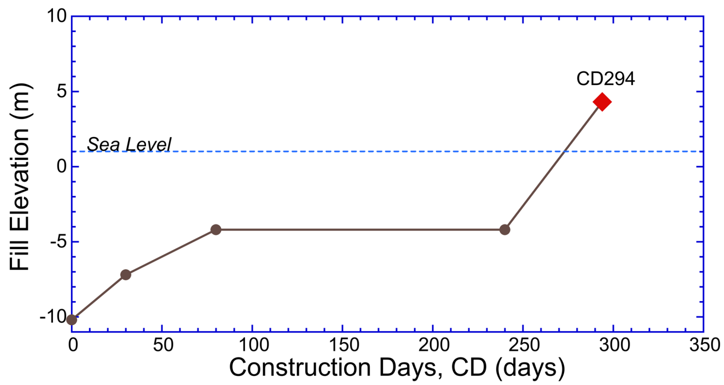
- Undrained stability analyses
  (USA, Ladd, 1991)
- Consolidation under Geotechnical Berm
- Undrained Stage 2 rockfill
- Sergipe clay: **MIT-E3**

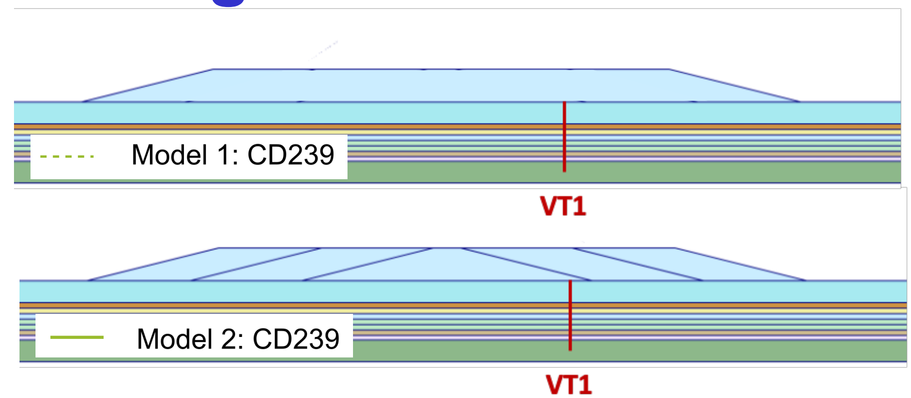


CD280: FS = 1.044

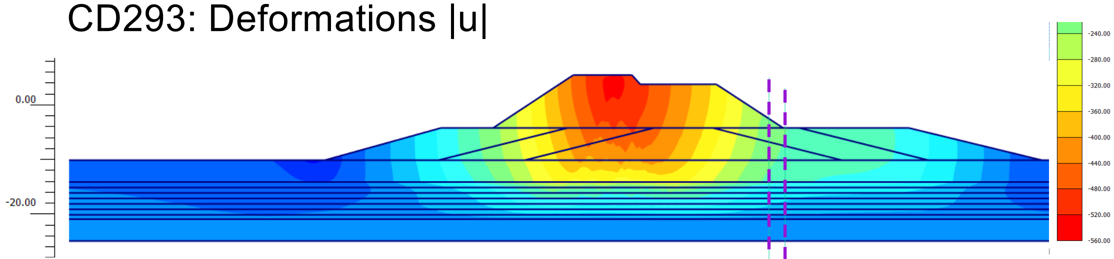


Deformation Analyses of Stage 2 Rockfill

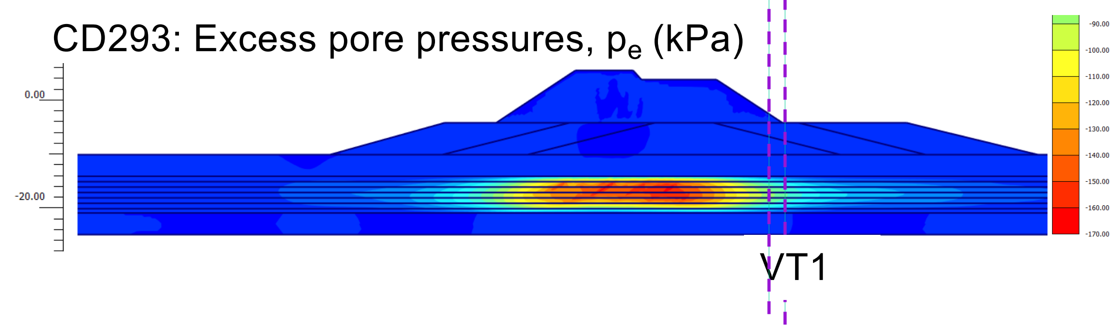


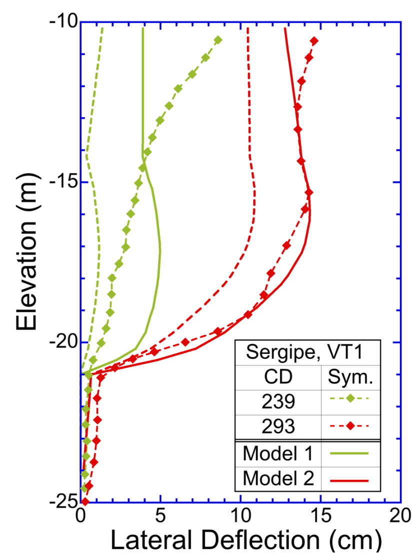


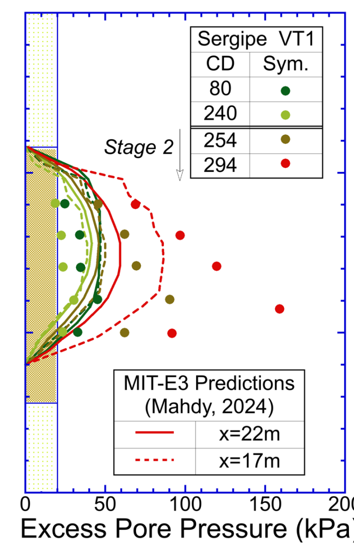
CD293: Deformations |u|



CD293: Excess pore pressures, p_e (kPa)







Sometimes, there is a good reason for discrepancies between model & data

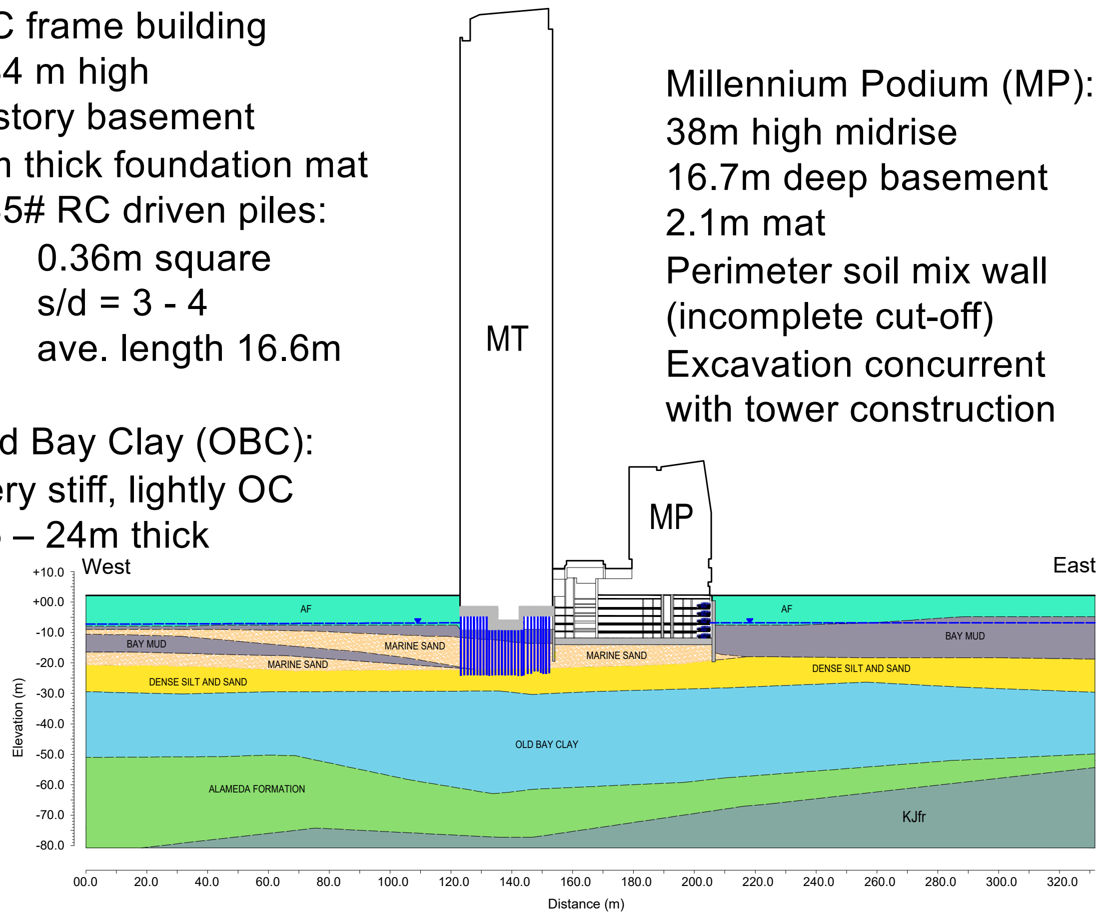
Millennium Tower, 301 Mission St., San Francisco

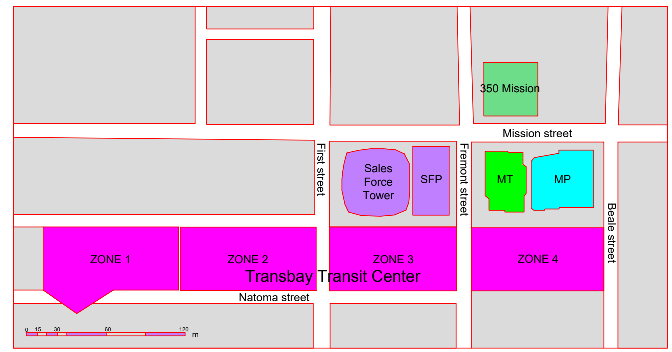
Millennium Tower (MT):
RC frame building
184 m high
1 story basement
3m thick foundation mat
945# RC driven piles:

- 0.36m square
- s/d = 3 - 4
- ave. length 16.6m

Millennium Podium (MP):
38m high midrise
16.7m deep basement
2.1m mat
Perimeter soil mix wall
(incomplete cut-off)
Excavation concurrent
with tower construction

