33rd Spencer J. Buchanan Lecture

Friday, November 7, 2025at 2 PM
College Station Hilton
https://briaud.engr.tamu.edu/buchananlecture/

From Civil Engineering to Politics

The 2025 Spencer J. Buchanan Lecture

By The Honorable Andrew Card

Soil Models for Geotechnical Design, Prediction and Problem Solving

The 2024 Terzaghi Lecture

By Dr. Andrew Whittle

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SPENCER J. BUCHANAN

Spencer J. Buchanan, Sr. was born in 1904 in Yoakum, Texas. He graduated from Texas A&M University with a degree in Civil Engineering in 1926, and earned graduate and professional degrees from the Massachusetts Institute of Technology and Texas A&M University.

He held the rank of Brigadier General in the U.S. Army Reserve, (Ret.), and organized the 420th Engineer Brigade in Bryan-College Station, which was the only such unit in the Southwest when it was created. During World War II, he served the U.S. Army Corps of Engineers as an airfield engineer in both the U.S. and throughout the islands of the Pacific Combat Theater. Later, he served as a pavement consultant to the U.S. Air Force and during the Korean War he served in this capacity at numerous forward airfields in the combat zone. He held numerous military decorations including the Silver Star. He was founder and Chief of the Soil Mechanics Division of the U.S. Army Waterways Experiment Station in 1932, and also served as Chief of the Soil Mechanics Branch of the Mississippi River Commission, both being Vicksburg, Mississippi.

Professor Buchanan also founded the Soil Mechanics Division of the Department of Civil Engineering at Texas A&M University in 1946. He held the title of Distinguished Professor of Soil Mechanics and Foundation Engineering in that department. He retired from that position in 1969 and was named professor Emeritus. In 1982, he received the College of Engineering Alumni Honor Award from Texas A&M University.

He was the founder and president of Spencer J. Buchanan & Associates, Inc., Consulting Engineers, and Soil Mechanics Incorporated in Bryan, Texas. These firms were involved in numerous major international projects, including twenty-five RAF-USAF airfields in England. They also conducted Air Force funded evaluation of all U.S. Air Training Command airfields in this country. His firm also did foundation investigations for downtown expressway systems in Milwaukee, Wisconsin, St. Paul, Minnesota; Lake Charles, Louisiana; Dayton, Ohio, and on Interstate Highways across Louisiana. Mr. Buchanan did consulting work for the Exxon Corporation, Dow Chemical Company, Conoco, Monsanto, and others.

Professor Buchanan was active in the Bryan Rotary Club, Sigma Alpha Epsilon Fraternity, Tau Beta Pi, Phi Kappa Phi, Chi Epsilon, served as faculty advisor to the Student Chapter of the American Society of Civil Engineers, and was a Fellow of the Society of American Military Engineers. In 1979 he received the award for Outstanding Service from the American Society of Civil Engineers.

Professor Buchanan was a participant in every International Conference on Soil Mechanics and Foundation Engineering since 1936. He served as a general chairman of the International Research and Engineering Conferences on Expansive Clay Soils at Texas A&M University, which were held in 1965 and 1969.

Spencer J. Buchanan, Sr., was considered a world leader in geotechnical engineering, a Distinguished Texas A&M Professor, and one of the founders of the Bryan Boy's Club. He died on February 4, 1982, at the age of 78, in a Houston hospital after an illness, which lasted several months.

The Spencer J. Buchanan '26 Chair in Civil Engineering

The College of Engineering and the Department of Civil Engineering gratefully recognize the generosity of the following individuals, corporations, foundations, and organizations for their part in helping to establish the Spencer J. Buchanan '26 Professorship in Civil Engineering. Created in 1992 to honor a world leader in soil mechanics and foundation engineering, as well as a distinguished Texas A&M University professor, the Buchanan Professorship supports a wide range of enriched educational activities in civil and geotechnical engineering. In 2002, this professorship became the Spencer J. Buchanan '26 Chair in Civil Engineering.

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1993	Ralph B. Peck	"The Coming of Age of Soil Mechanics: 1920 - 1970"
1994	G. Geoffrey Meyerhof	"Evolution of Safety Factors and Geotechnical Limit State Design"
1995	James K. Mitchell	"The Role of Soil Mechanics in Environmental Geotechnics"
1996	Delwyn G. Fredlund	"The Emergence of Unsaturated Soil Mechanics"
1997	T. William Lambe	"The Selection of Soil Strength for a Stability Analysis"
1998	John B. Burland	"The Enigma of the Leaning Tower of Pisa"
1999	J. Michael Duncan	"Factors of Safety and Reliability in Geotechnical Engineering"
2000	Harry G. Poulos	"Foundation Settlement Analysis – Practice Versus Research"
2001	Robert D. Holtz	"Geosynthetics for Soil Reinforcement"
2002	Arnold Aronowitz	"World Trade Center: Construction, Destruction, and Reconstruction"
2003	Eduardo Alonso	"Exploring the Limits of Unsaturated Soil Mechanics: the Behavior of Coarse Granular Soils and Rockfill"
2004	Raymond J. Krizek	"Slurries in Geotechnical Engineering"
2005	Tom D. O'Rourke	"Soil-Structure Interaction Under Extreme Loading Conditions"
2006	Cylde N. Baker	"In Situ Testing, Soil-Structure Interaction, and Cost Effective Foundation Design"
2007	Ricardo Dobry	"Pile response to Liquefaction and Lateral Spreading: Field Observations and Current Research"
2008	Kenneth Stokoe	"The Increasing Role of Seismic Measurements in Geotechnical Engineering"
2009	Jose M. Roesset	"Some Applications of Soil Dynamics"
2010	Kenji Ishihara	"Forensic Diagnosis for Site-Specific Ground Conditions in Deep Excavations of Subway Constructions"
2011	Rudolph Bonaparte	"Cold War Legacy – Design, Construction, and Performance of a Land-Based Radioactive Waste Disposal Facility"
2012	W. Allen Marr	"Active Risk Management in Geotechnical Engineering"
2013	Andrew J. Whittle	" Importance of Undrained Behavior in the Analysis of Soil-Structure Interaction"
2014	Craig H. Benson	"Landfill Covers: Water Balance, Unsaturated Soils, and a Pathway from Theory to Practice"
2015	William F. Marcuson III	"Katrina in Your Rearview Mirror"
2016	Edward Kavazanjian	"Bio-Geo-Alchemy: Biotechnological Carbonate Precipitation for Hazard Mitigation and Ground Improvement."
2017	Jonathan D. Bray	"Turning Disaster into Knowledge"
2018	Paul W. Mayne	"Versatility of Cone Penetration Tests in GeoCharacterization"
2019	Gregory B. Baecher	"Putting Numbers on Geotechnical Judgment""
2020	Lidija Zdravkovic	"Soil Characterisation for advanced Geotechnical design: Parameter Derivation"

The texts of the lectures and a DVD's of the presentations are available by contacting:

Dr. Jean-Louis Briaud
Spencer J. Buchanan '26 Chair Distinguished Professor
Zachry Department of Civil Engineering
Texas A&M University
College Station, TX 77843-3136, USA
Tel: 979-845-3795
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2021	Philippe Jeanjean	"Offshore Geotechnics: From oil and Gas to Renewable Energy"
2022	Mark W. Buchanan	"Risk Mitigation in the Changing Relationship between Contractors and Engineers"
2023	Marc Ballouz	"Geotechnical Engineering Marriage Between Theory and Practice"
2024	Adda Athanasopoulos-Zekkos	"From Miles to Inches: Big Data Frameworks for Levee Health Assessment
2025	Andrew H. Card Jr.	“From Civil Engineering to Politics.”

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AGENDA

The Thirty-Third Spencer J.
Buchanan Lecture Friday, November
7, 2025 Hilton Hotel and Conference
Center College Station, TX

2:00 p.m.	Introduction by Dr. Jean-Louis Briaud
2:10 p.m.	Introduction of Dr. Andrew Whittle by Jean-Louis Briaud
2:15 p.m.	"Soil Models for Geotechnical Design, Prediction and Problem Solving." 2024 Terzaghi Lecture by Dr. Andrew Whittle
3:30 p.m.	Introduction of The Honorable Andrew Card by Jean-Louis Briaud
3:35 p.m.	"From Civil Engineering to Politics." 2024 Buchanan Lecture by the Honorable Andrew Card
4:30 p.m.	Closure with Jean-Louis Briaud
5 p.m.	Reception at the Briaud Residence: 3013 Coronado Dr. College Station, TX 77845

Biographies

Andrew J. Whittle

Andrew J. Whittle is the Edmund K. Turner Professor of Civil and Environmental Engineering at MIT. He is an expert in geotechnical engineering, whose research deals principally with formulation of constitutive models for representing the complex mechanical properties of soils. His research has been widely used in the design of foundation systems for deepwater oil production facilities and in major urban excavation and tunneling projects. He has led research efforts in a variety of environmental sensing applications including wireless sensor networks for city-scale monitoring of water distribution systems. Whittle is a licensed professional engineer (PE and P.Eng.) and an active consultant who has worked on more than 30 major onshore and offshore construction projects. He was an expert involved in the investigations into the collapse of the Nicoll Highway in Singapore and has also served on review panels for hurricane protection systems in New Orleans (NRC), 'stem-to-stern' safety of the Big Dig tunnels (Boston), causes of construction delays for the XRL project (Hong Kong), and the CVN Technical Review Panel for the MoSE Flood Defense System (Venice). He also served as a member of the Board of Directors for the Massachusetts Department of Transportation (2009-2015). Whittle earned his BSc. in Civil Engineering from Imperial College, London (1981), his ScD from MIT (1987) and has been a faculty member at MIT faculty for more than 37 years. He has co-authored more than 270 papers, has received numerous awards for his research including the prestigious ASCE Terzaghi Lecture (2024) and was elected to the National Academy of Engineering in 2010.

Andrew H. Card, Jr.

Andrew H. Card, Jr., "Andy Card" served as the Chief Executive Officer of The George & Barbara Bush Foundation from November 2023 to March 2025. Secretary Card assumed the interim role as the Foundation prepared for its centennial celebration, 41 at 100: A Celebration of George H.W. Bush, which commemorated President Bush's 100th birthday.

Mr. Card previously served as Chairman of the National Endowment for Democracy in Washington, D.C. from January 2018 until January 2021. From June 2020 until December 2020, he also served as the Interim Chief Executive Officer of the George & Barbara Bush Foundation. In August 2016, Card retired as President of Franklin Pierce University with its anchor campus in Rindge, NH and other campuses in Lebanon, Manchester and Portsmouth, NH, and Goodyear AZ. Prior to that appointment, Mr. Card served as Executive Director of the Office of the Provost and Vice President for Academic Affairs at Texas A&M University from August 2013 until December 2015. He served as Acting Dean of The Bush School of Government and Public Service at Texas A&M from July 5, 2011, until Dean Ryan Crocker's return from service as the U.S. Ambassador to Afghanistan on August 1, 2013. The Bush School was founded by President George H. W. Bush and is located near the George Bush Presidential Library and Museum Center on the west campus of Texas A&M University in College Station, Texas.

Mr. Card, the second longest tenured White House Chief of Staff, has served in senior government roles under three U.S. Presidents. Mr. Card served on the Board of Directors of public corporation Union Pacific, on the Board of Directors of Hyliion, on the Board of Directors of Draganfly, Inc., the Aurora Tech Industry Advisory Council, on the Board of Lorillard until it was purchased by RIA in 2015, and on a number of other non-profit boards. He also was on the Edward M. Kennedy Institute Board, the Business Advisory Board of BrainStorm Cell Therapeutics, the Global Advisory Board of Alexander Proudfoot, and the Advisory Board of the U.S. Chamber of Commerce. He is also a professional speaker represented by the Washington Speakers Bureau (WSB).

Mr. Card, appointed in November 2000, served as Chief of Staff to President George W. Bush from January 2001 to April 2006. In this capacity, he coordinated the priorities of the Administration's agenda, the development of policies, and appointments of Cabinet Secretaries and senior officials throughout the government. On September 11, 2001, Card is the one who whispered in President Bush's ear while the President was sitting in a classroom in Florida, that terrorists had attacked the United States. Card then led a government-wide reorganization to best allocate resources to deal with the aftermath of 9-11 and the new terrorist environment.

Prior to his tenure as White House Chief of Staff, Card managed and ran the Republican National Convention in Philadelphia at the request of nominee Texas Governor George W. Bush. Before that, Card was Vice President-Government Relations for General Motors Corporation, one of the world's largest automobile manufacturers. In this role Card directed the company's international, national, state and local government affairs activities and represented GM on matters of public policy before the U.S. Congress and the Administration. From 1993 to 1998, Card was President and Chief Executive Officer of the American Automobile Manufacturers Association, the trade association whose members were Chrysler Corporation, Ford Motor Company, and General Motors Corporation. When Chrysler became part of Daimler Corporation, Card oversaw the dissolution of the nearly 100 year old trade association.

Mr. Card served as Deputy Chief of Staff and then as a Cabinet Member for President George H.W. Bush as the 11th Secretary of Transportation from 1992 to 1993. In this role, in August 1992, at the request of President Bush, Secretary Card coordinated the Administration's disaster relief efforts in the wake of the massive Hurricane Andrew. He also directed President Bush's transition office during the transition from the Bush Administration to the Clinton Administration. Prior to that he served as Special Assistant (1983 to 1987) and later as Deputy Assistant to the President and Director of Intergovernmental Affairs for President Ronald Reagan (1988) where he was liaison to governors, statewide elected officials, state legislators, mayors and other elected officials. From March 1987 until March 1988, Card ran the successful New Hampshire Presidential Primary Campaign for George H. W. Bush.

He is a graduate of the University of South Carolina with a B.S. in Engineering. He also attended the U.S. Merchant Marine Academy and the John F. Kennedy School of Government at Harvard University. Card served in the U.S. Navy from 1965 to 1967.

Card has been the recipient of many honorary degrees and awards.

Card is a native of Holbrook, Massachusetts and got his start in politics as an elected official in Holbrook and then as Member of the Massachusetts House of Representatives from 1975-1983. He served as a Minority Whip from 1977-1983. In 1982 he was named Legislator of the Year by the National Republican Legislators Association and received the Distinguished Legislator Award from the Massachusetts Municipal Association. He was a candidate for the Republican Nomination for Governor of Massachusetts in 1982.

He and his wife, The Reverend Kathleene (Bryan) Card, also from Holbrook, Massachusetts, have three children and six grandchildren.

"Soil Models for Geotechnical Design, Prediction and Problem Solving."

The 2025 Terzaghi Lecture By
Dr.Andrew J. Whittle.

Geo-Congress 2024

Vancouver, Canada | February 25–28, 2024

2024

Soil Models for Geotechnical Design, Prediction and Problem Solving

Andrew J. Whittle

Massachusetts Institute of Technology

60th Karl Terzaghi Lecture

Geo-Congress, Vancouver

February 2024

1

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

"For the Author, theoretical soil mechanics never was an end in itself. Most of his efforts have been devoted to the digest of field experience and to the development of the technique of the application of the physical properties of soils to practical problems"

Karl Terzaghi
Preface to 'Theoretical Soil Mechanics', 1943

2

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
  - Pile set-up
- **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
  - Seismic SSI: Role of upscaling using macro-elements

3

Soil Behavior & Generalized Soil Models

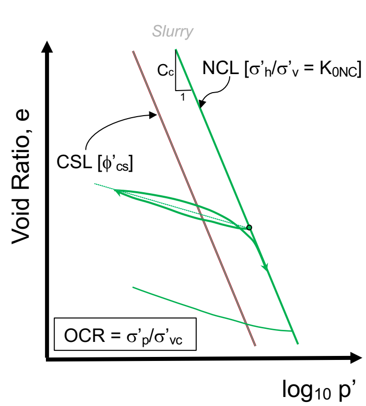
4

- **Slide 1 drained, dense vs MC and HS triaxial**

5

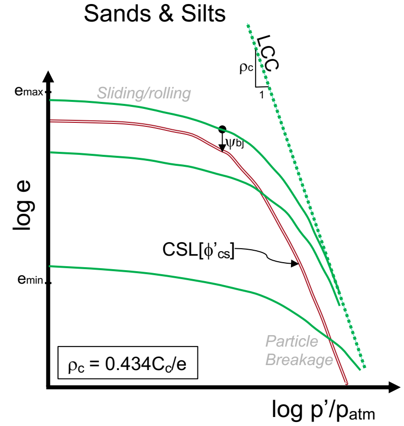
One-Dimensional Consolidation & Three Soil Models

Clays



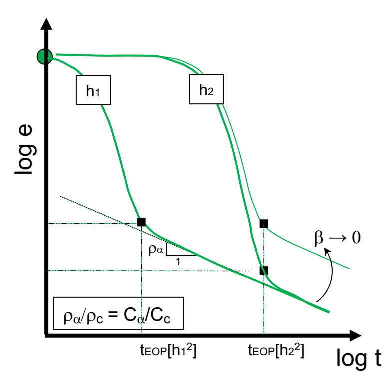
MIT-E3 (1987):
Elasto-plastic
Anisotropy associated with NCL
Load reversal: Elastic behavior
Reload: Bounding surface plasticity

Sands & Silts



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

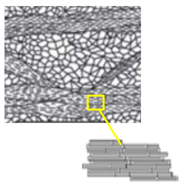
Time scaling (clays+?)



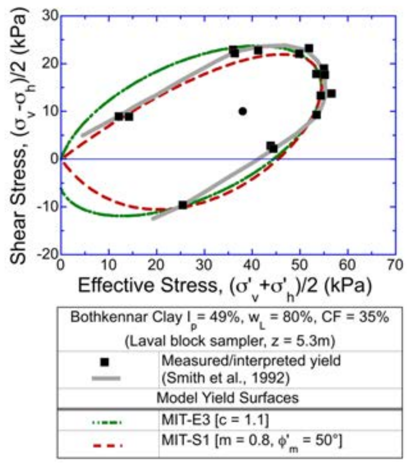
MIT-SR (2016):
Elasto-viscoplastic
Internal strain history state, R_a
Steady state, β
At EOP: NCL unique for $\beta = 0$

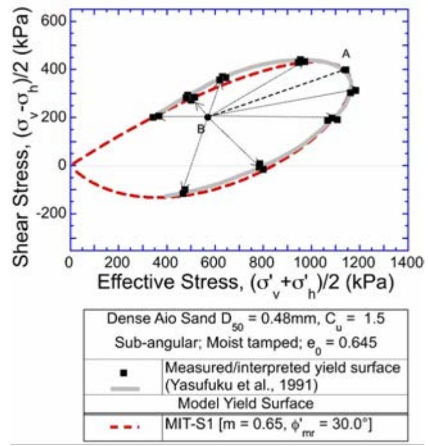
6

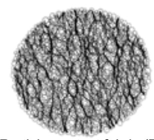
Initial Yield Surfaces of Soils



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







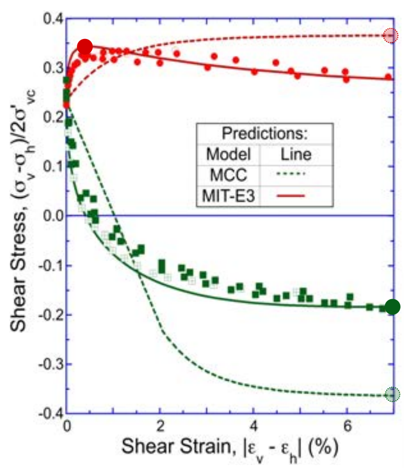
Particle contact fabric (DEM)
(Thornton & Barnes, 1986)

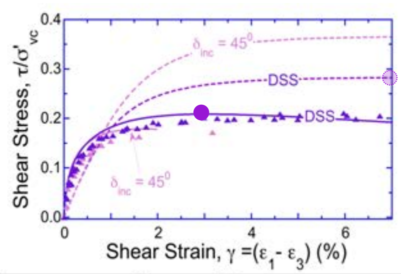
Measured data described by elasto-plastic model with single yield function
Inherent anisotropy linked to prior consolidation history
Rotation of yield surface linked to particle fabric

7

Model Validation: Undrained Plane Strain Shear Tests

[Resedimented BBC, OCR = 1]





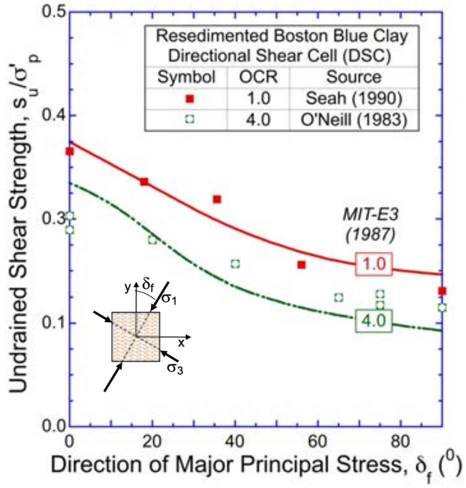
Measured Data:

Symbol	δ_{inc}(°)	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)

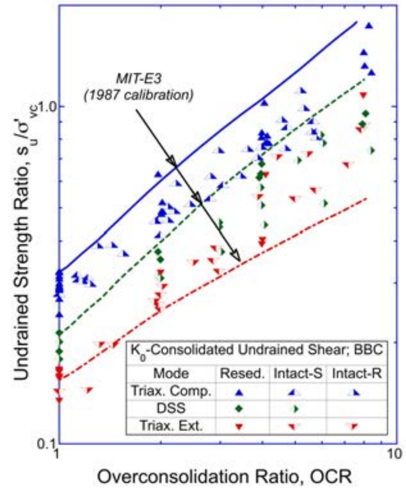
MCC: limitation of isotropic model with unique s_u at critical state
MIT-E3: capability to predict anisotropic stress-strain-strength properties of NC clay

8

Evaluation of Undrained Strength Anisotropy for BBC



Effects of Shear Direction
OCR = 1 vs OCR =4



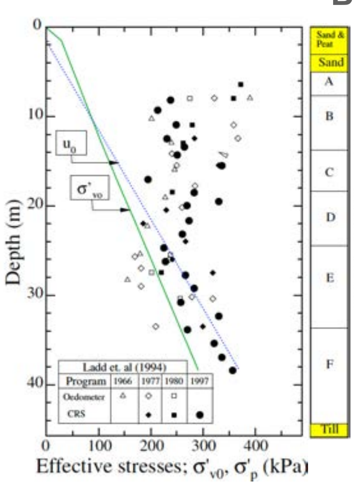
Intact & Resedimented BBC (1992 – 2016)
Model **accuracy reduces** for OCR > 3 - 4

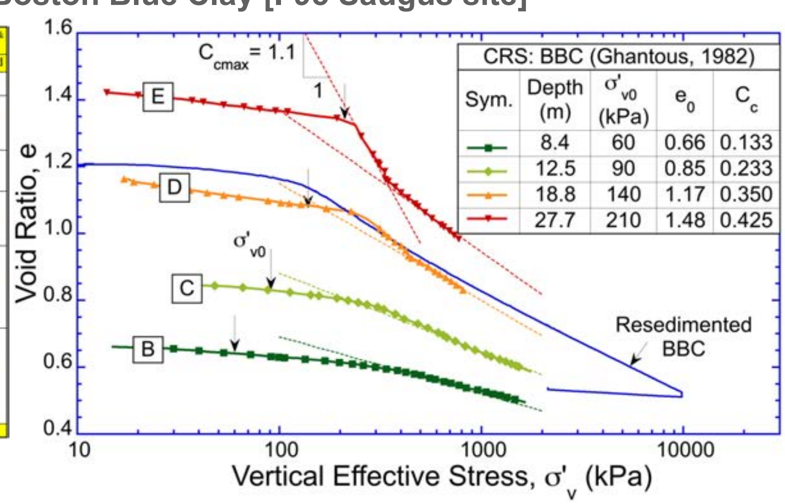
Accept limitations: No edits to model formulation; No adjustments to input parameters

9

1-D Compression Properties of Natural Clay

Boston Blue Clay [I-95 Saugus site]

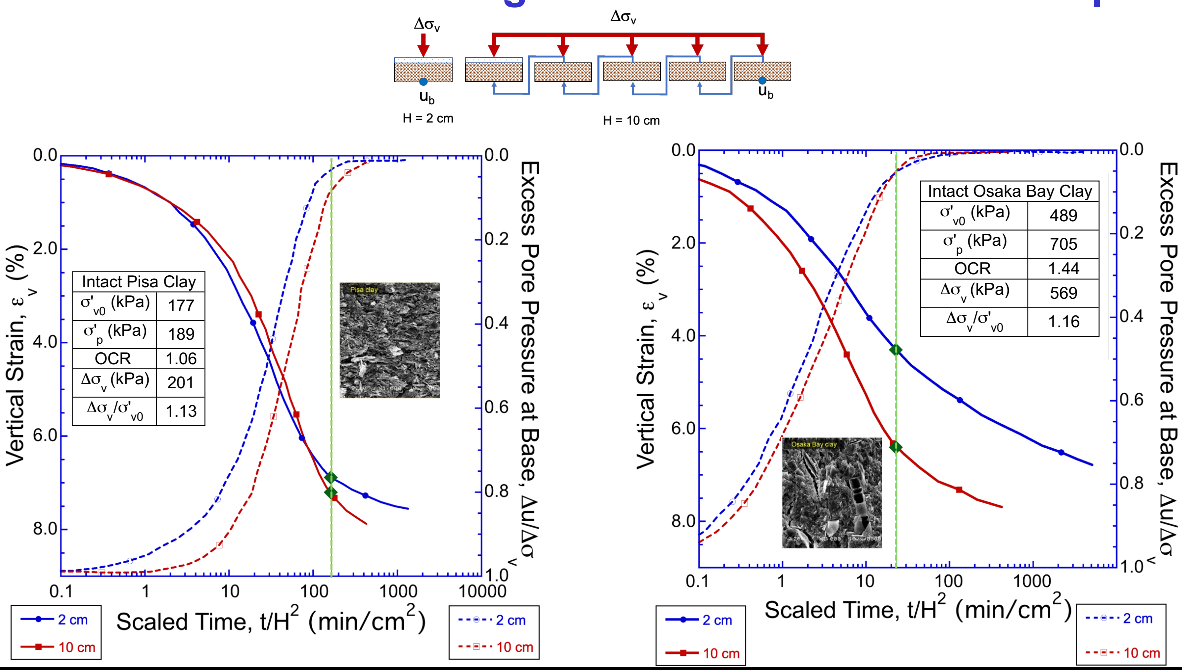




Behavior reflects complex Holocene geology of Boston area
Little physical evidence to explain differences in sub-layer properties
Sub-layers: Selection of compression index (C_c) will reflect stress range of interest

10

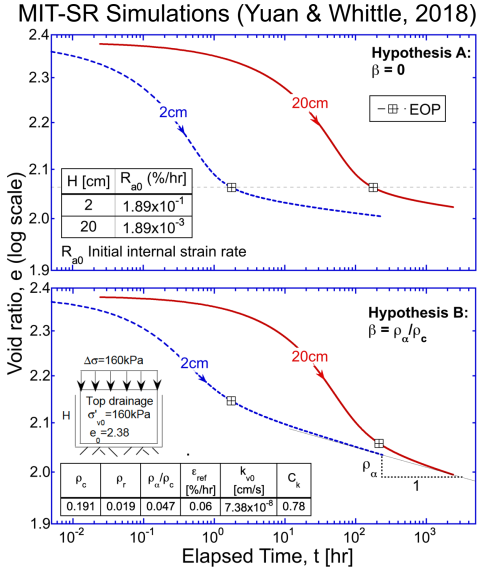
Measured Data: Long-Term Consolidation & Creep



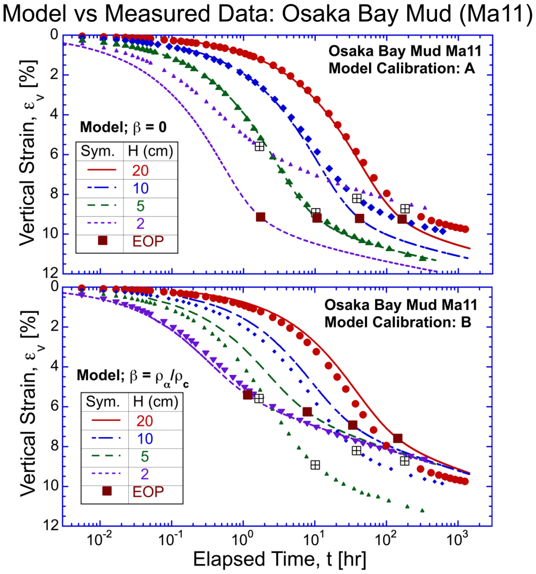
11

Scale Effects: Primary & Secondary Compression

MIT-SR Simulations (Yuan & Whittle, 2018)



Model vs Measured Data: Osaka Bay Mud (Ma11)

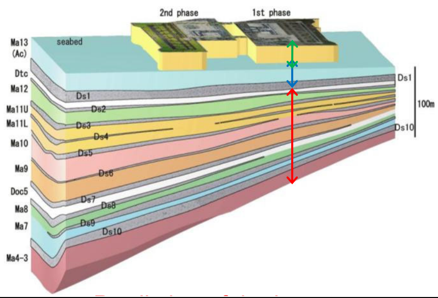


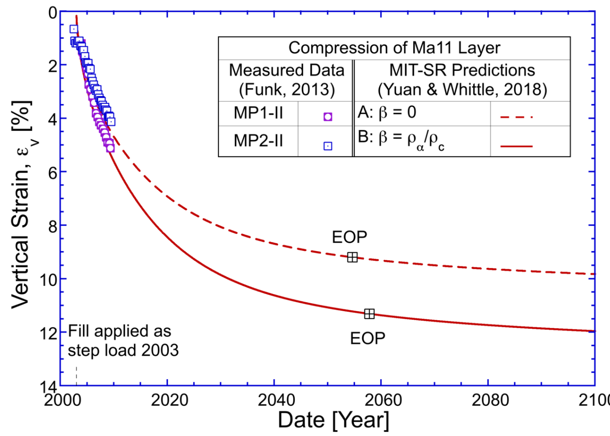
Unique capability of MIT-SR model:
Can simulate both Hypothesis A & B