Old Bay Clay (OBC):
Very stiff, lightly OC
15 – 24m thick

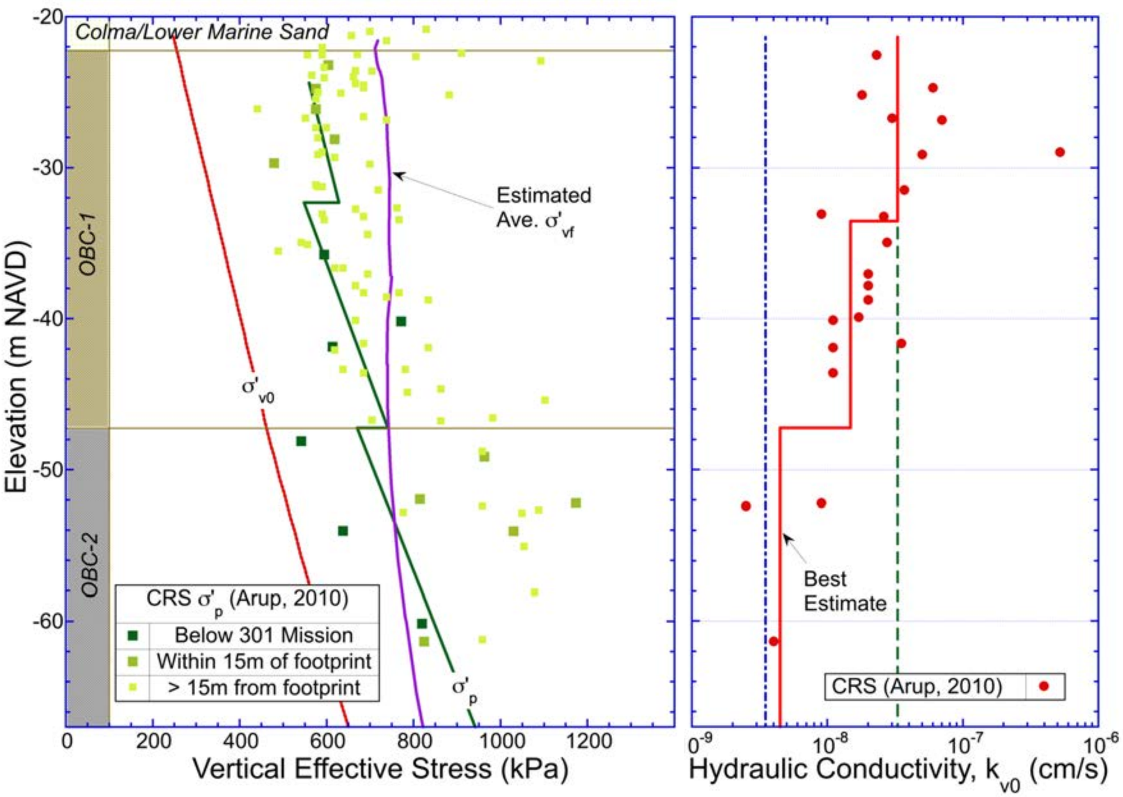


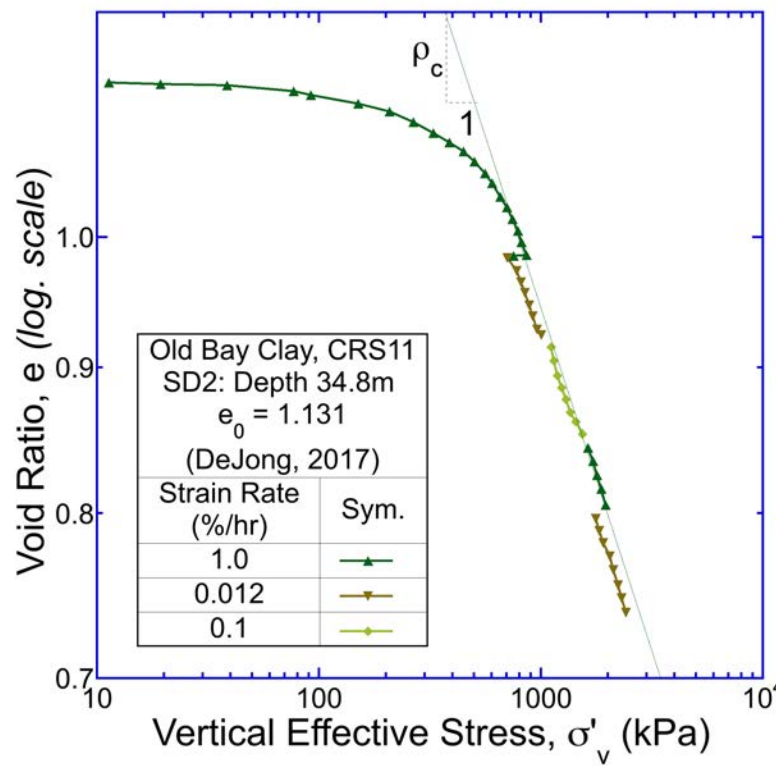


Site plan:
MT & MP: completed 2009

Adjacent Projects
Transbay Transit Center: 2011-2018
350 Mission: 2012-2015
Sales Force Tower & P: 2014-2018

Why is MIT-SR Model Useful for Analysis of Millennium Tower?





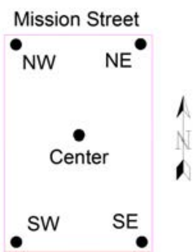
Special program of 1D compression tests [DeJong, 2017]

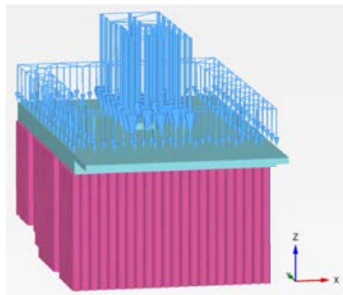
Foundation loads (MT) cause loading into NC regime (OBC-1)

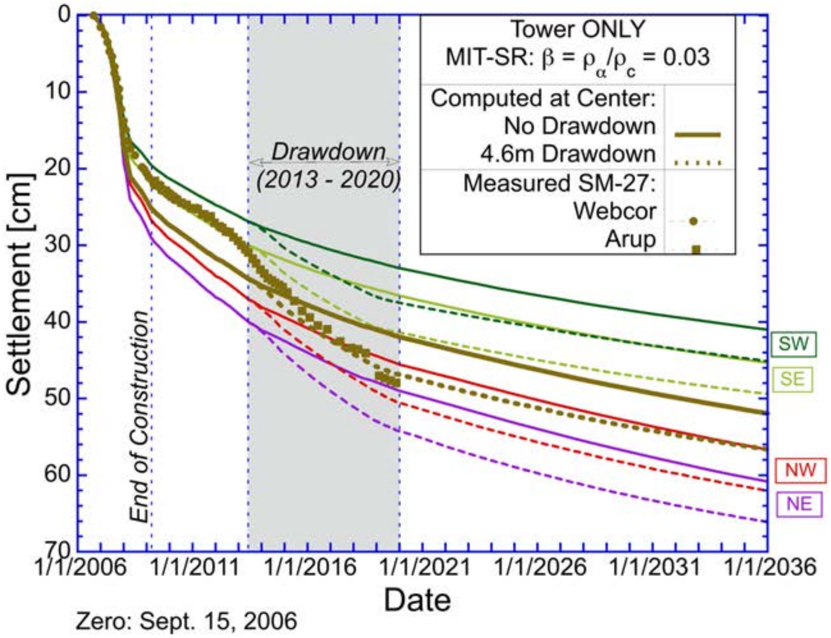
Extensive SI & laboratory data available (Arup, 2010) [post MT-construction]

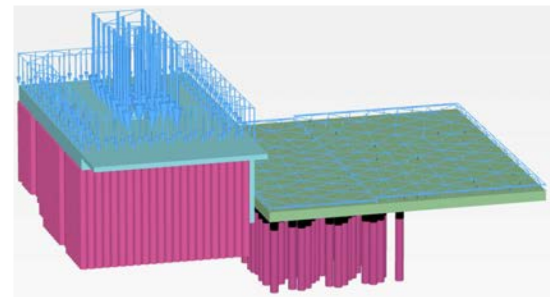
MIT-SR simulates OC-NC transition with primary consolidation & creep