Inconsistent results
Two calibrations: MIT-SR bounds the data

12

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)

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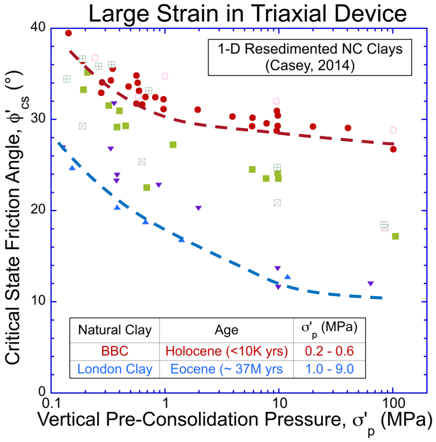
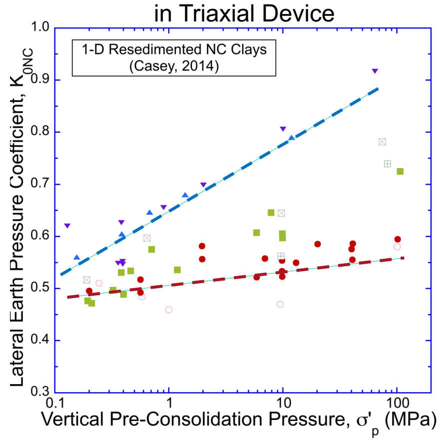
Surprising Clay Behavior at High Consolidation Stress

Measured for Shearing to Large Strain in Triaxial Device



Measured during 1-Consolidation in Triaxial Device



Resedimented clays

Clay	Sym.	w_L (%)	I_p (%)
Presumpscot (ME)	○	33.1	13.7
Boston Blue Clay	●	46.5	22.7
Ursa Clay (GOM)	⊠	51.7	28.0
Ugnu Clay (Alaska)	■	56.4	30.0
SF Bay Mud	⊞	60.2	28.6
London Clay (UK)	▲	73.8	48.4
Eugene Isle. (GOM)	▼	85.8	62.9

Highlights limitations in current soil models which assume ϕ'_{cs} and K_{0NC} are constant!

Practical significance: Resedimented vs intact behavior

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Applications for Clays

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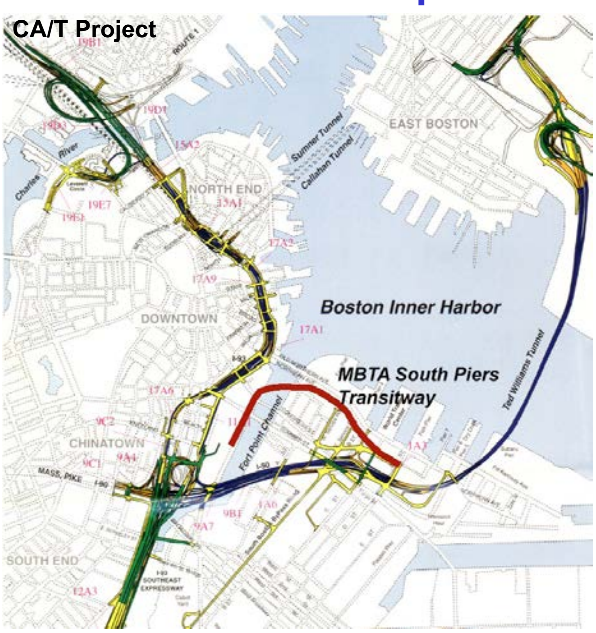
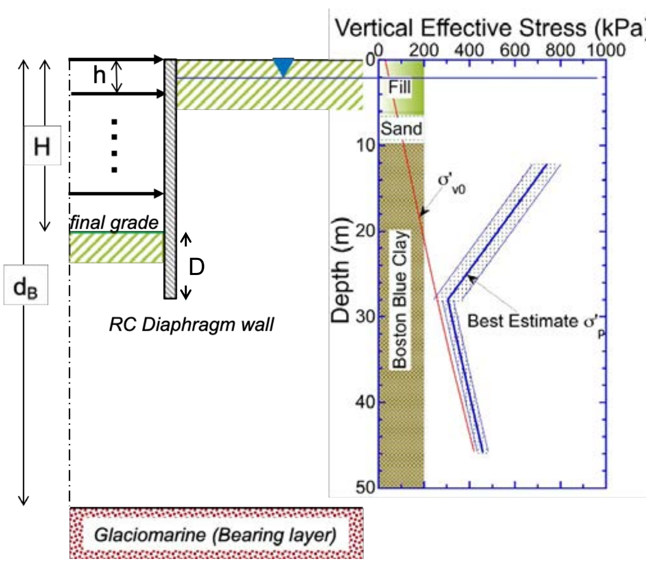
Deep Excavations in Boston





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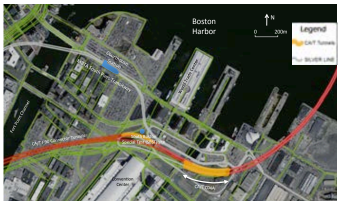
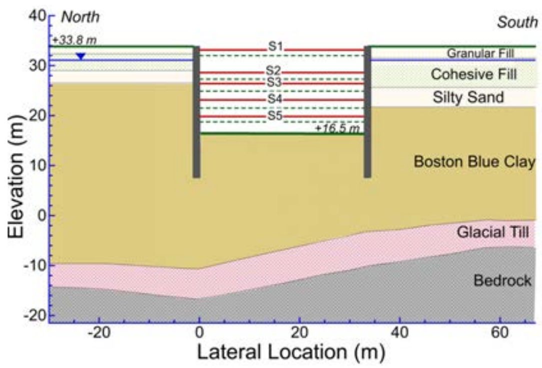
Courthouse Station Project





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

[Whittle et al., 2015]

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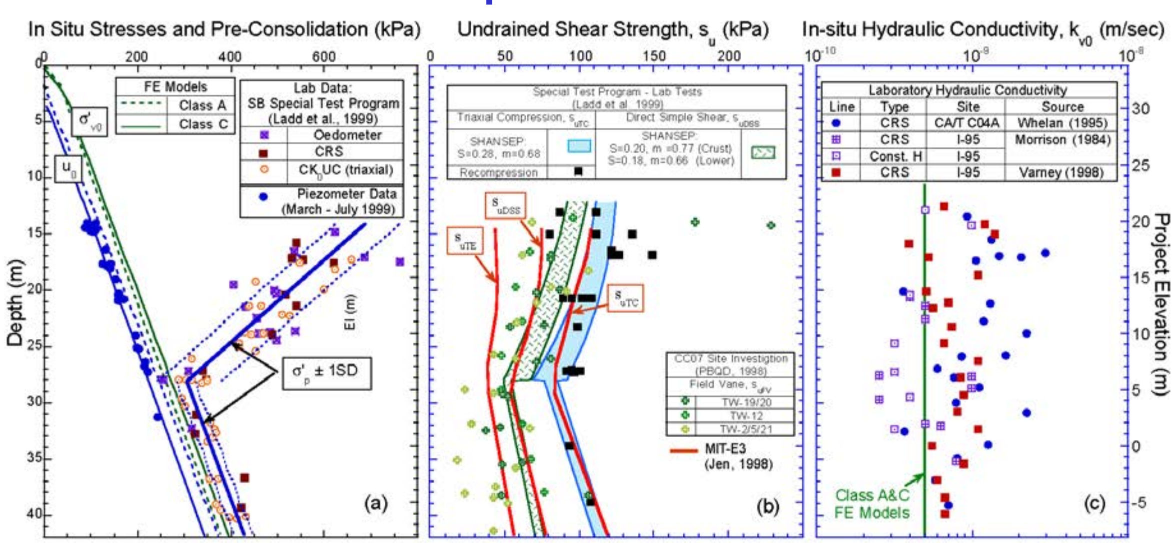
In Situ Properties: South Boston



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]

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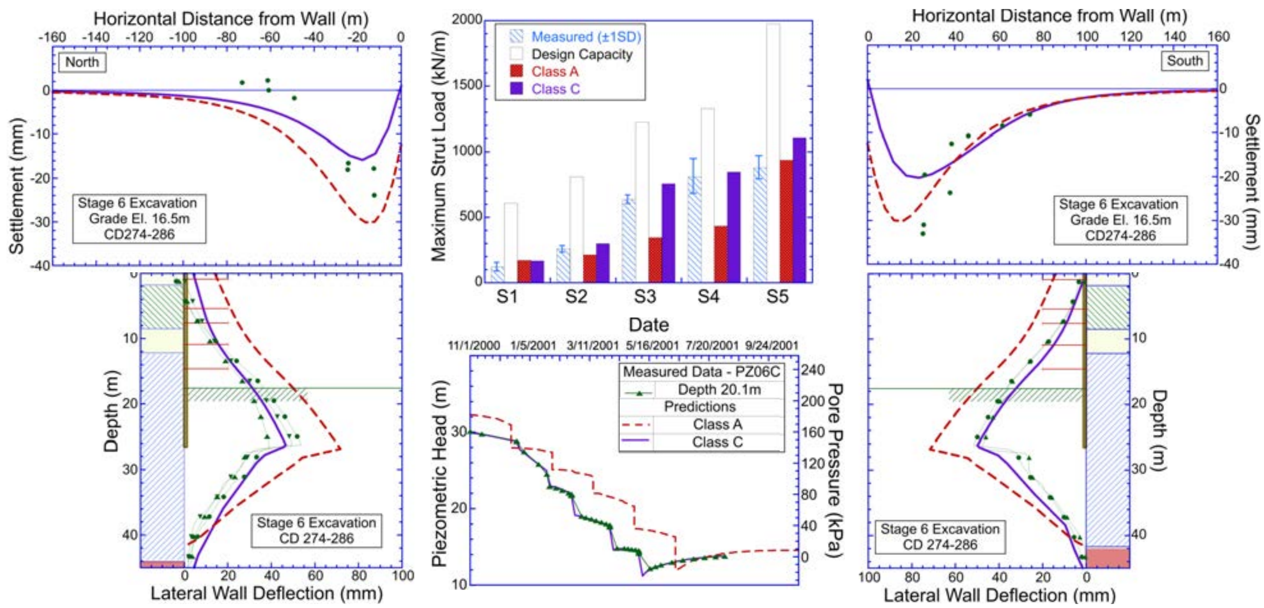
Performance of Excavation Support Systems

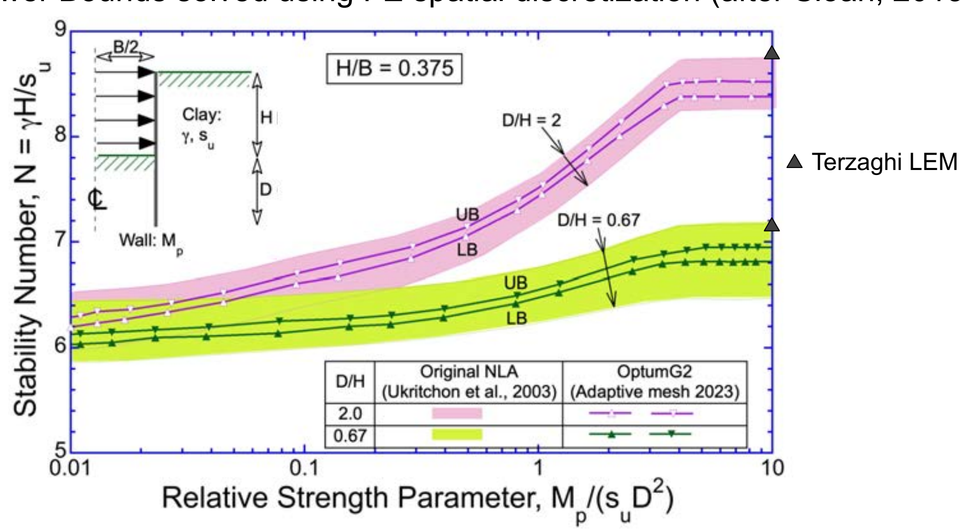
Class A vs Class C Predictions: Courthouse Station



[Whittle et al., 2015]

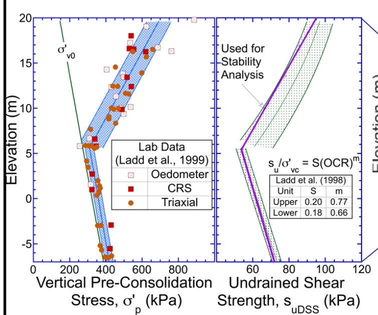
Stability Using Numerical Limit Analyses (NLA)

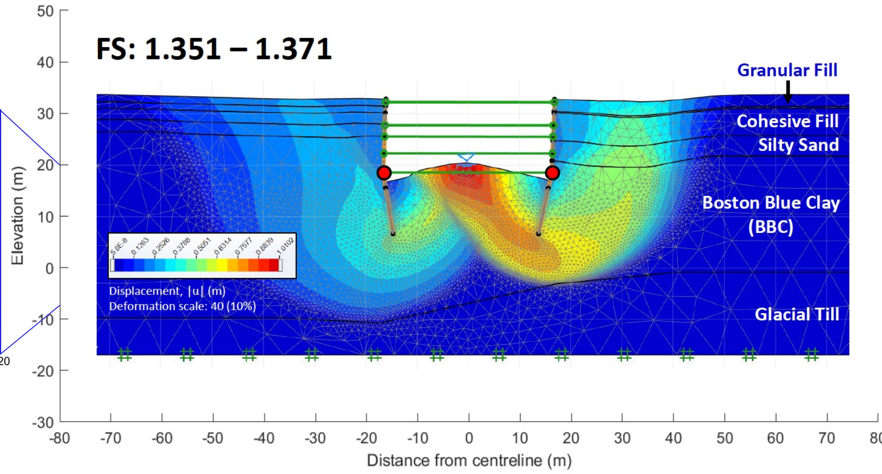
Upper & Lower Bounds solved using FE spatial discretization (after Sloan, 2013)



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

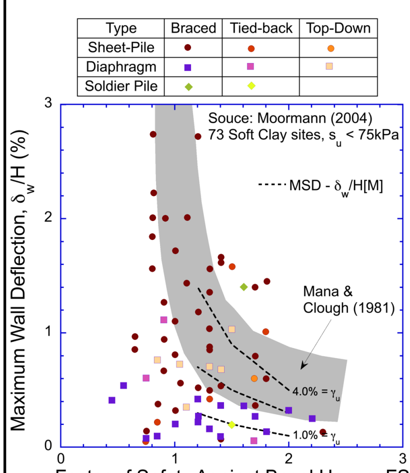




Upper Bound Failure Mechanism
Rigid plastic soil behavior
FS solved by strength reduction

[John, pers. comm., 2024]

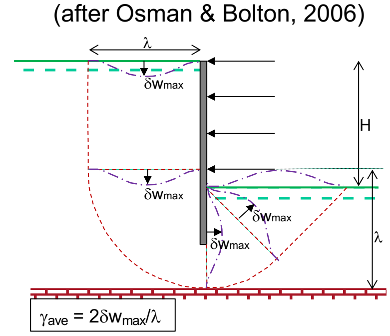
Wall Deflection and Control of Construction



Mobilization Factor, $M = s_u/\tau$

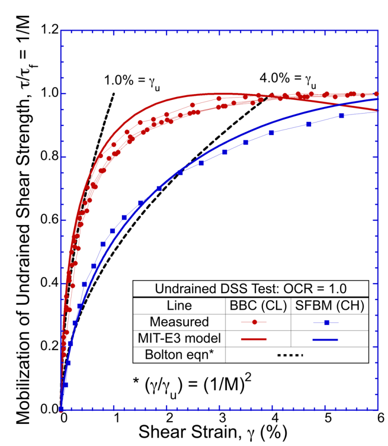
Empirical data exhibit large scatter
LEM – not accurate for FS

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



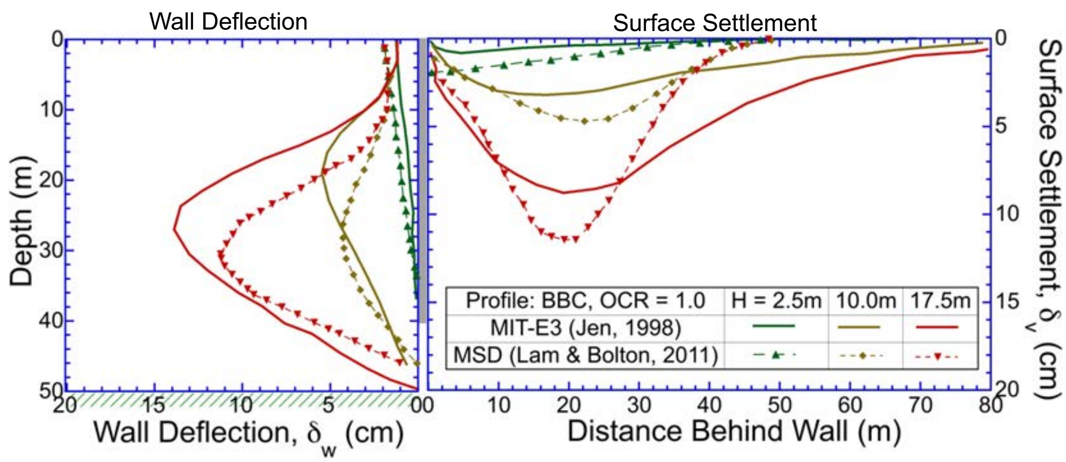
$\gamma_{ave} = 2\delta w_{max}/\lambda$

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

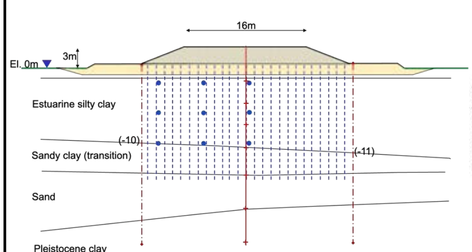


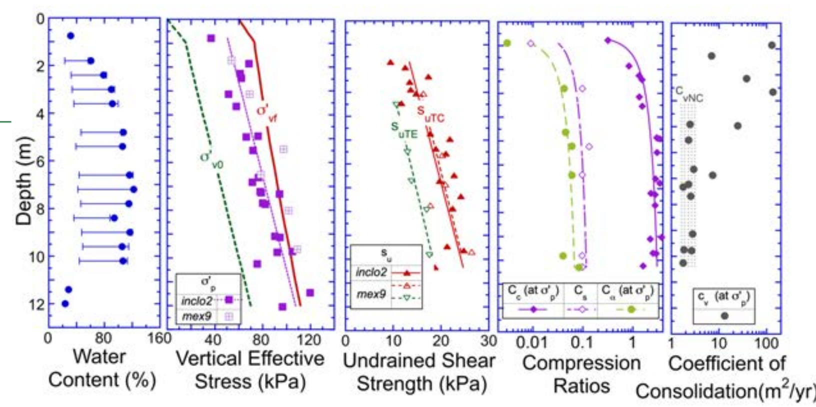
MSD: Computed incrementally using M from MIT-E3 (DSS shear mode)

- 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

Ballina Test Embankment





Class A predictions

Practitioners, students & academics

Many analyses performed with similar soil models (& FE software)

Two groups selected:

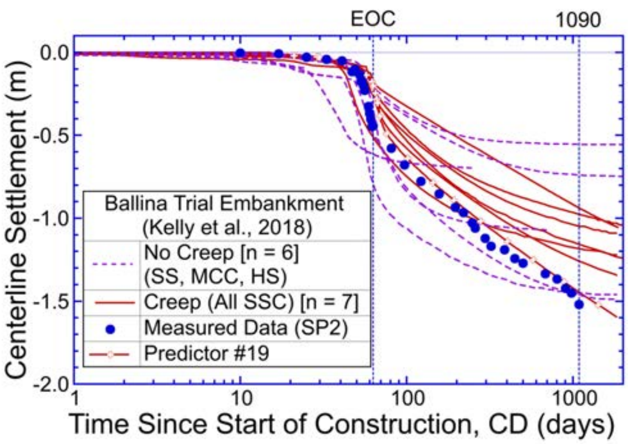
No Creep: All based on conventional compression (C_c, C_s)

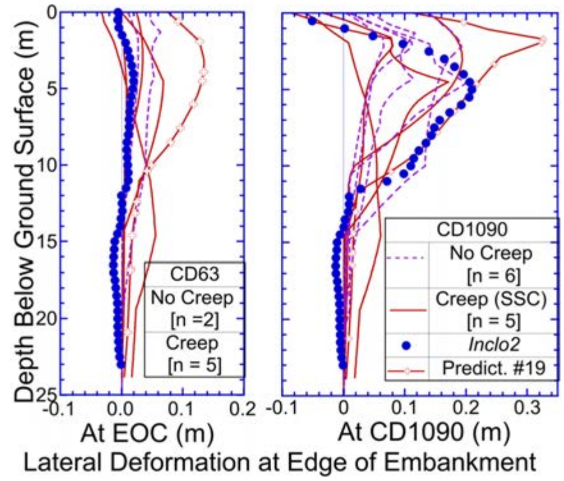
Creep: All use same isochrone model (Soft Soil Creep: Hyp. B)

None of these analyses consider anisotropy

After Kelly et al. (2018)

Ballina: Model Predictions vs Measurements





Settlements:
Large scatter in magnitude
Most suggest primary compression completed in 1yr
Creep constitutes major component of deformations
#19 highlighted

Pervasive discrepancy in lateral spreading:
Overestimated at End of Construction
Underestimated in 3yrs of consolidation
Confirms role of anisotropy from Ladd et al. (1994)

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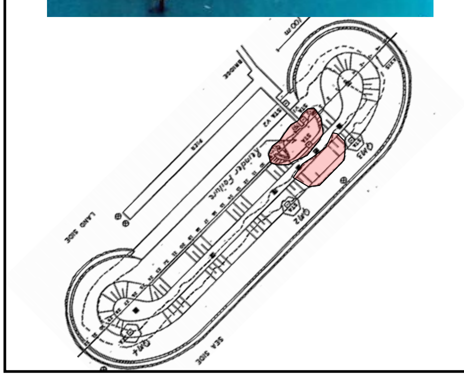
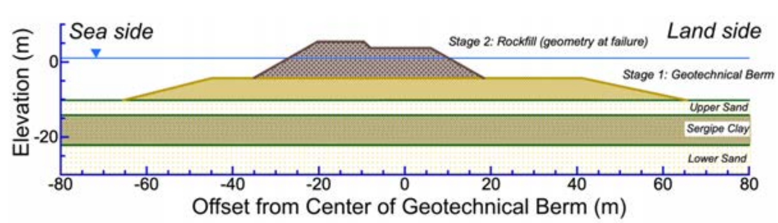
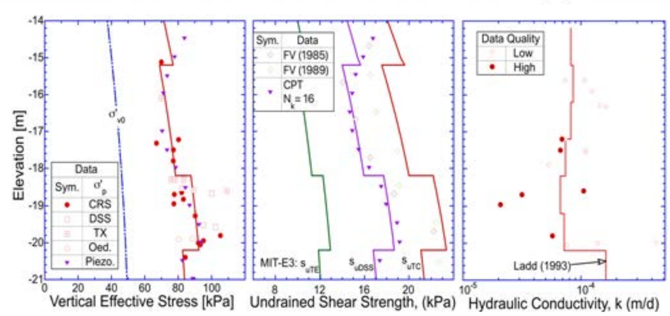
Failure of Offshore Rockfill Breakwater, Sergipe







Forensic study: Ladd & Lee (1993)
Included lab tests, calibration of MCC & MIT-E3 models

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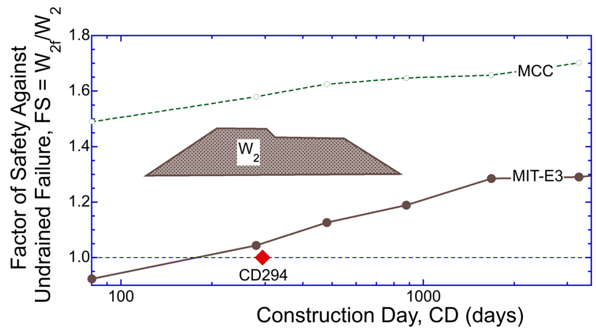
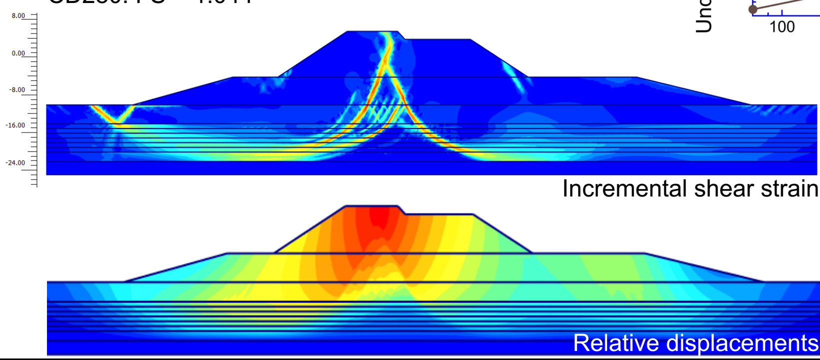
Undrained Stability Analyses

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



CD280: FS = 1.044



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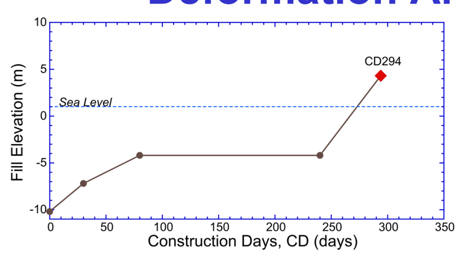
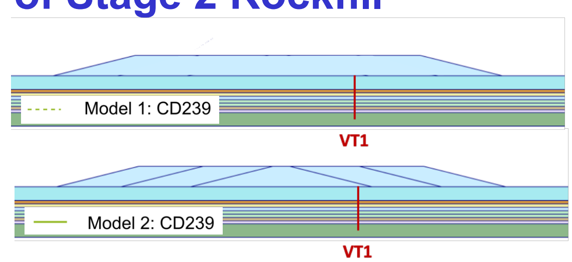
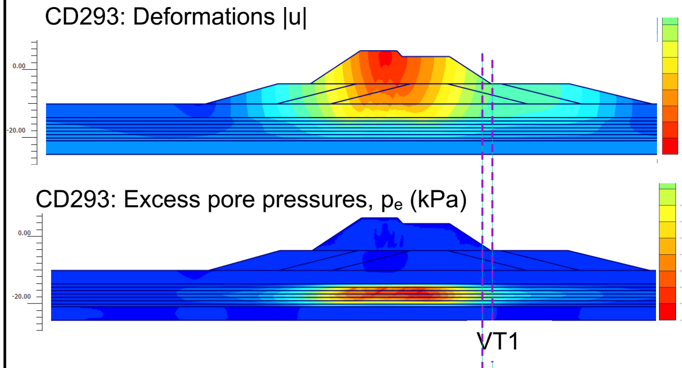
Deformation Analyses of Stage 2 Rockfill

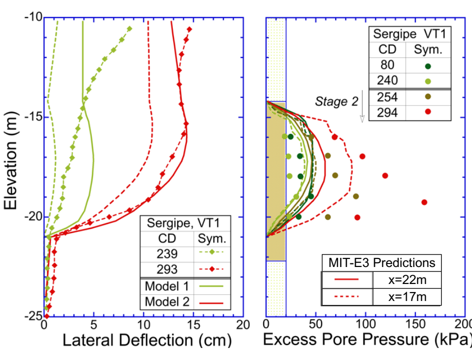




CD293: Deformations |u|

CD293: Excess pore pressures, p_e (kPa)





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

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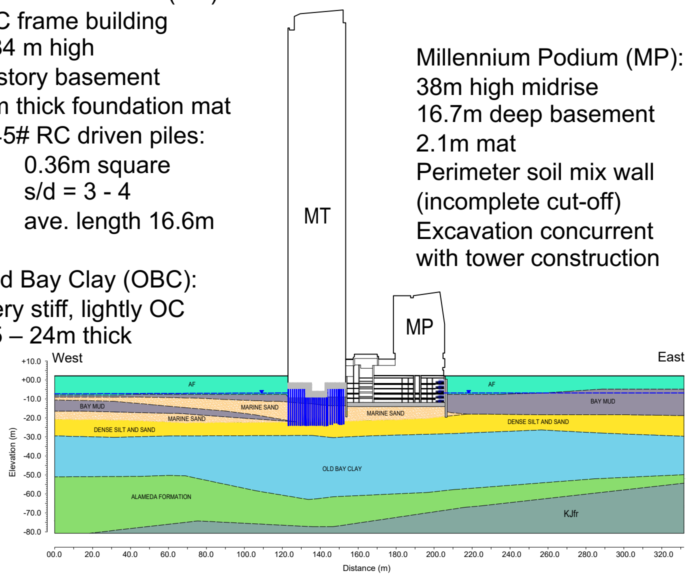
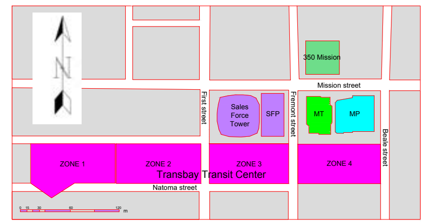
Millennium Tower, 301 Mission St., San Francisco