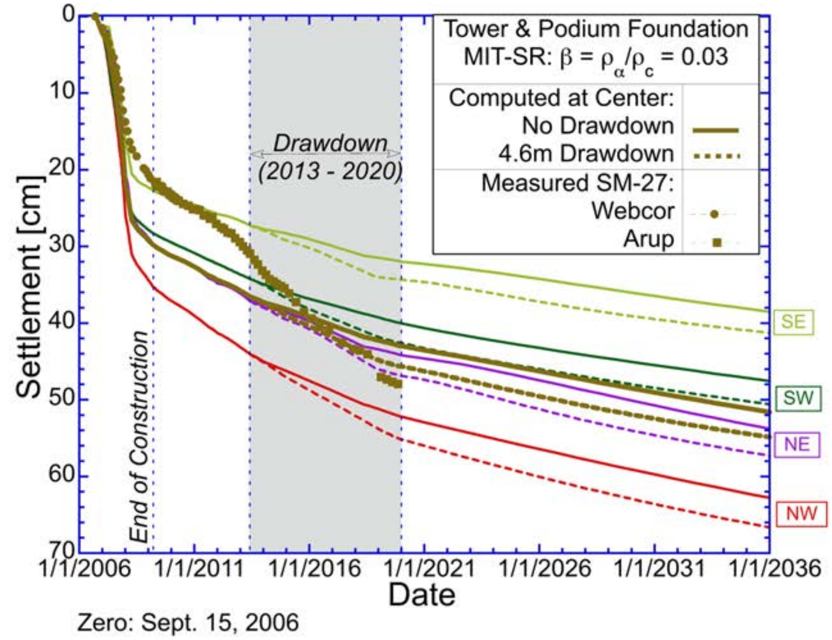
Foundation Settlements









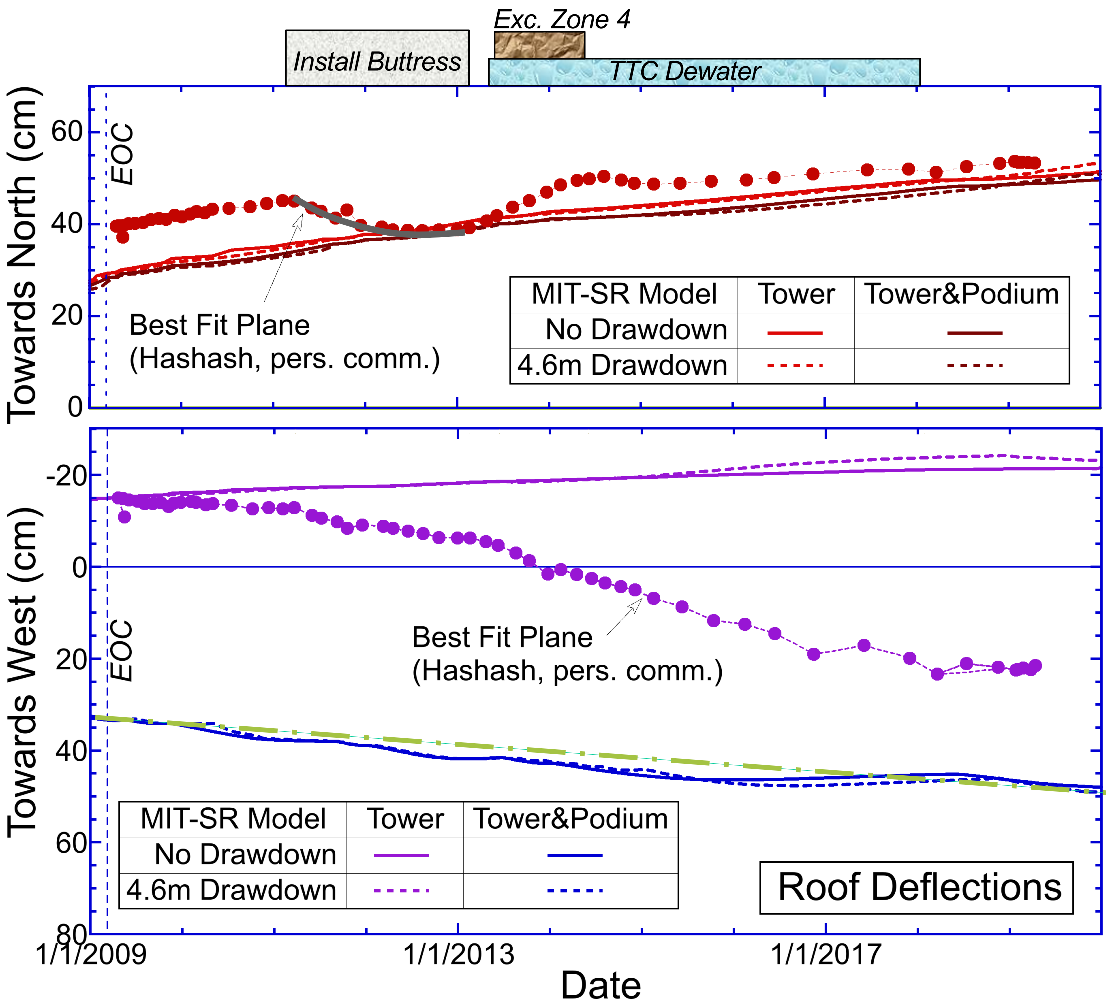


Drawdown adds ~4cm to settlements
Drawdown does not affect tilt direction

Small effect on magnitude of settlement
Large effect of podium on mat tilt direction

Evaluation of Tower Tilt: Roof Level Deflections

[Assuming Planar Deformation of Foundation Mat]



Towards North:

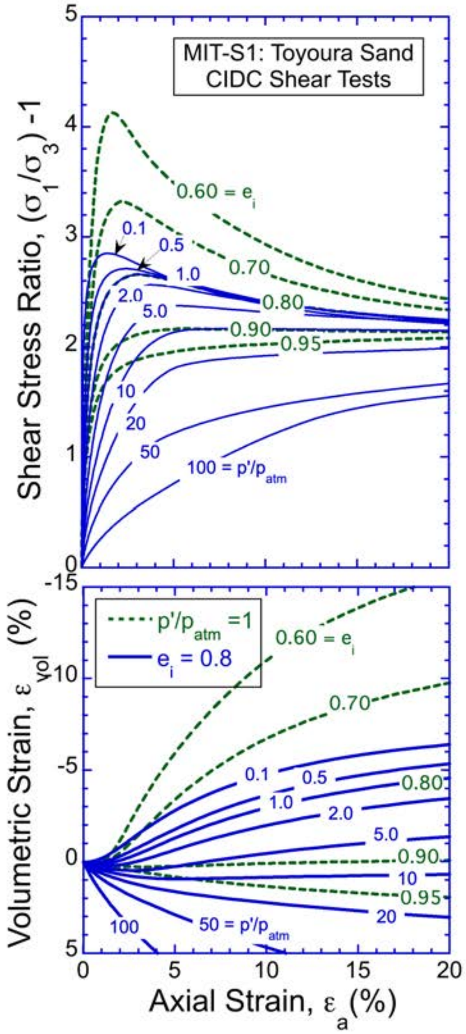
- Significant tilt measured at EOC (35 - 40 cm)
- Model predictions in reasonable agreement with measured response
- Drawdown & podium have little effect
- Reversal in 2012: ground loss of TTC buttress

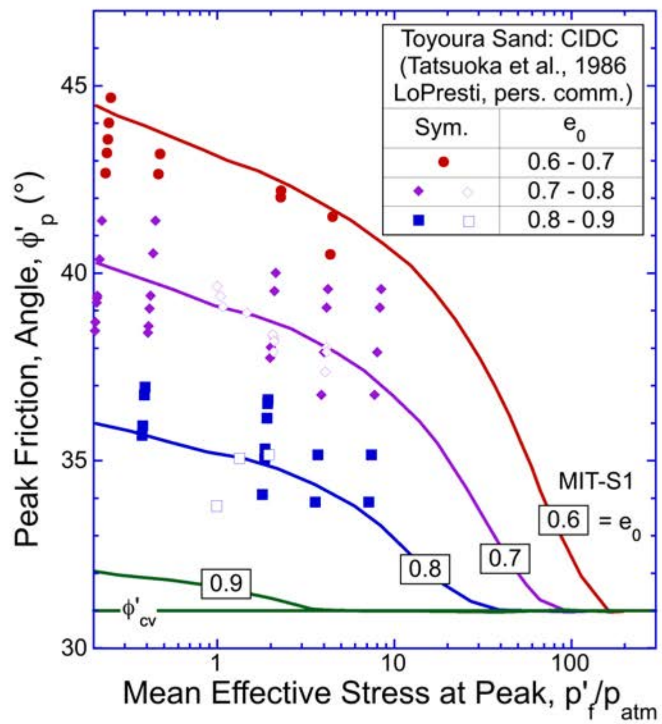
Towards West:

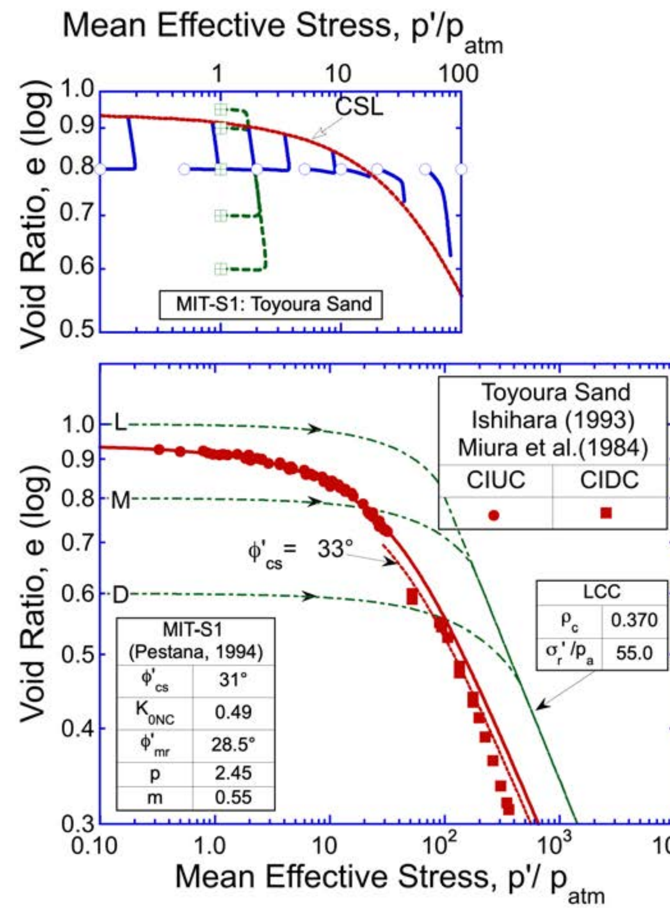
- Measured tilt
  - At EOC (15 cm to East)
  - Subsequent tilt (35 cm to West)
- Podium construction has major impact on EOC predictions **(unrealistic)**
- Similar results reported - Stewart et al. (2023)
- Subsequent E-W tilt NOT predicted by these foundation models
- Cause?