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

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

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





Site plan:
MT & MP: completed 2009

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

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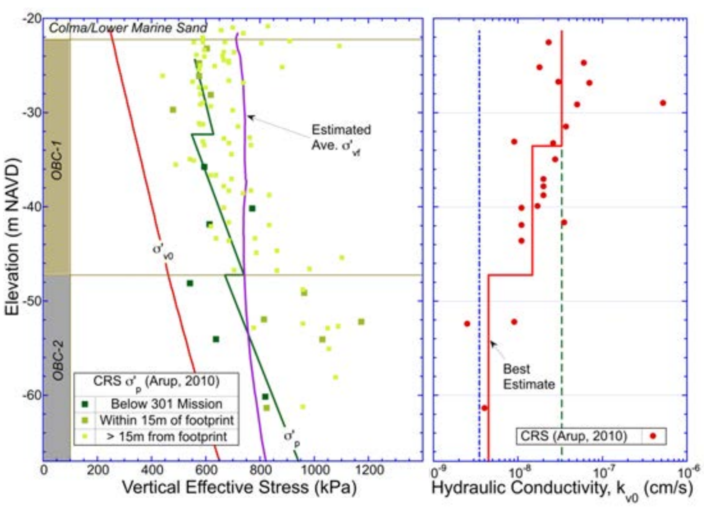
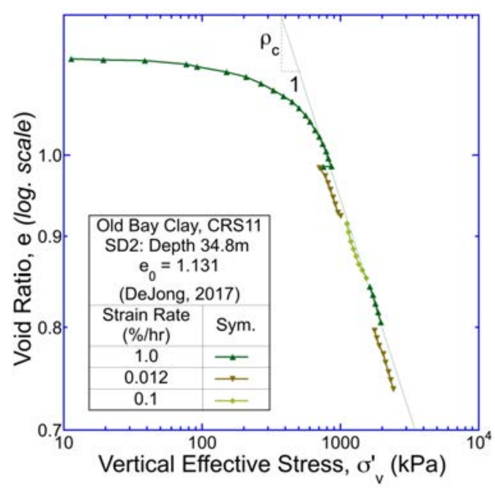
Why is MIT-SR Model Useful for Analysis of Millennium Tower?





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

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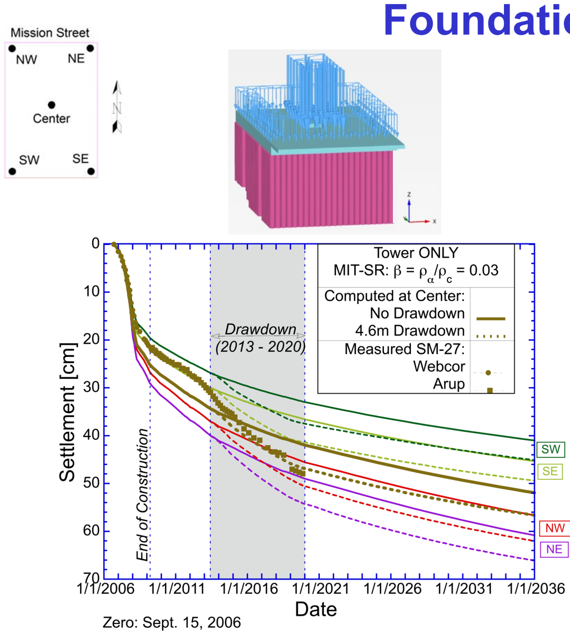
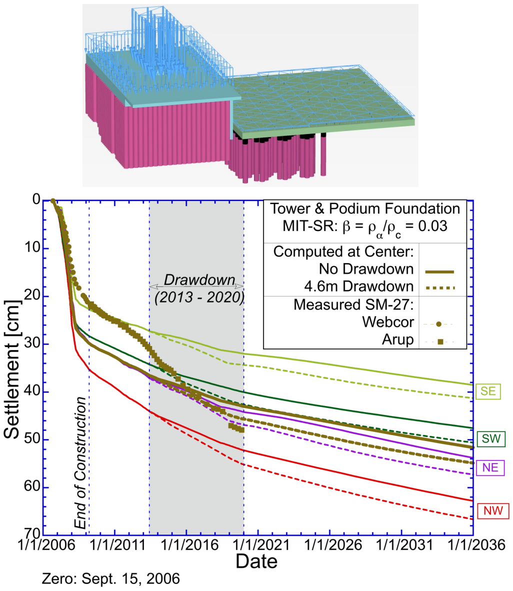
Foundation Settlements





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

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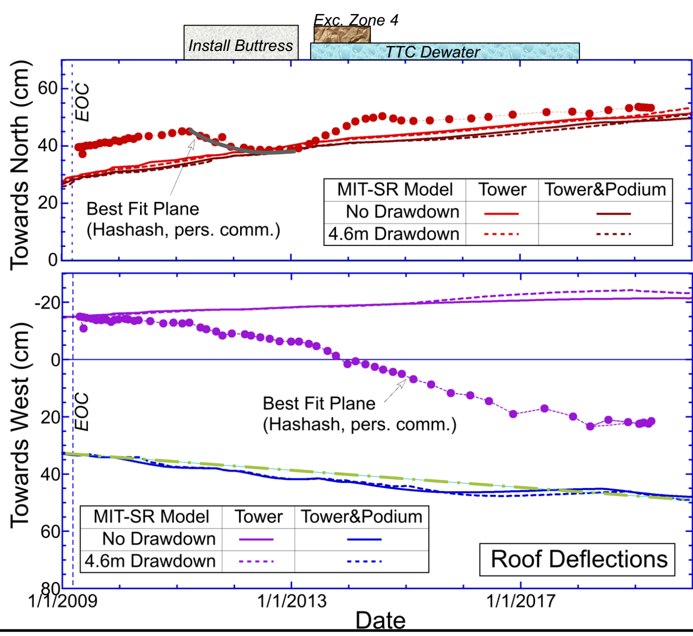
Evaluation of Tower Tilt: Roof Level Deflections

[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)**
- Subsequent E-W tilt NOT predicted by foundation models
- Cause?
- Similar results reported - Stewart et al. (2023)

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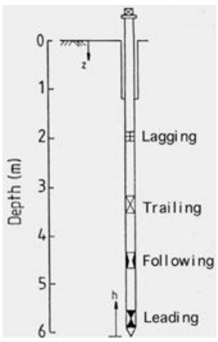
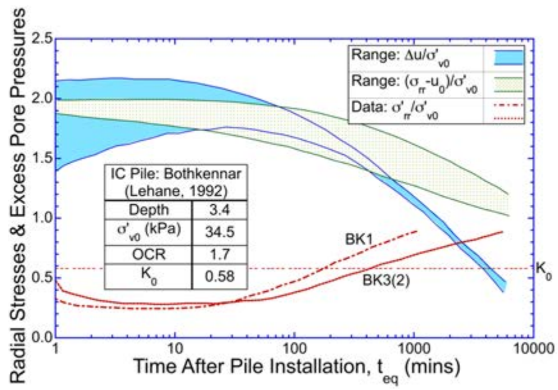
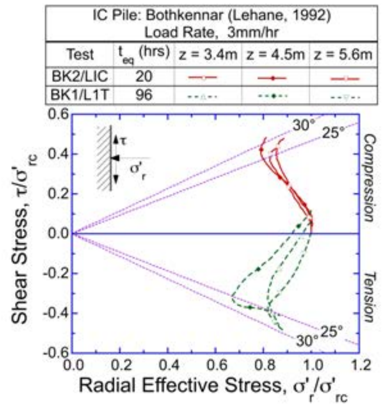
Set-Up and Axial Load Capacity of Driven Piles

[Data from Instrumented Model Pile]



IC Pile (Jardine, 2019)
Diameter 10.2 cm
Jacked at 50 cm/min
[σ_{rr}, u, τ]





Max. $\tau/\sigma'_{rc} = \rho$
Peak condition: $\tan\delta = \tau/\sigma'_r$

Lab. element tests:
$s_{uDSS}/\sigma'_{v0} = 0.44 \pm 0.02$

Can pile set-up be predicted by soil model?

33

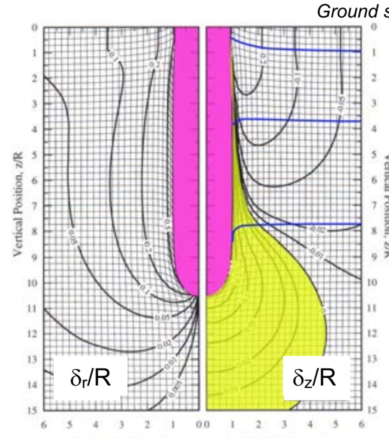
Analyses of Driven Piles in Clays

- **Pile installation: A VERY DIFFICULT PROBLEM**
  (Baligh, 1985):
  - Large deformations & shear strains
  - Large gradients of deformations, stresses & pore pressures
  - Complex changes in stresses & soil properties
  - Contact conditions of pile soil interface
- **Area of active research:**
  - FE with automated re-meshing
  - Meshless methods (MPM etc.)

Stage	Assumptions	Method
Installation	Undrained **Kinematically Controlled**	Strain Path Method
Set-Up	Radial consolidation	Nonlinear FE: deformation & flow
Axial Load	Undrained $f_s[s_{uR}]$	Elemental simple shear

Same generalized soil model [MIT-E3] used in all stages
Near-field predictions strongly affected by soil model

Ground surface



Ground deformation components
Closed Ended Pile; L/R = 10

- **Shallow Strain Path Method**
  - (SSPM: Sagaseta & Whittle, 2001)
  - Direct analytical solutions: **Far-field** deformations caused by pile installation
  - Ground movement due to tunneling in clay

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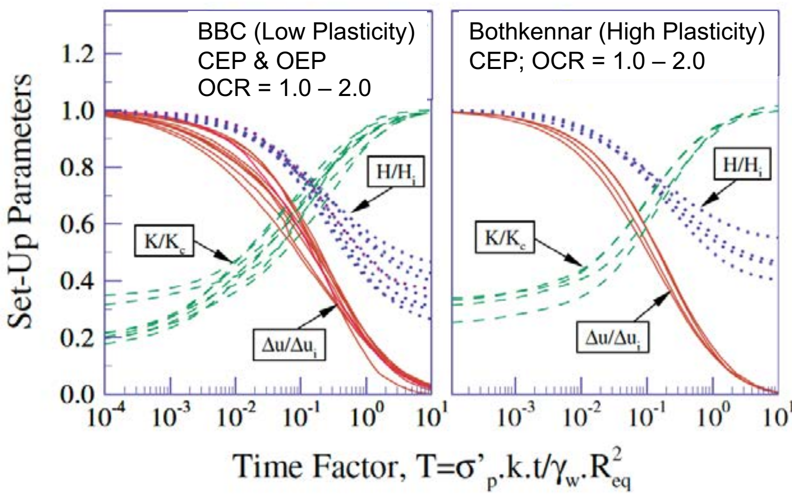
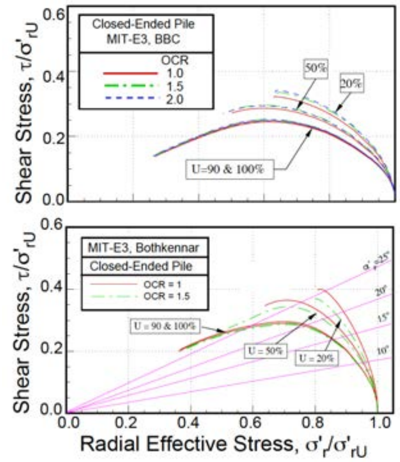
Numerical Simulations





Effect of partial set-up on predicted pile shaft capacity

$K_c = \sigma'_{rc}/\sigma'_{v0}$: Normal stress acting on pile at full set-up
Δu_i, H_i: excess pore pressure & radial total stress during penetration
σ'_p: pre-consolidation stress; k: hydraulic conductivity
$R_{eq} = \sqrt{(Dw)}$: Equivalent radius

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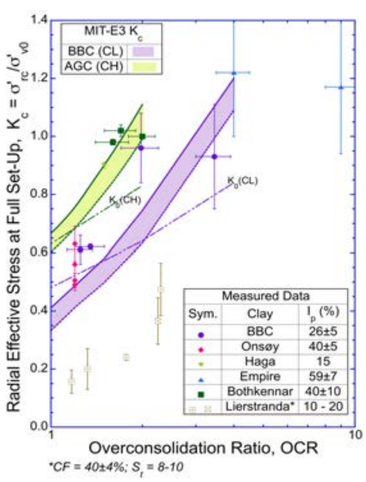
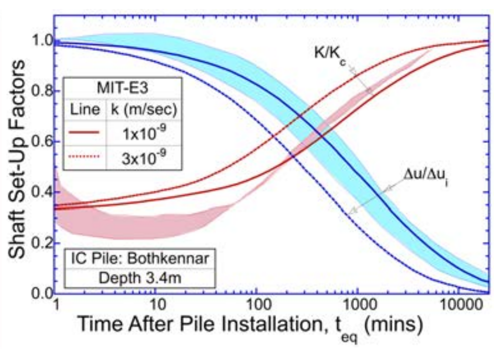
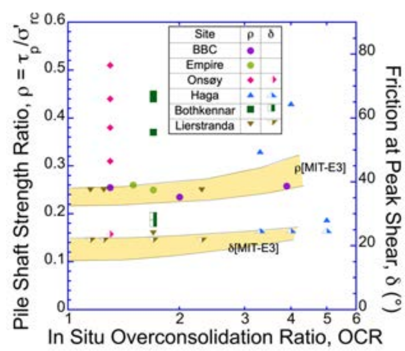
Evaluation of Set-Up Predictions

[Predictions reflect capabilities & limitations of soil model (MIT-E3)]







K_c - trends in good agreement with most of measured data (except at Lierstranda)
Highly credible predictions of set-up factors
ρ, δ - small range predicted by model (*remolded* behavior independent of OCR)
ρ - large scatter in measured data
ρ, δ predictions generally lower bound on measured data

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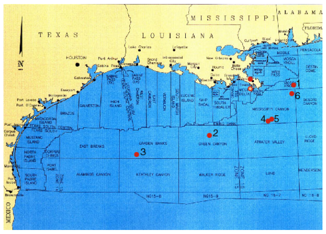
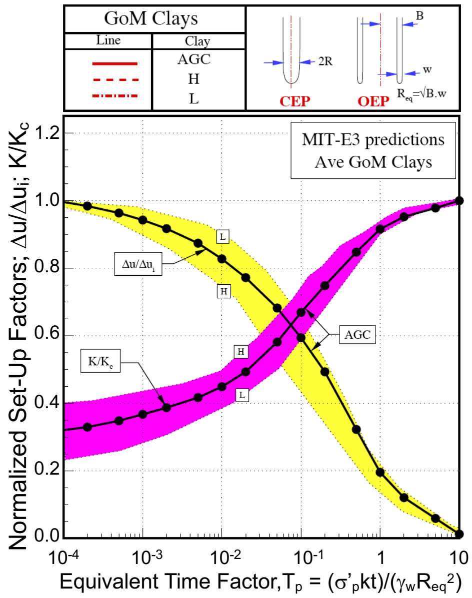
Design Charts for TLP Piles: Gulf of Mexico