Sands

Prediction of Sand Behavior: MIT-S1 Model

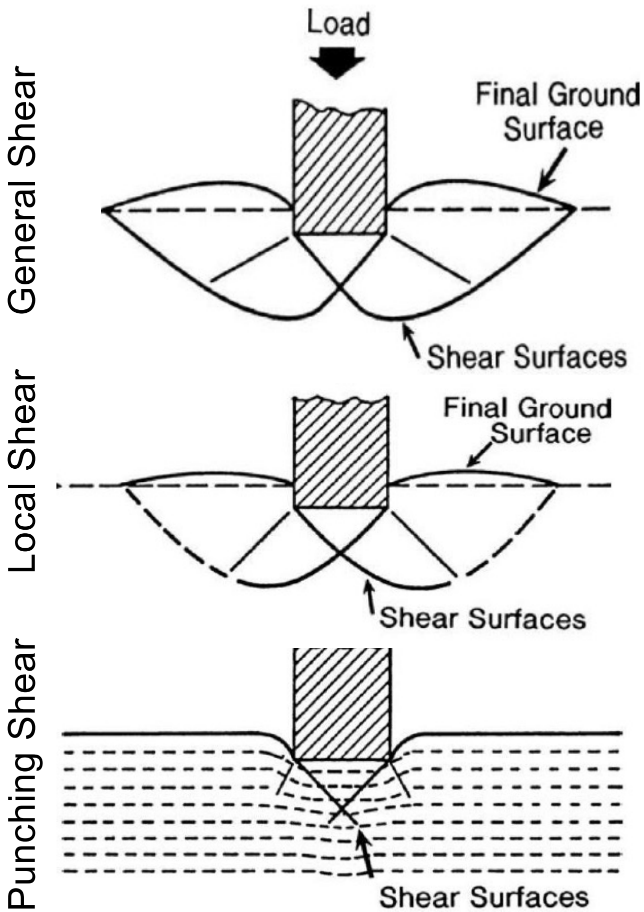




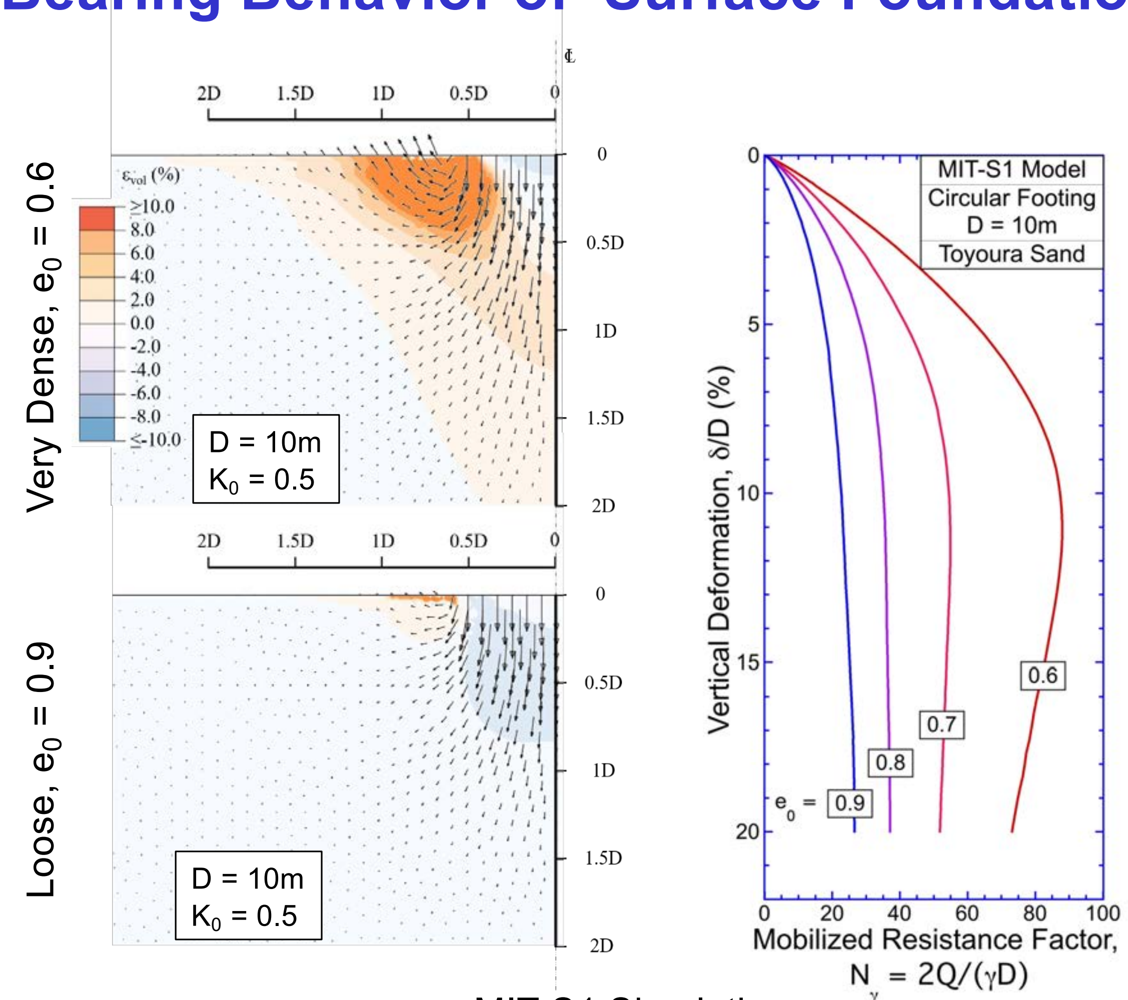


[from Pestana, PhD 1994]

Effects of Sand Density on Bearing Behavior of Surface Foundation

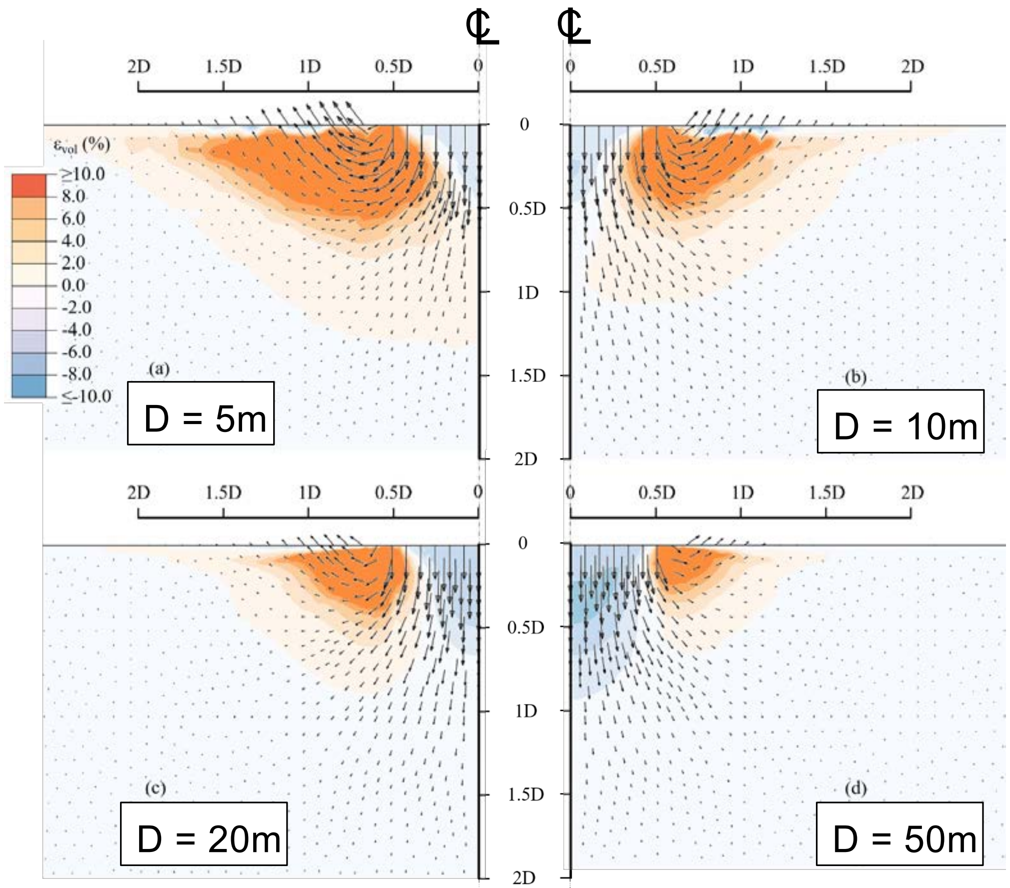


Interpreted Model Tests
(DeBeer & Vesic, 1958)

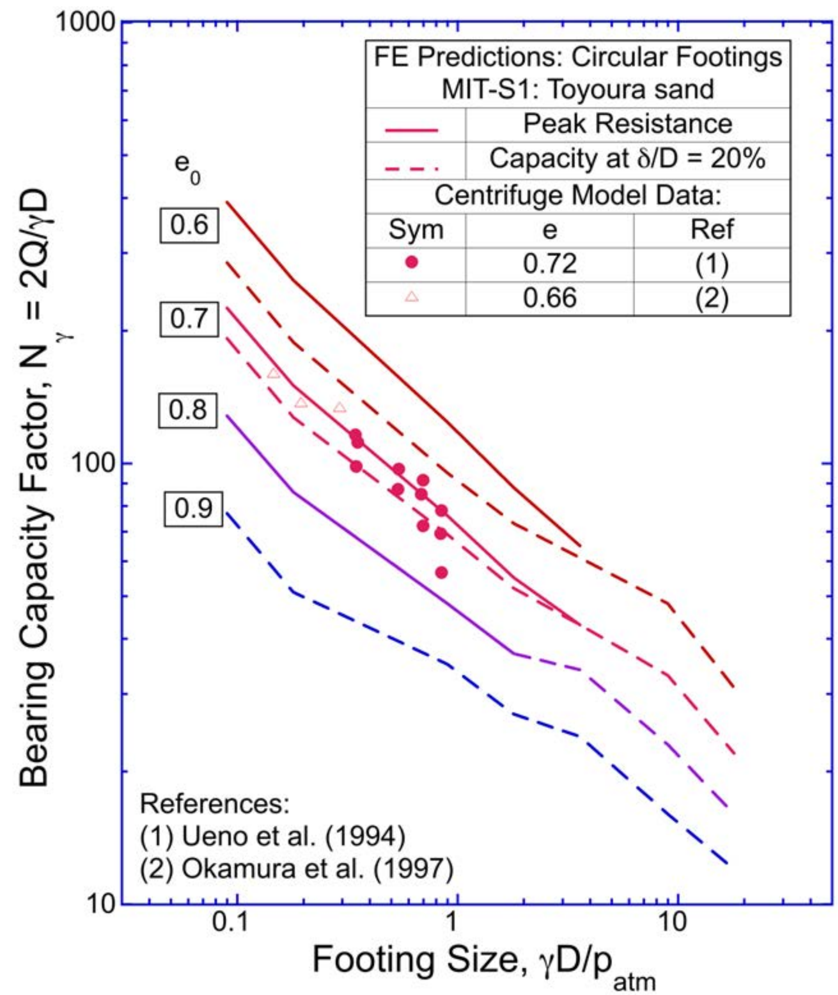


MIT-S1 Simulations
(Chen et al., 2020)

Effect of Foundation Size on Bearing Capacity



Very dense sand, e_0 = 0.6, K_0 = 1.0



Results provide basis for study of effects of spatial variability in sands

Chen et al. (2020)

Spontaneous/Static Liquefaction of Upstream Tailings Dam

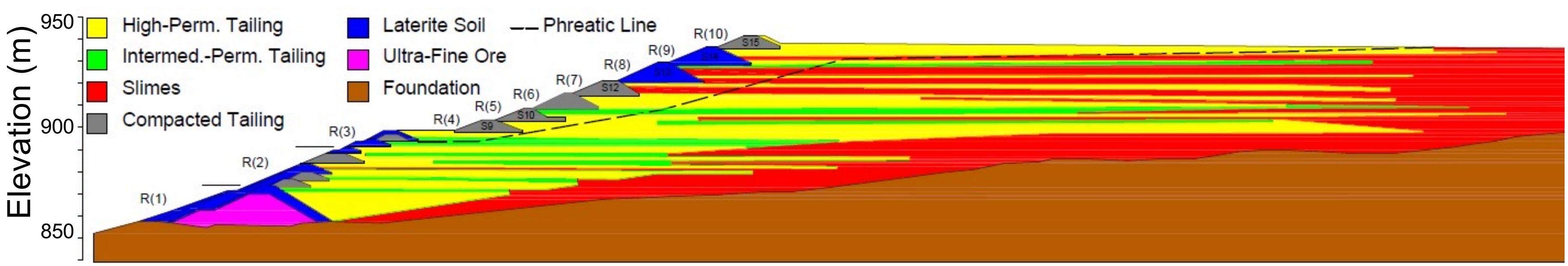
Brumadinho, MG, Brazil January 2019

Córrego do Feijão Dam 1:

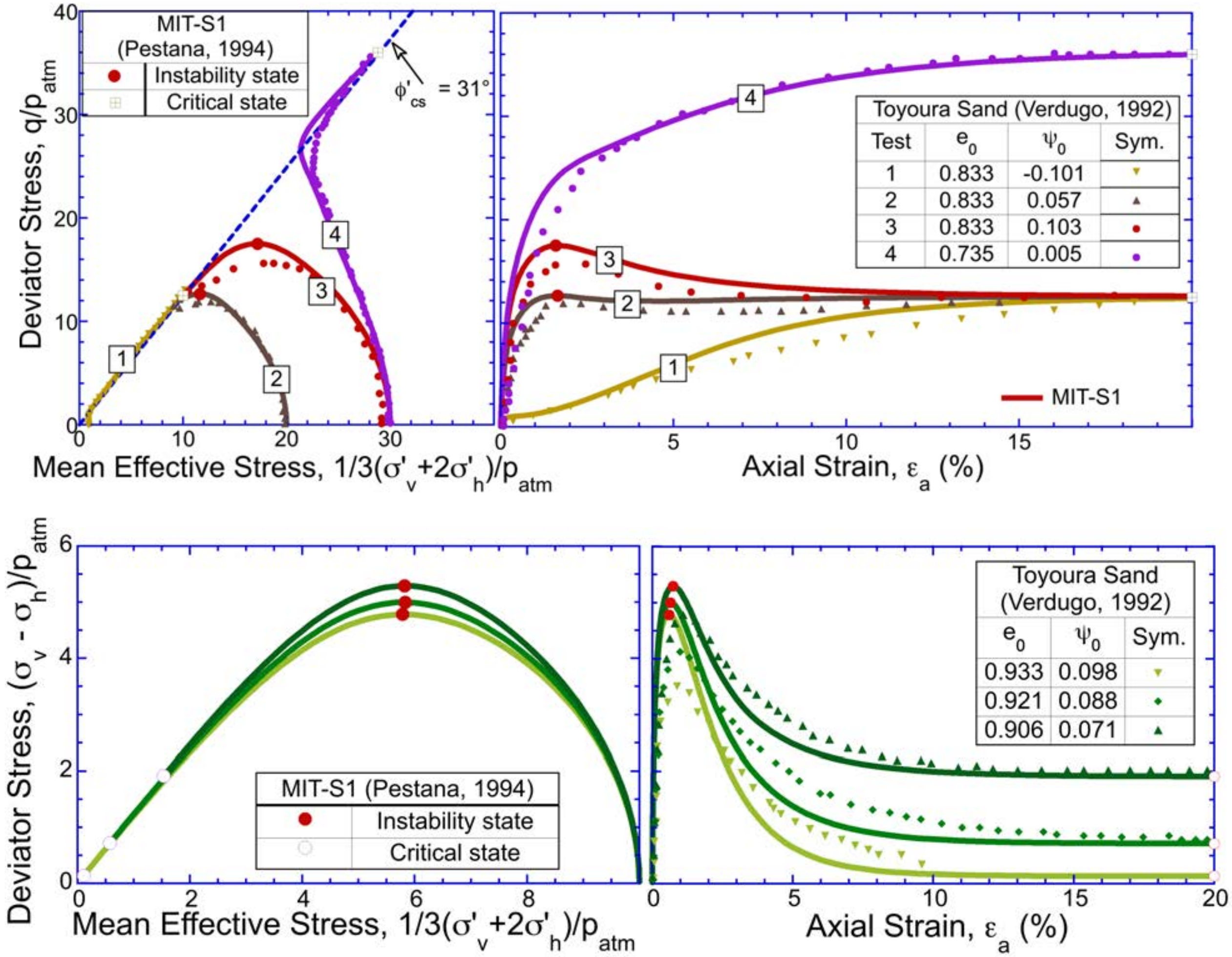
12M m^3 ***iron ore tailings*** released; 260 lives lost; $7B compensation settlement (2021)

Failure occurred 3 years after end of operations

Prohibition on upstream construction for tailings (Brazil, 2020)

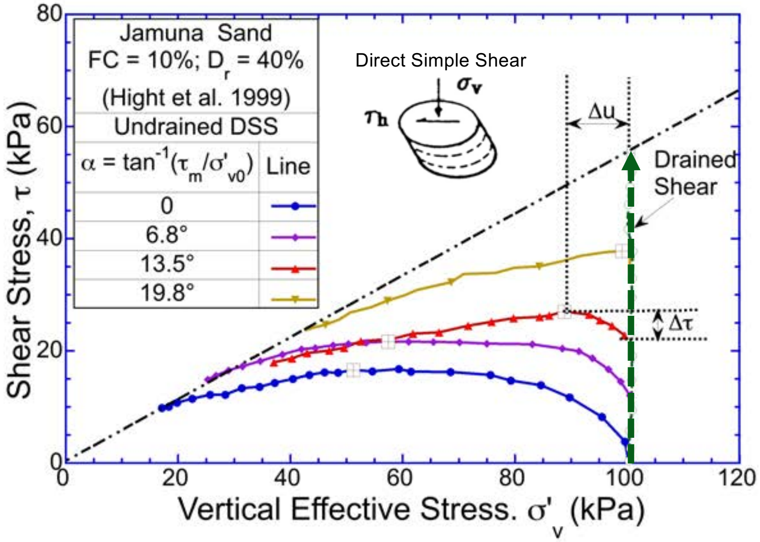


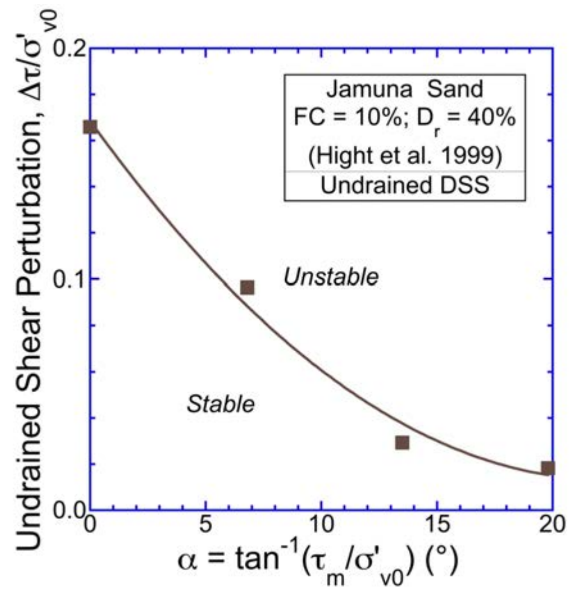
MIT-S1 Predictions: Undrained Shear Behavior of Sands



Current methods require estimates of ψ from piezocone penetration

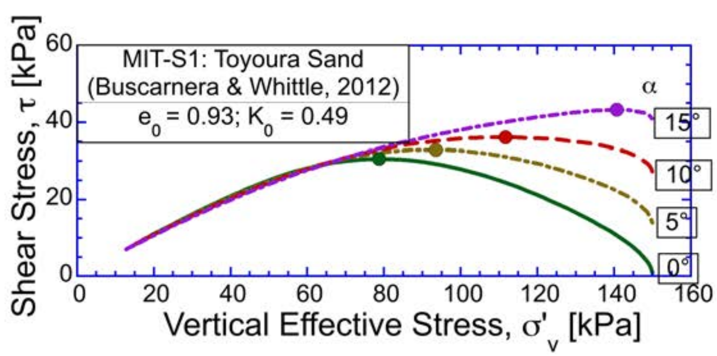
Triggering Shear Stress & Consolidation State

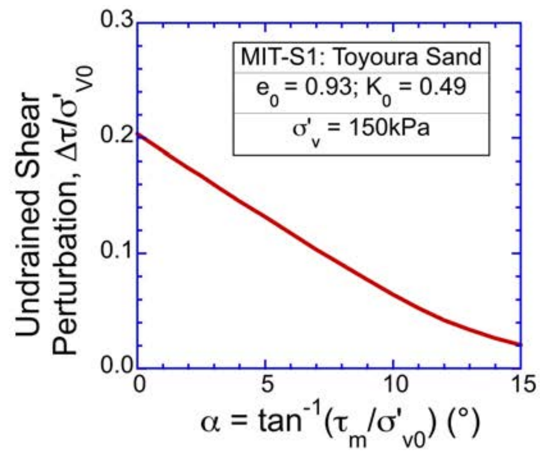




Drained response stable

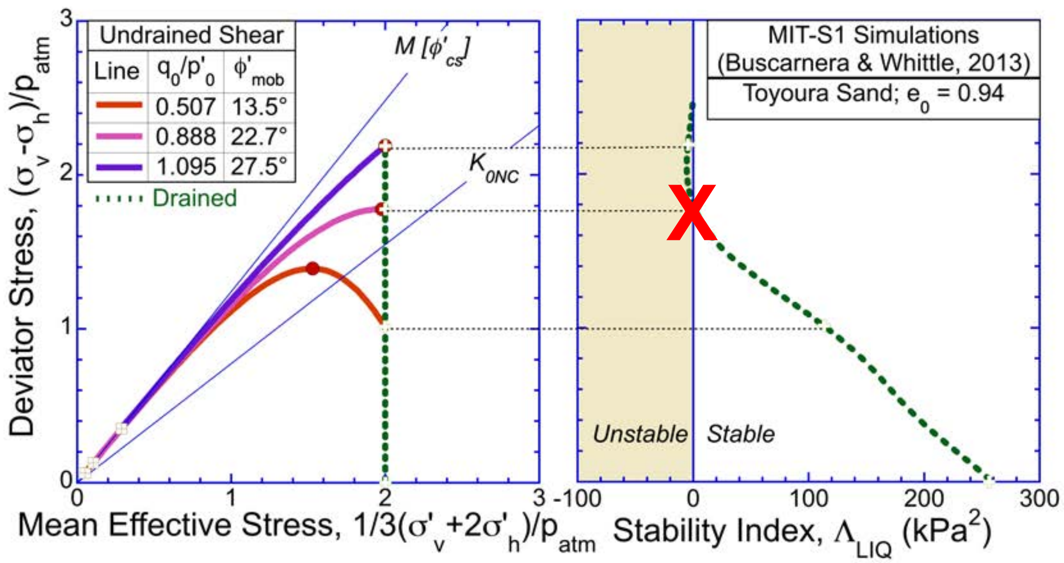
Switch to undrained shearing:
Perturbation Δτ causes instability

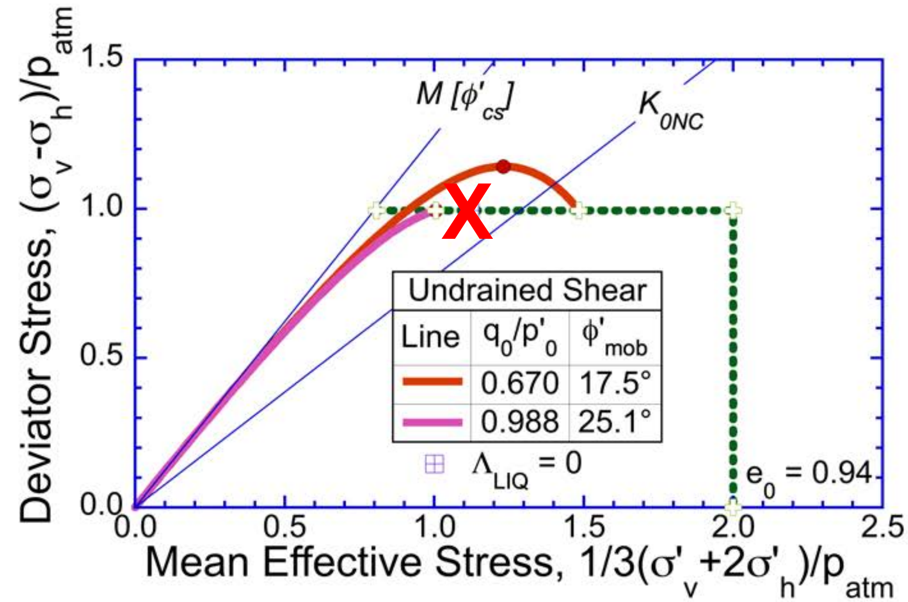




MIT-S1: Infinite Slope
Predicts undrained instability
Depends on yield surface orientation

Model Prediction of Latent Instability Caused by Undrained Shear Perturbation



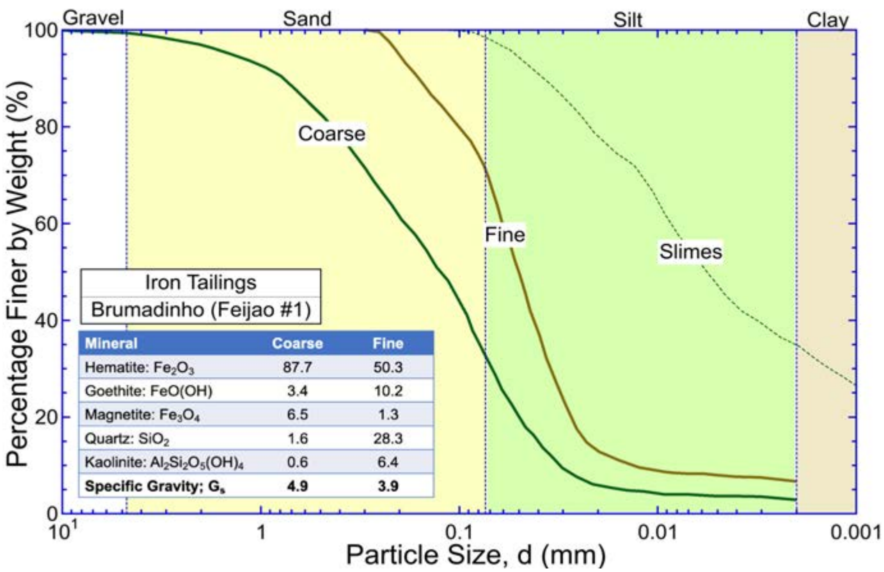


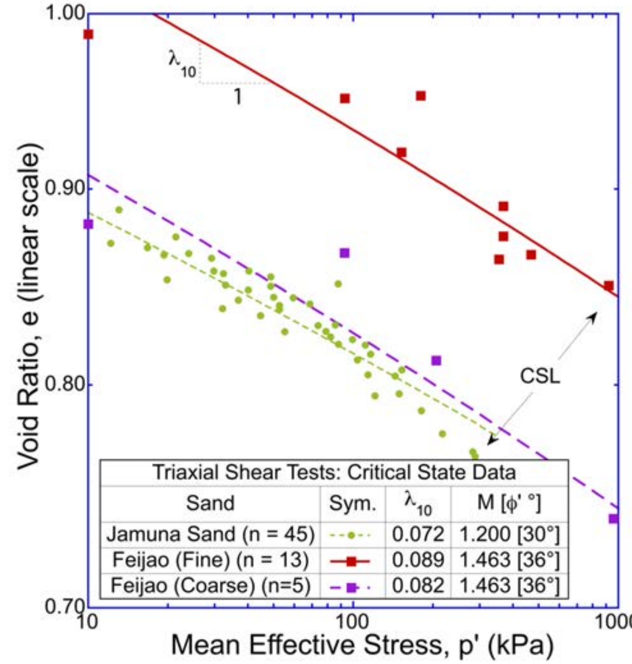
Undrained instability occurs when $\Lambda_{LIQ} = 0$
Λ_{LIQ} available for any elasto-plastic soil model
MIT-S1: very loose Toyoura sand ($\psi = 0.04$)

Increase in pore pressure:
$\Lambda_{LIQ} = 0$ occurs at $\phi'_x = 22.7°$
i.e., $FS_x = \tan\phi'_{cs}/\tan\phi'_x = 1.44$!!

- Highlights limitations of existing methods for interpreting instability
- Quantitative predictions strongly dependent on constitutive model

Challenge in Evaluating Liquefaction Stability of Tailings





Hydraulic fill: particle segregation
Fine vs coarse - affect engineering properties

Large difference in estimated CSLs
Note: similarity to Jamuna silt
Separate model calibration MIT-S1 [CSL, LCC]

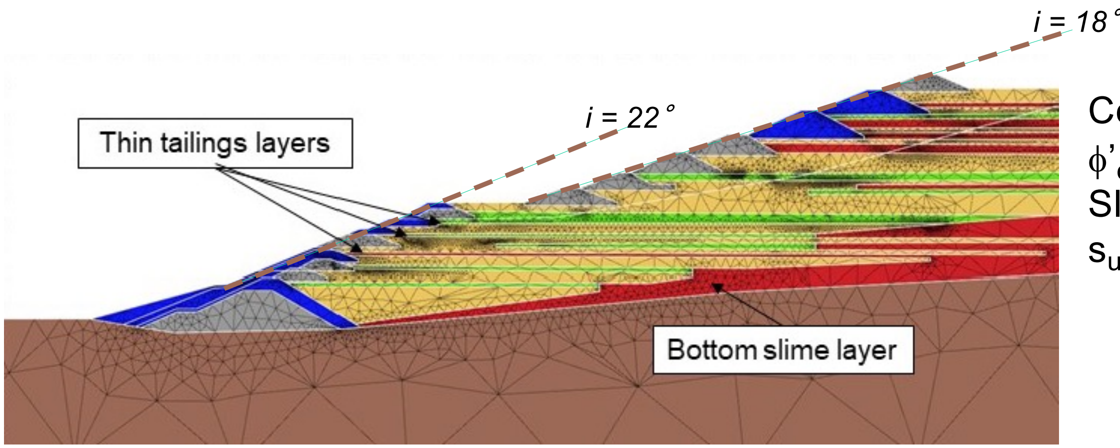
Application of advanced soil model requires:

Site stratigraphy (hydraulic fill) & in situ state (void ratio, fabric)

Limited data available for Brumadinho failure:

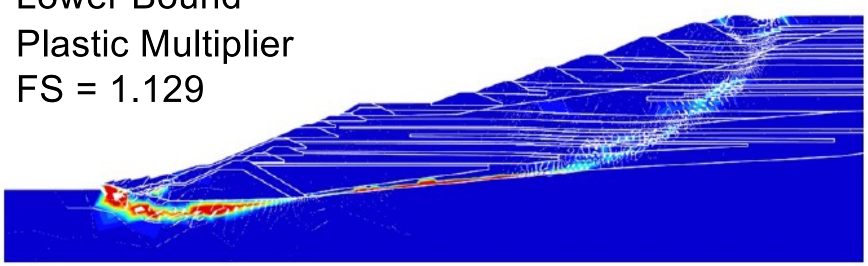
Application of advanced soil model involves large uncertainties: **Better to use simpler approach**

Stability Analyses using Numerical Limit Analyses

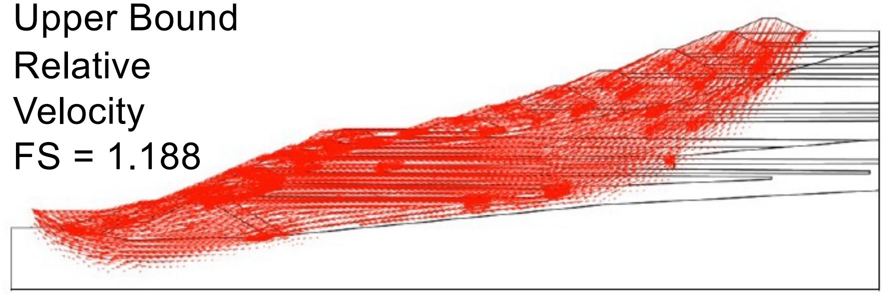


Coarse & Fine tailings:
$\phi'_{cs} = 36°$, $\gamma_t = 25, 27 kN/m^3$
Slimes:
$s_u/\sigma'_{v0} = 0.22$, $\gamma_t = 27 kN/m^3$

Lower Bound
Plastic Multiplier
FS = 1.129



Upper Bound
Relative
Velocity
FS = 1.188



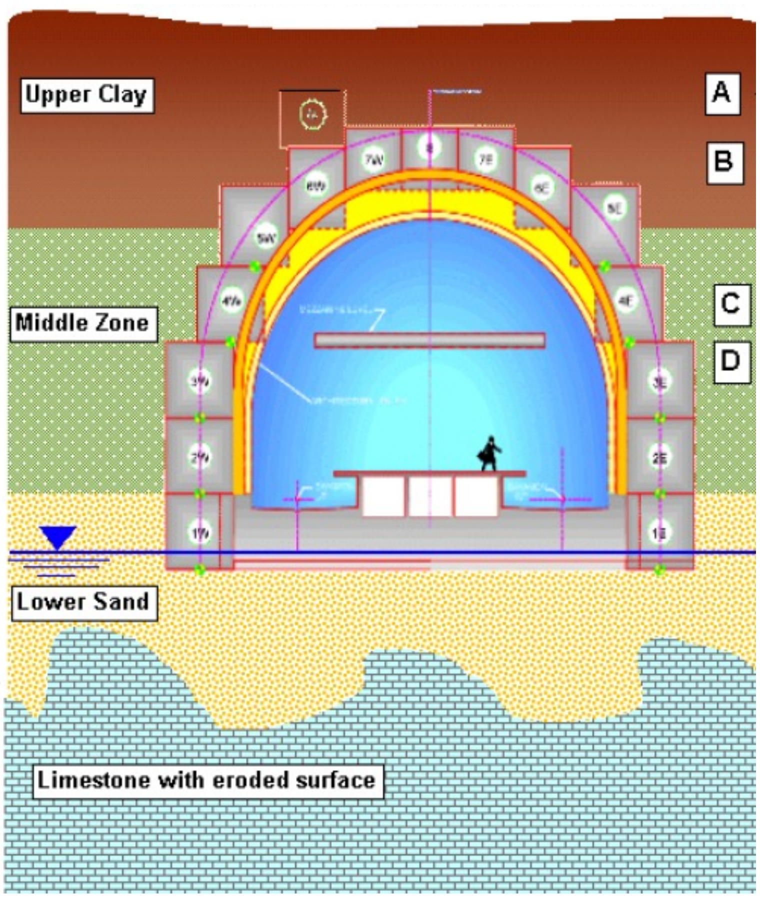
Mechanism consistent with observed failure
Conventional stability analyses reveal risks associated with latent instability:
i.e., $FS < FS_X$ [where $\Lambda_{LIQ} = 0$]