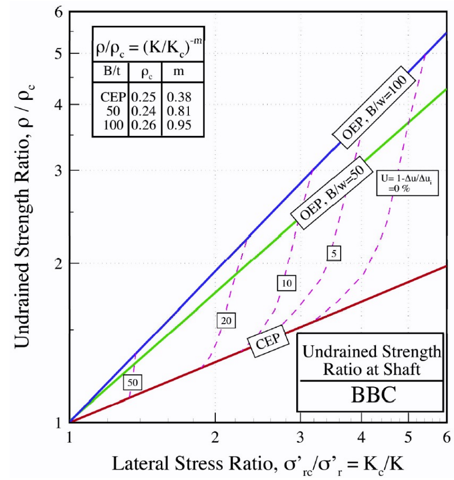
Average Gulf Clay [Whittle, Sutabutr & Germaine, 1999]



Set-up analyses completed for series of deepwater projects, GoM

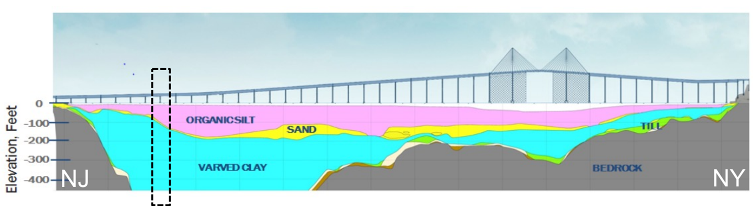
MIT-E3 model separately calibrated for each case





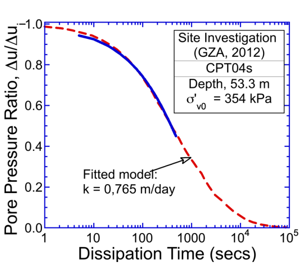
Considers partial set-up cases

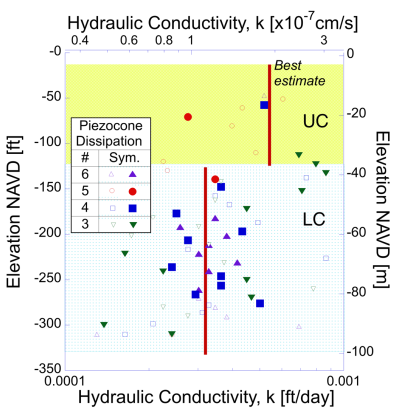
Tappan Zee Bridge: Prediction of Set-Up

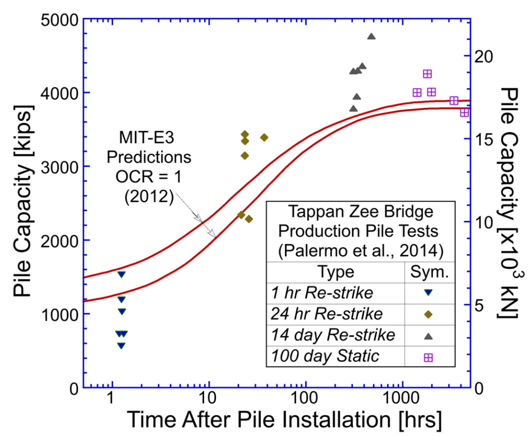


Production Piles: Steel Pipe
L = 100m, Dia. D = 1.22m, Wall w = 2.54cm

Predictions:
SPM & MIT-E3; AGC Parameters; OCR = 1

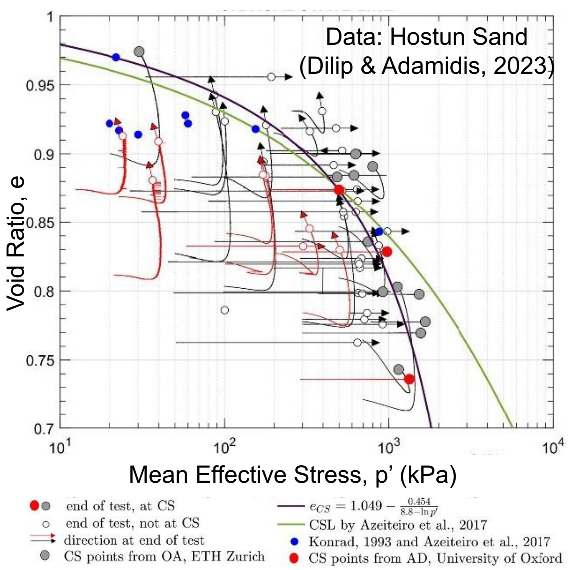




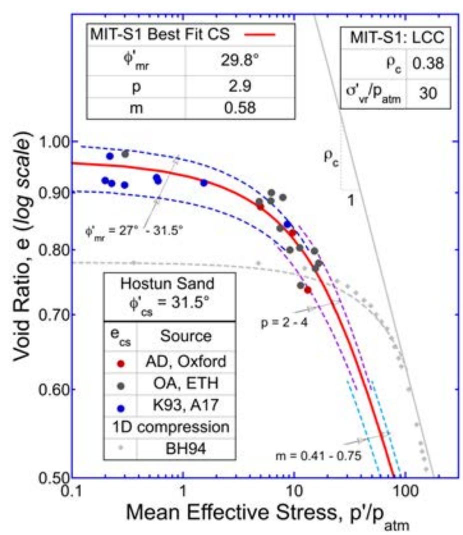


Sands

Problem of Model Calibration Based on Critical State

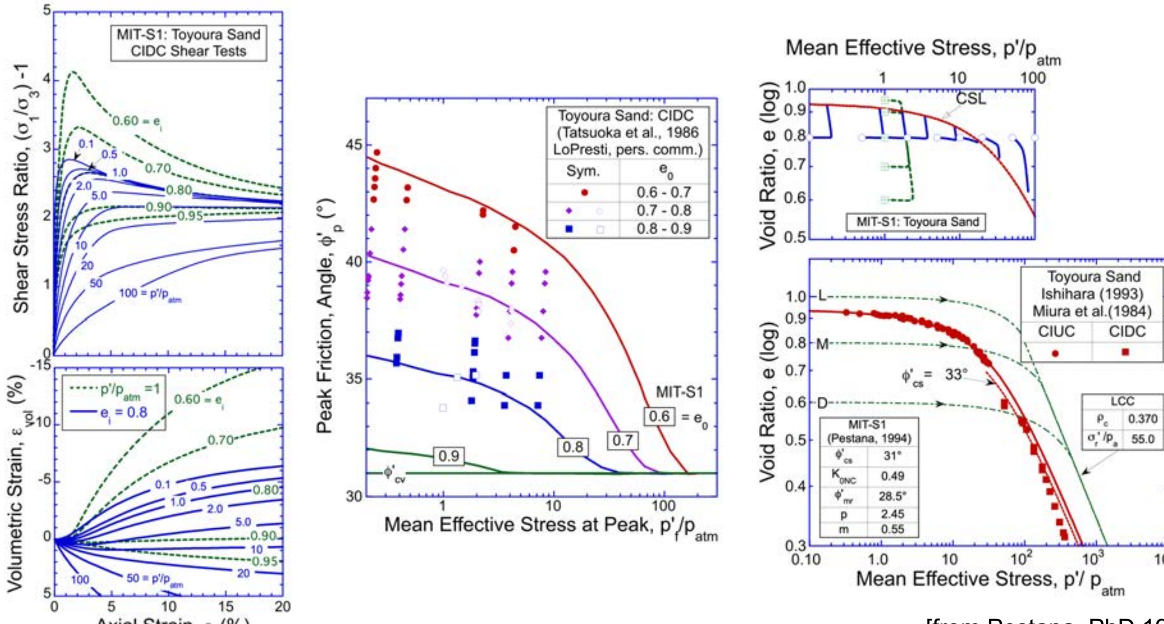


Challenge in interpretation of critical state & state parameter
Note: strain localization (material instability in drained shear)



MIT-S1 leverages 1D compression data (LCC)
CS well characterized by 3 parameters

Prediction of Sand Behavior: MIT-S1 Model



[from Pestana, PhD 1994]

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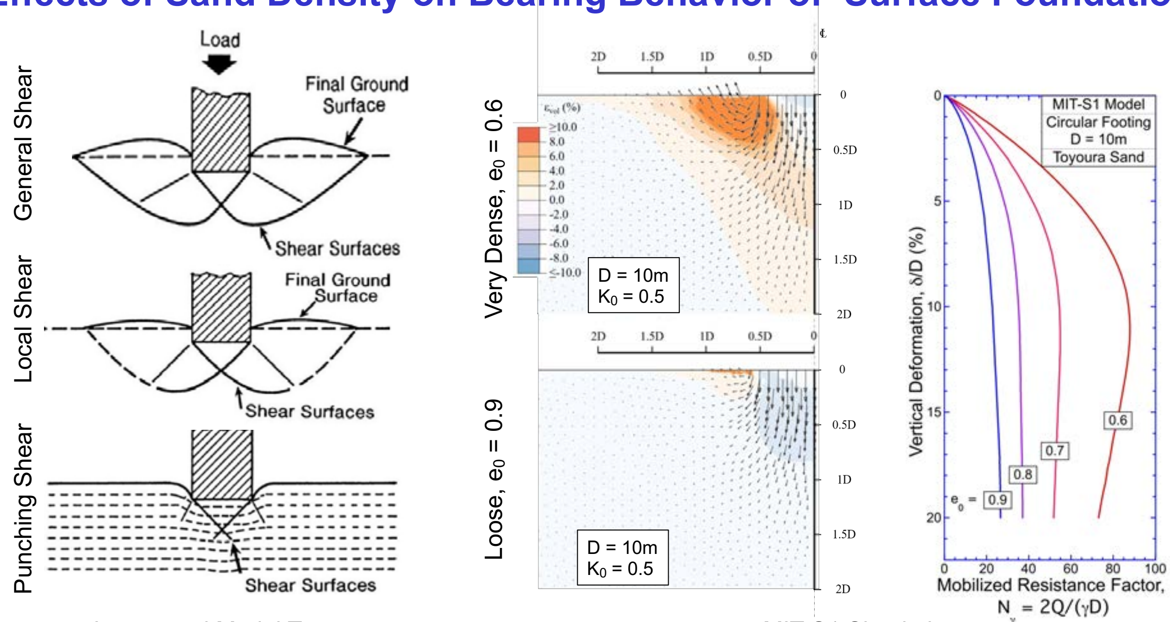
Effects of Sand Density on Bearing Behavior of Surface Foundation



Interpreted Model Tests
(DeBeer & Vesic, 1958)

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

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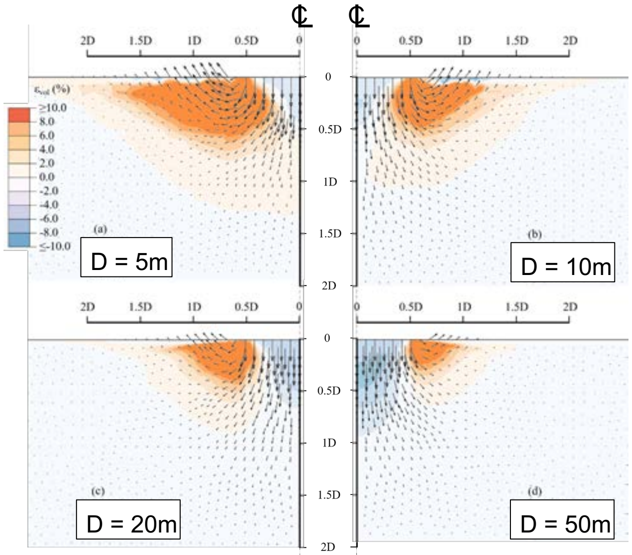
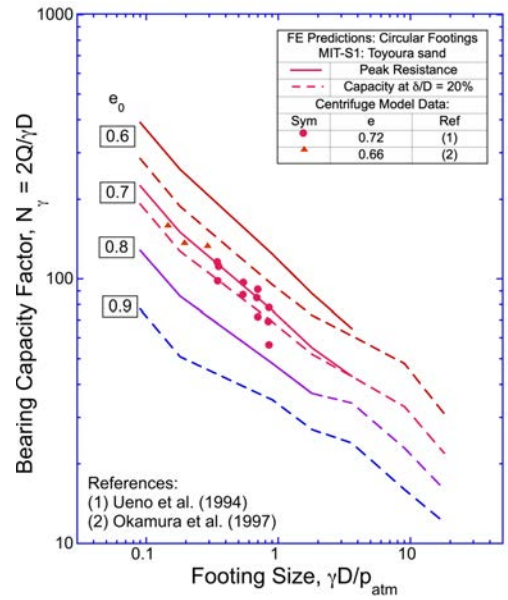
Effect of Foundation Size on Bearing Capacity



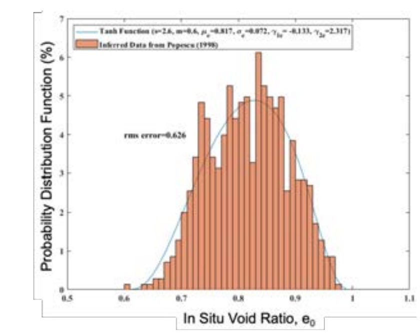
Very dense sand, e_0 = 0.6, K_0 = 1.0

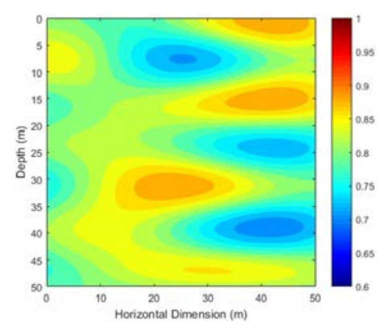


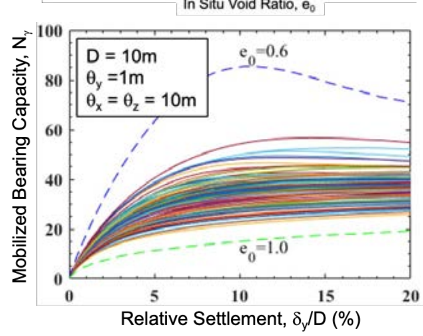
Results provide basis for study of effects of spatial variability in sands