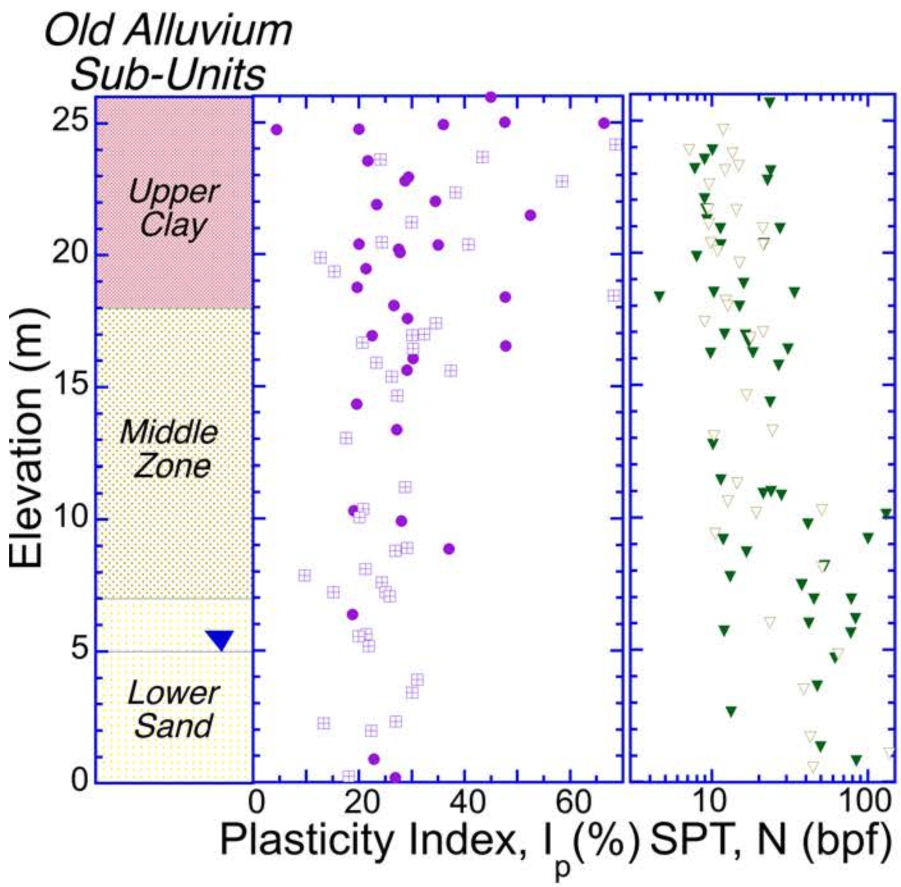
Whittle et al. (2021)

Complex Soils – Multiscale Modeling

Old Alluvium: Transported Residual Soil

[Block samples from Río Piedras, PR]





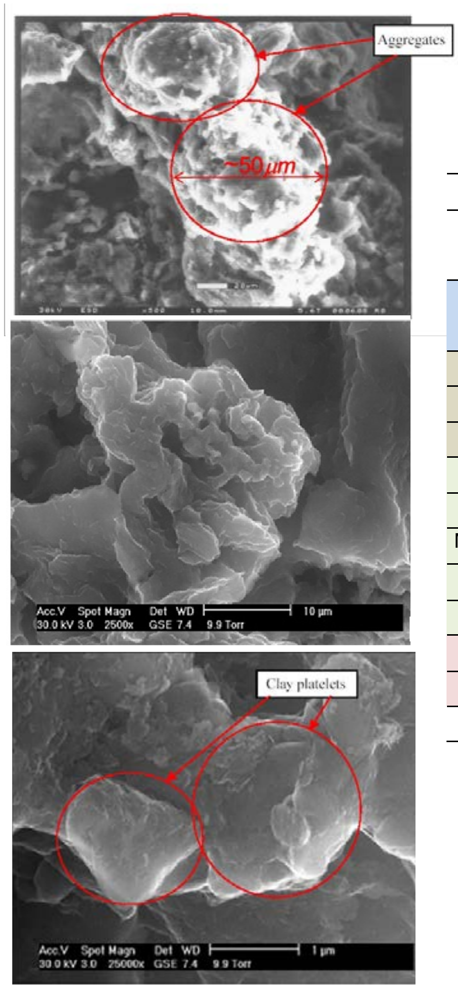
Intact Strength

Upper Clay:
c’ = 25kPa, ϕ’ = 24°

Middle Zone:
c’ = 25kPa, ϕ’ = 39°

Old Alluvium (Whittle & Bernal, 2003):
Early Pleistocene (1.0 - 1.6 Ma)

Understanding the Microstructure of Old Alluvium

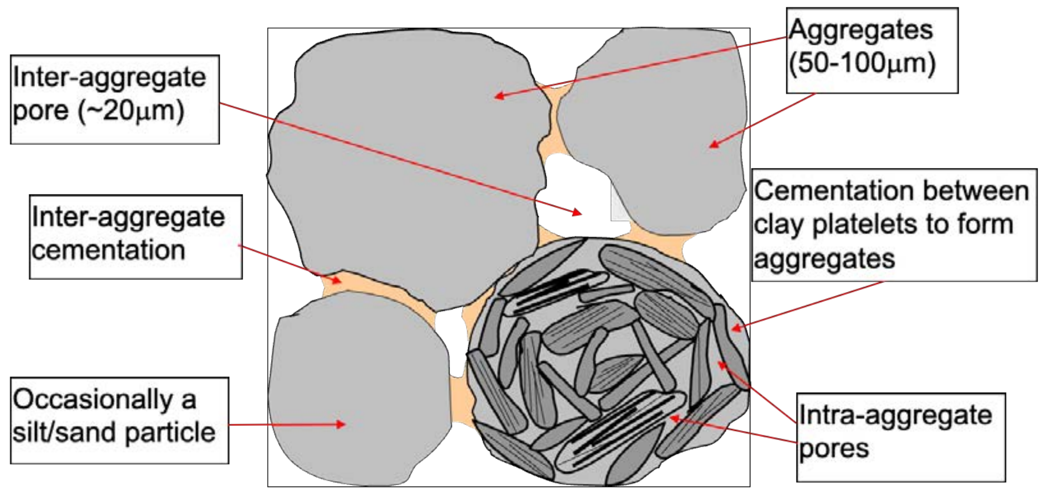


ESEM Imaging

(%wt)	Upper Clay (UC)		Middle Zone (MZ)	
Mineral	Air Dried	Oven-Dried	Air Dried	Oven Dried
Adsorbed water	12.43	0.00	8.39	0.00
Quartz	19.42	22.18	29.00	31.66
Orthoclase	8.19	9.35	15.44	16.86
Muscovite	trace	trace	trace	trace
Kaolinite	29.46	33.64	21.01	22.93
Nontronite	17.65	20.16	11.98	13.08
Montmorillonite	0.00	0.00	2.05	2.24
Illite	0.00	0.00	2.75	3.00
Pyrophyllite	0.00	0.00	2.75	3.00
Goethite	5.11	5.83	2.39	2.61
Hematite	2.76	3.15	0.00	0.00
Total	95.02	94.31	95.76	95.38

Quantitative Mineralogy
QXRD, TGA, CEC
Selective chem. dissolution

Representative Elemental Volume (REV)

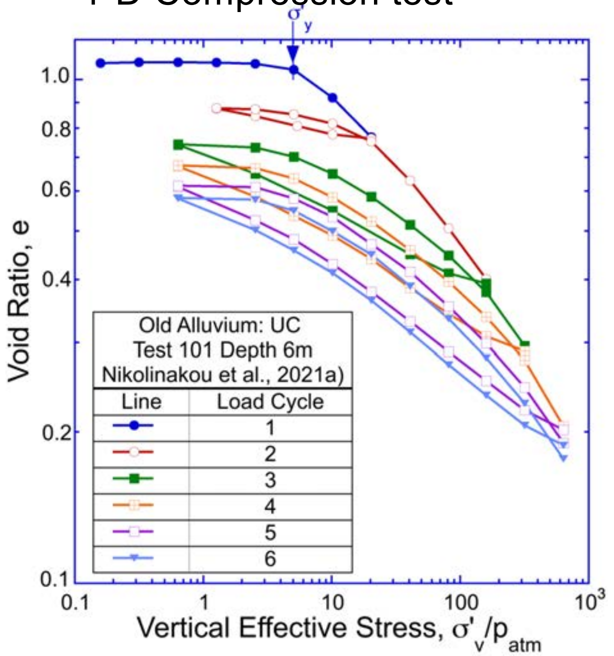


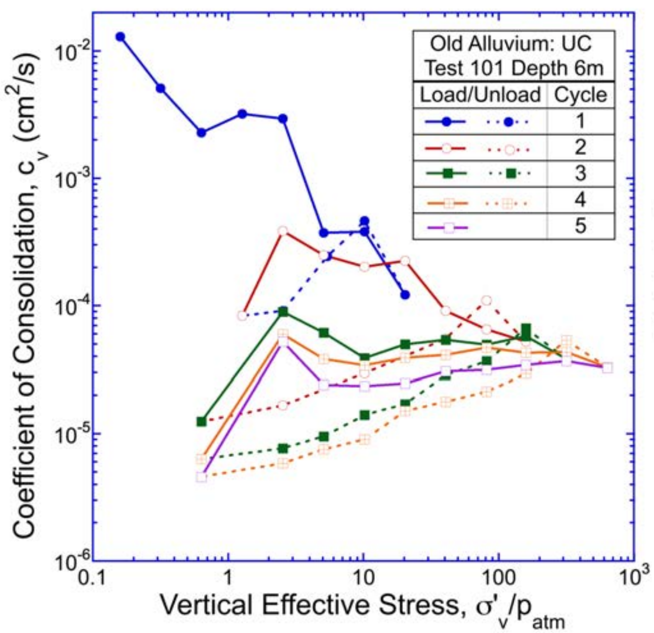
Clay platelets are coated and connected by Fe-oxides
Aggregates are connected by Fe-oxide cementation
Intact soil: double porosity (intra- and inter- aggregate voids)