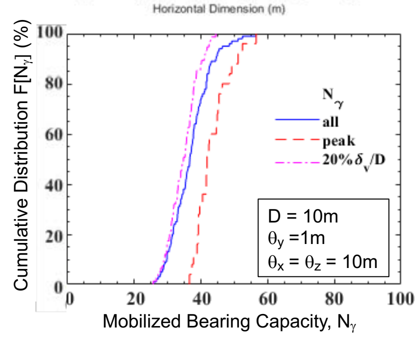
Chen et al. (2020)

Stochastic Model for Circular Foundation on Sand

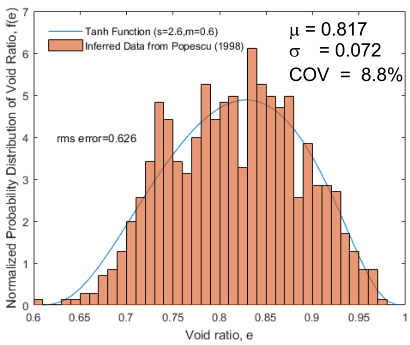




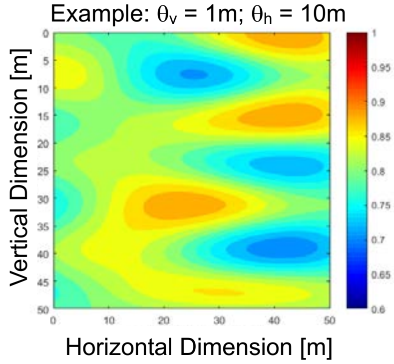




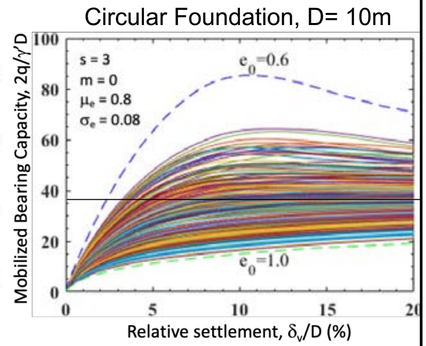
Use of Generalized Soil Model: Effects of Spatial Variability



Probability distribution function of void ratio:
Tokyo Bay sand (Popescu et al., 1998)
SPT N_1 data: arrays of 24 boreholes
Void ratio: D_r vs N_1 (Cubrinovski & Ishihara, 2002)
'*Bounded tanh*' PDF (Fenton & Griffiths, 2008)



Scale of fluctuation, θ:
Continuous random field
KL series expansion
Exponential autocorrelation



Effects of spatial variability:
Stochastic R-FEM simulations
Monte-Carlo simulations
MIT-S1 model:
- Toyoura sand
- Single set of input parameters
- Unique critical state

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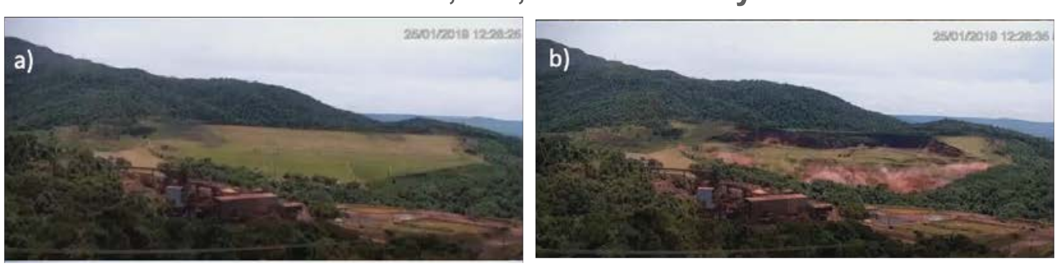
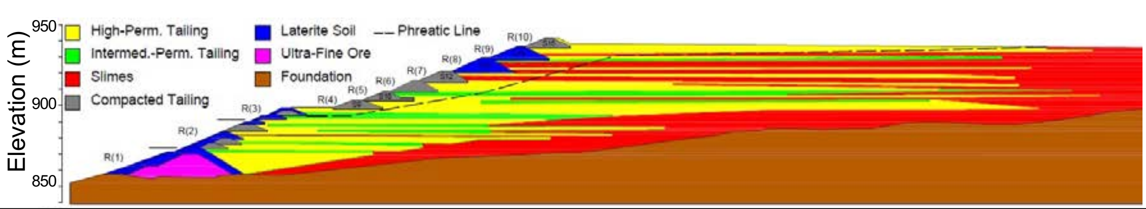
Spontaneous/Static Liquefaction of Upstream Tailings Dam

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)



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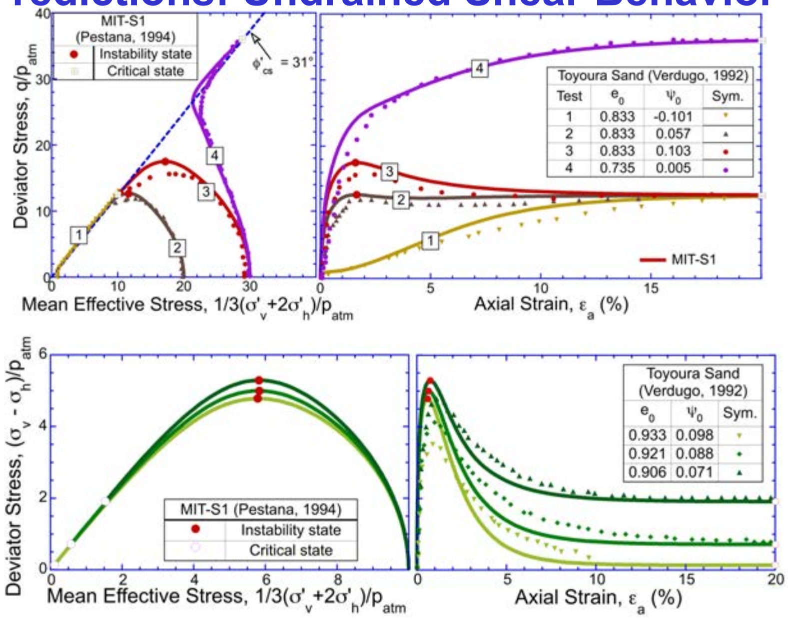
MIT-S1 Predictions: Undrained Shear Behavior of Sands



Current methods require estimates of ψ from piezocone penetration

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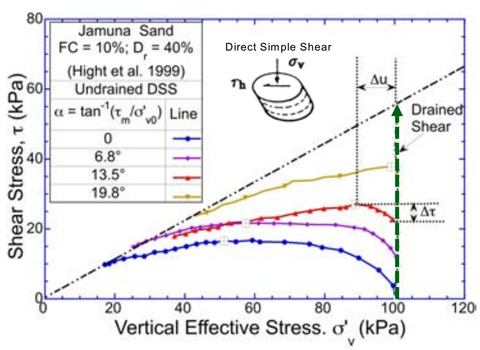
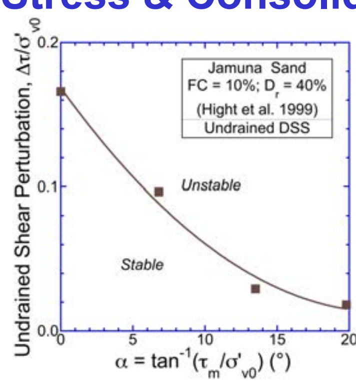
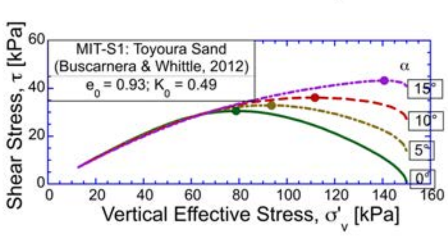
Triggering Shear Stress & Consolidation State

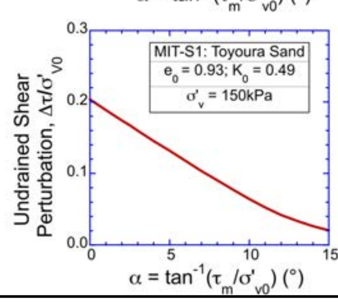




Drained response stable

Switch to undrained shearing:
Perturbation Δτ causes instability





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

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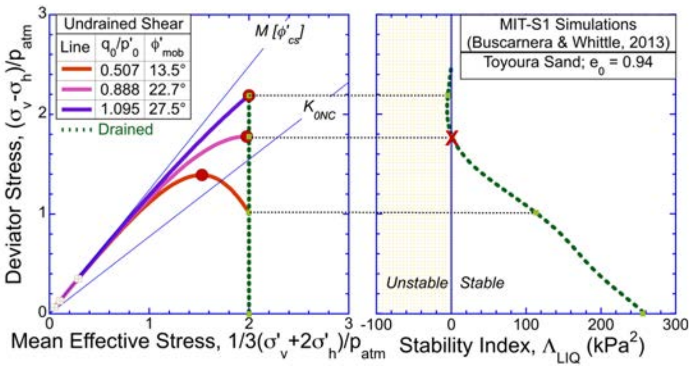
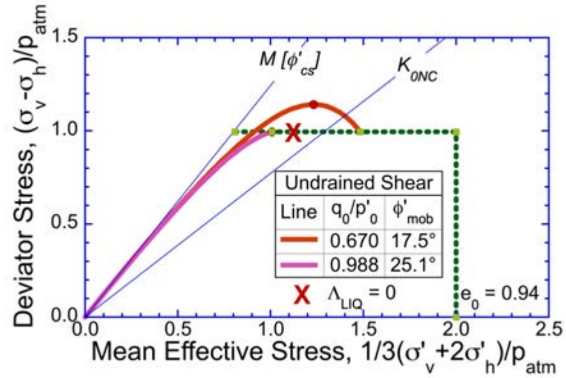
Model Prediction of Latent Instability Caused by Undrained Shear Perturbation





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

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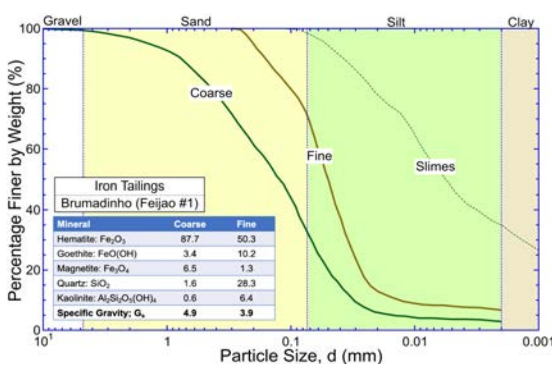
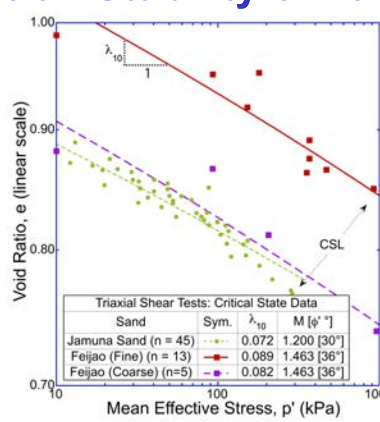
Challenge in Evaluating Liquefaction Stability of Tailings





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**

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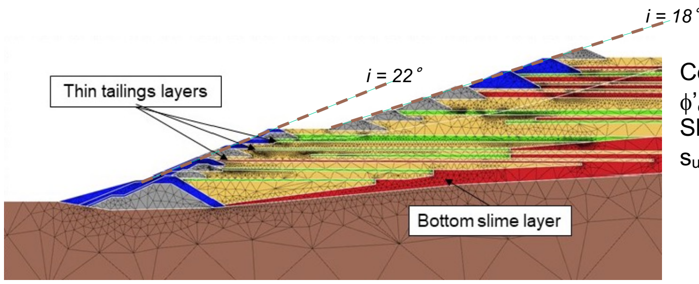
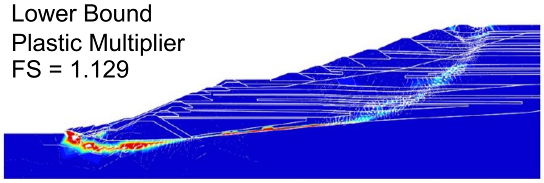
Stability Analyses using Numerical Limit Analyses

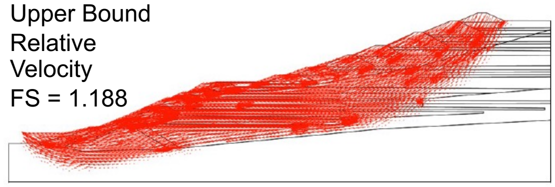


Coarse & Fine tailings:
ϕ'_{cs} = 36°, γ_t = 25, 27kN/m^3
Slimes:
s_u/σ'_{v0} = 0.22, γ_t = 27kN/m^3

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 Λ_{LIQ} = 0]

Whittle et al. (2021)

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Complex Soils – Multiscale Modeling

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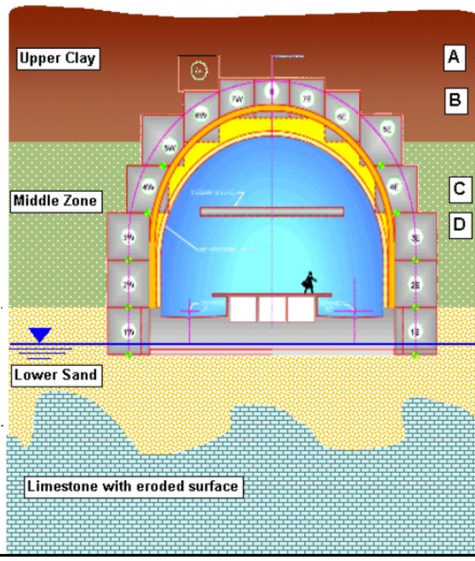
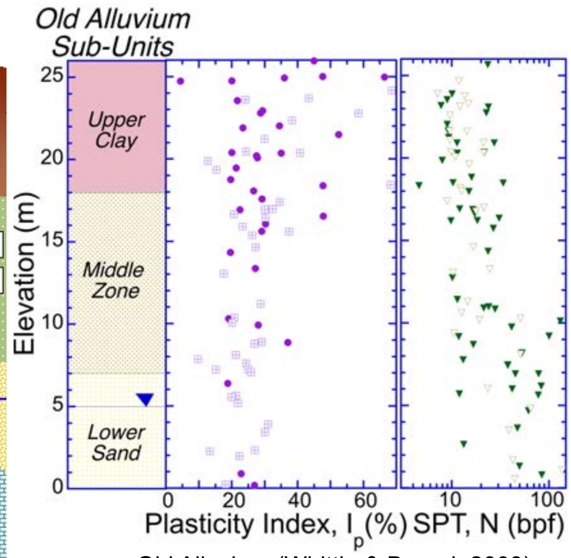
Old Alluvium: Transported Residual Soil

[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)