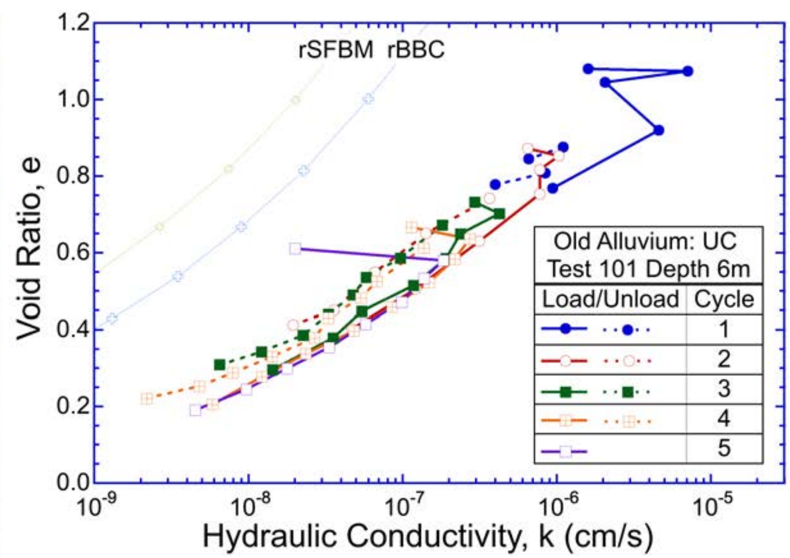
(Zhang et al., 2004)

Effect of Degradation of Microstructure on Engineering Properties of Old Alluvium

1-D Compression test



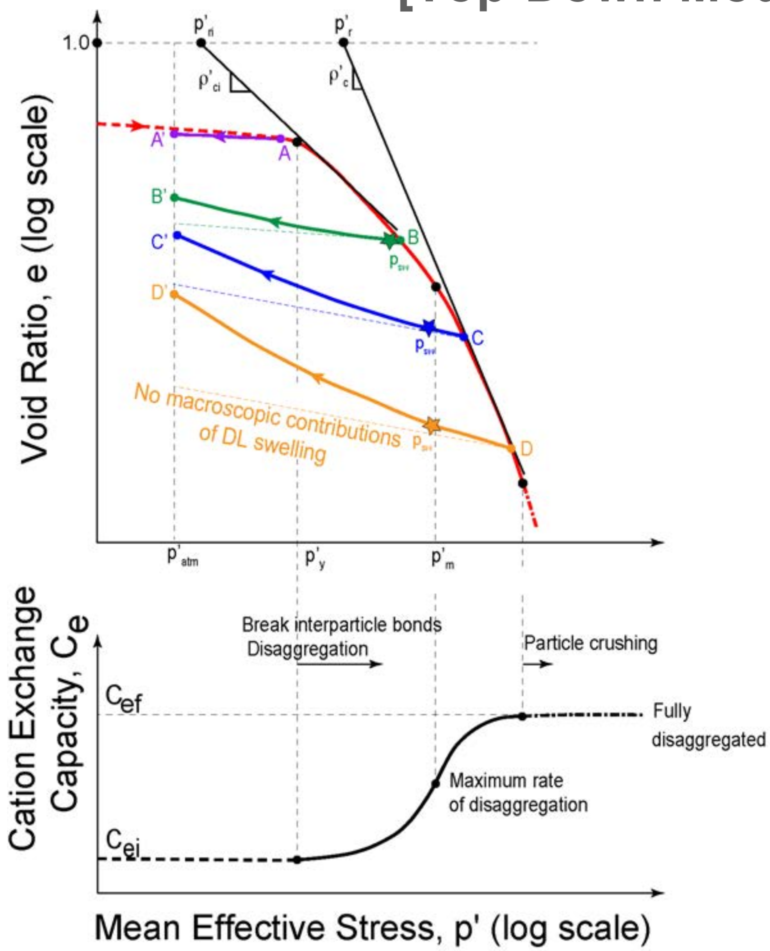




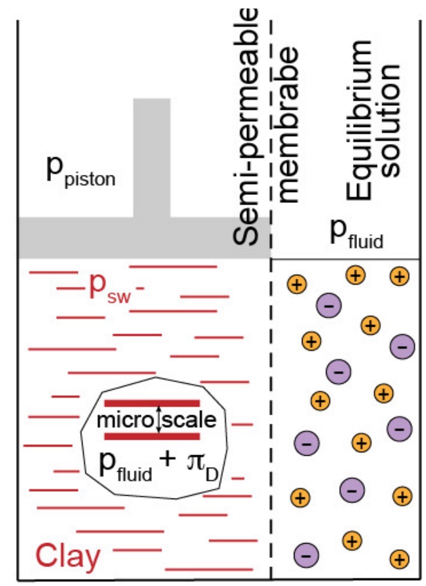
Large swelling potential released by compression above yield stress (σ'_y)
Swelling strains are initially constrained by cementation of clay aggregates
Very large reduction in c_v
Hydraulic conductivity remains much higher than typical clays

Model of Disaggregation and Swelling of Old Alluvium

[Top-Down Modelling Approach]



(Nikolinakou & Whittle, 2021)



Assumptions:

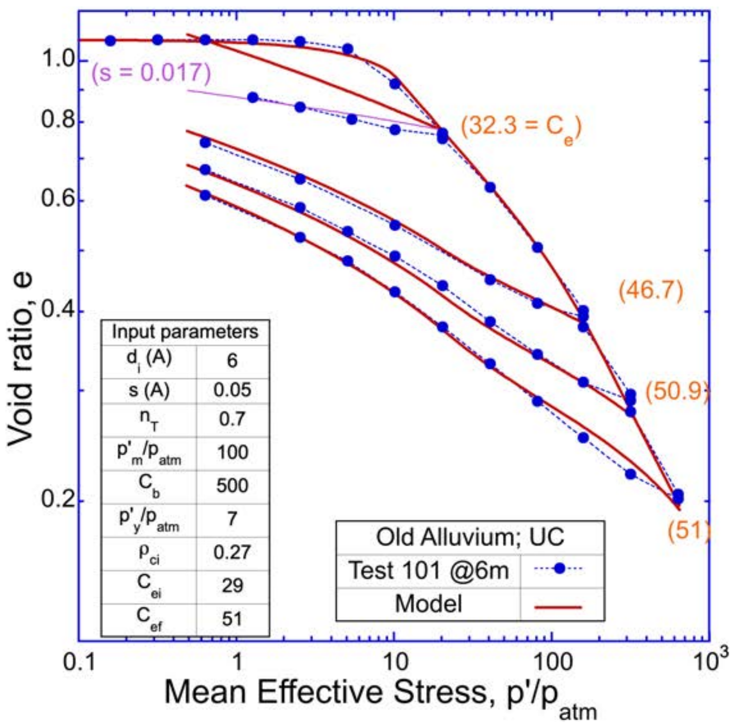
Microscale swelling:

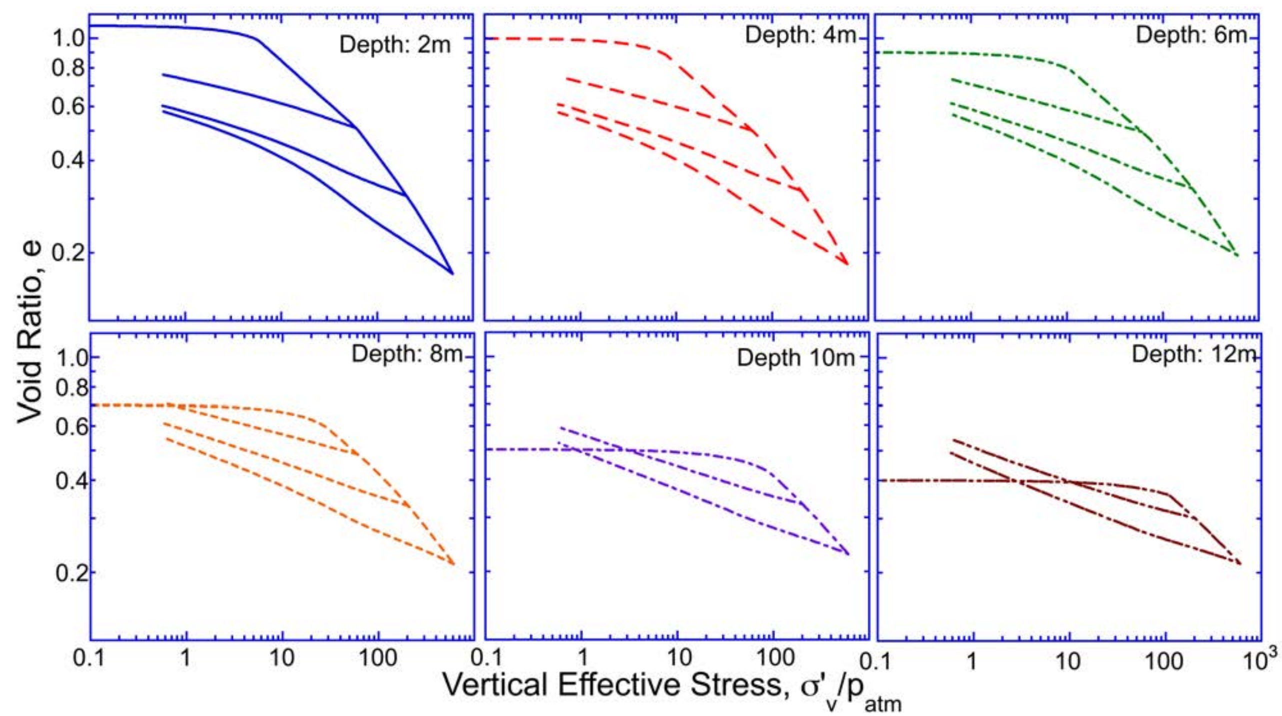
electrostatic repulsion $\pi_D[C_e]$

Macroscale: swelling pressure, p_{sw}

Micro-macro relation depends on surface area of swelling minerals exposed to pore fluid [After Alonso, 1998]

Model of 1-D Compression for Old Alluvium





Model predicts compression and swelling properties based on:

- Calibration for UC (6m) and MZ (10m)
- Interpolation of state variables (e_0, C_e)

First attempt to simulate mechanical behavior of residual soil profile

We have not quantified predicted effects of destructuration on shear yet

Summary

- **Soil Models**
  - Reflect understanding of soil behavior
  - Benefit from advances in lab testing capabilities
- **Accurate predictions are achievable**
  - Deformations & stability
  - Require good site investigation & model calibration
  - Careful validation shows credible scaling from lab to field
- **Constitutive models offer insights**
  - Solution of complex problems
  - Latent instability in hydraulic fills
  - *Set-up behavior of driven piles*
- **Insights into effective use of simplified methods**
  - Numerical Limit Analyses (NLA) for stability
  - Potential design (e.g. MSD; *SSPM*)
- **Future**
  - Multi-scale models of materials (micro-macro behavior)
  - *Upscaling methods (macro-elements for seismic SSI)*
  - *Meshless methods (large deformation problems)*

- ***Note: I plan to submit a journal paper based on this lecture (2024)***