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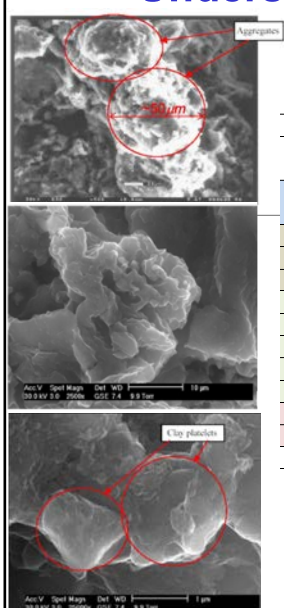
Understanding the Microstructure of Old Alluvium

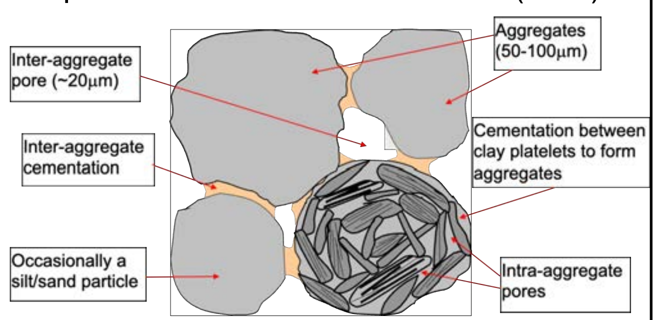


ESEM Imaging

(%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)

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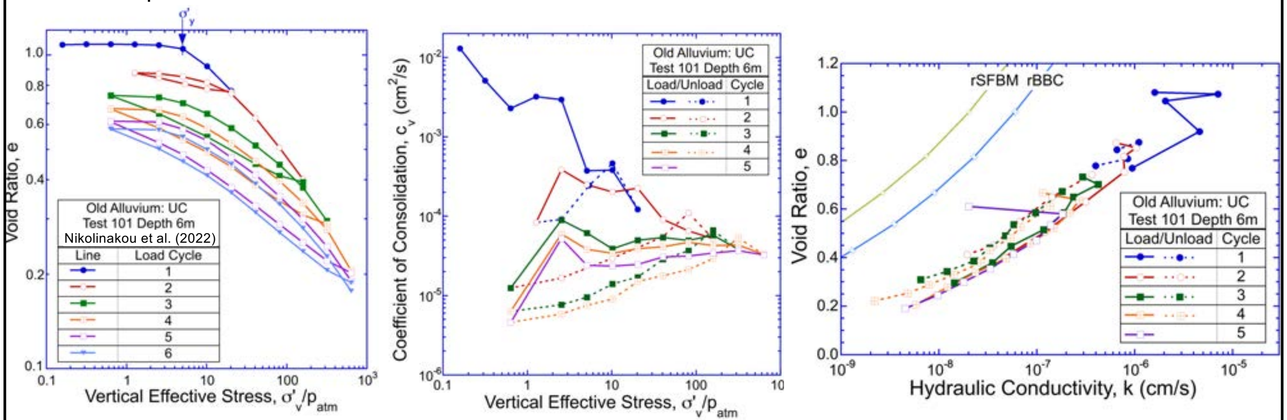
Effect of Degradation of Microstructure on Engineering Properties of Old Alluvium

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

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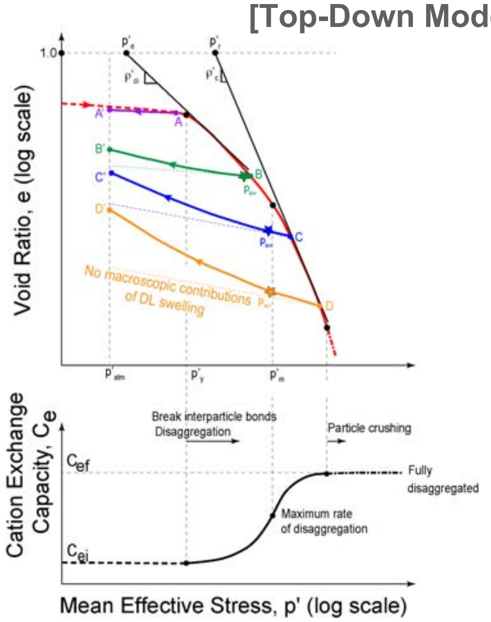
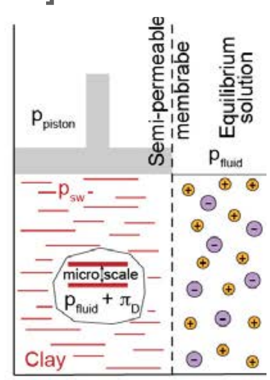
Model of Disaggregation and Swelling of Old Alluvium

[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 (s)
After Alonso (1998)

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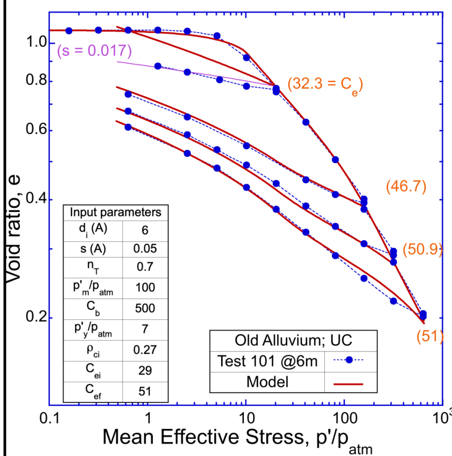
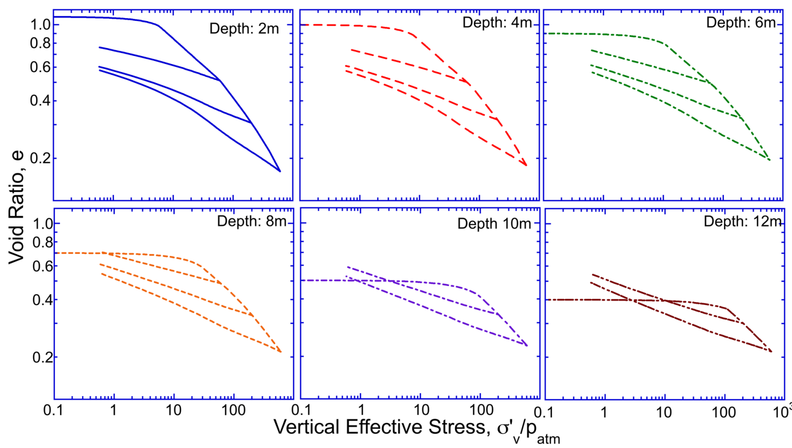
Model of 1-D Compression for Old Alluvium





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

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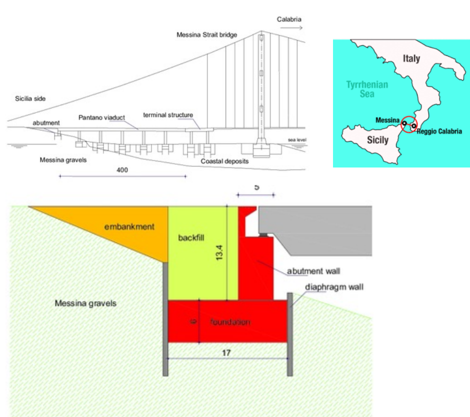
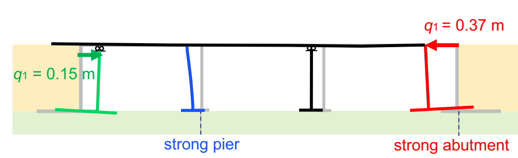
Modeling of Seismic Bridge Deck-Abutment Interactions

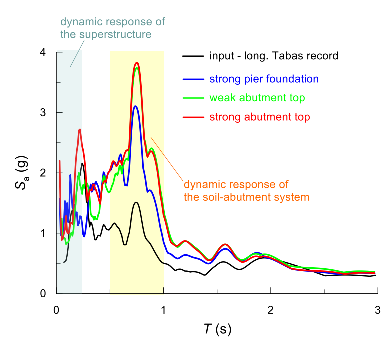
- Original motivation



Messina Straits bridge & Pantano viaduct
Transfer longitudinal seismic forces to abutment
(Calisto & Rampello, 2013)

Conceptual model: Deformations after seismic event





Elastic response spectra (5% damping)

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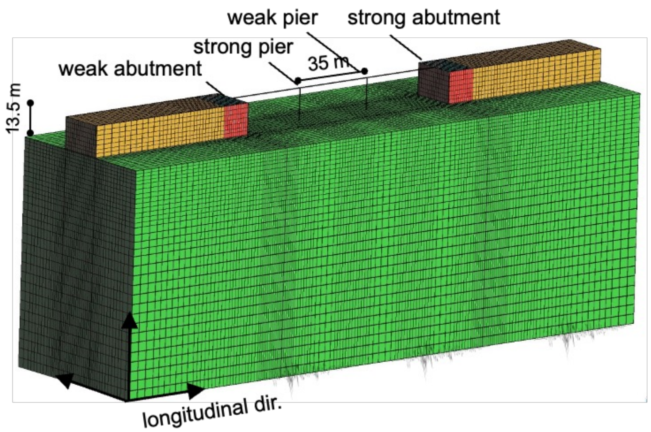
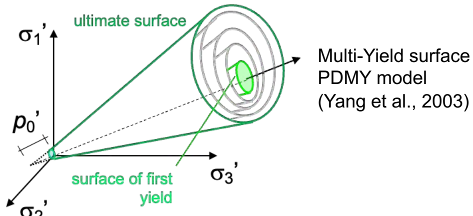
Coupled-Continuum Finite Element Model

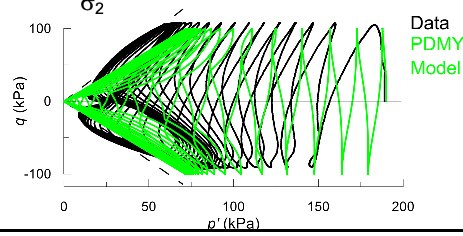


OpenSeesSP FE model

- 150,000 elements (brick, shell & beam types)
- Longitudinal base acceleration input
- **Computational time ~ 4weeks**

Cyclic response of soils:
PDMY & SaniSand models
Foundations: Calibrated to Messina gravel
Embankment: Compacted fill
Reduced friction at soil-structure contacts





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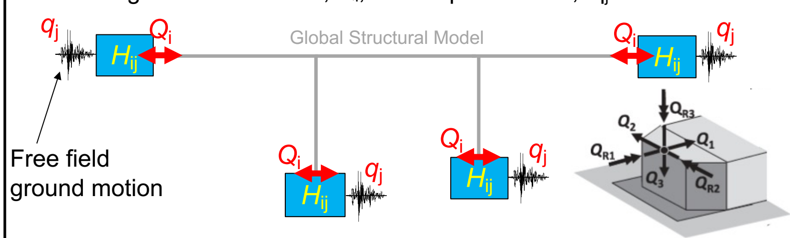
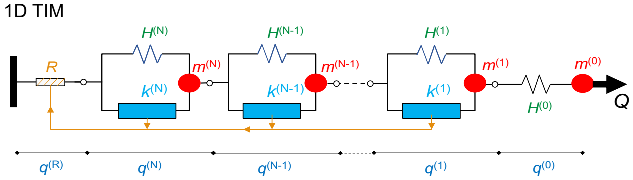
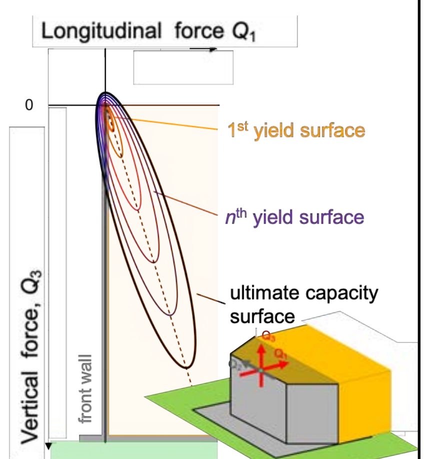
Macro-Element Representation of Soil-Structure Interaction

Thermodynamic Inertial Macro-element (TIM; H_{ij})
Relate generalized forces, Q_i, and displacements, q_j





TIM: Multisurface plasticity model
nonlinear & inertial response
Formulation based on Prévost (1977), Houlsby (2017)



(Gorini et al., 2021, 2022)

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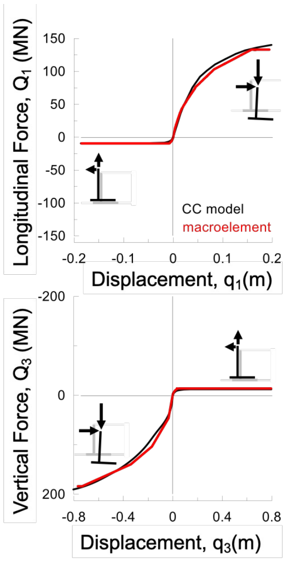
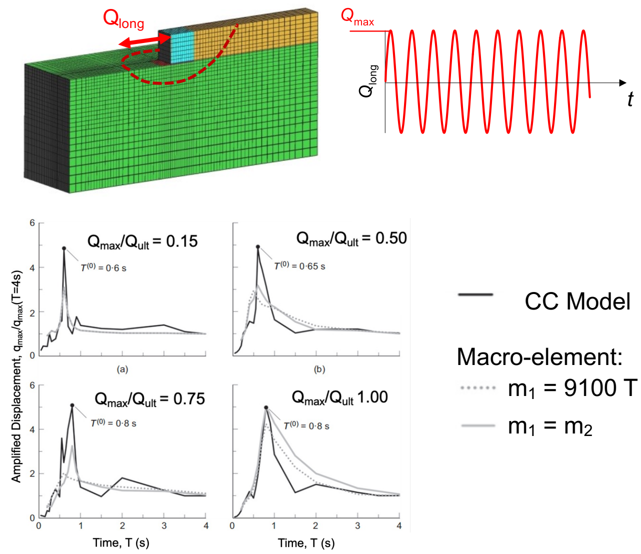
Calibration of Macro-Element



Static push-over models



Calibration of inertial masses for TIM

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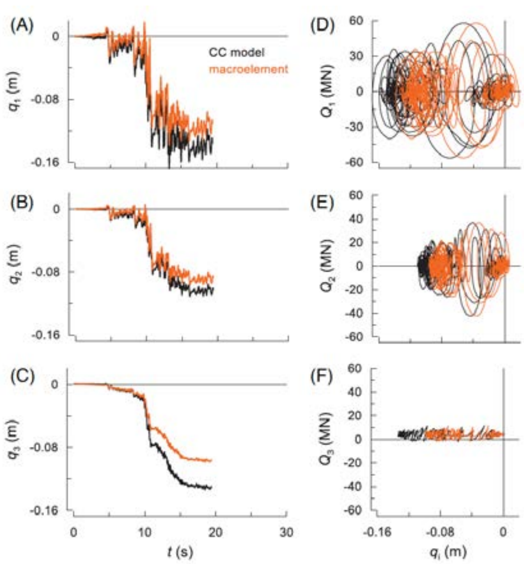
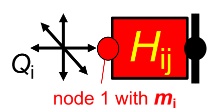
Macro-Element (ME) vs Coupled Continuum (CC) SSI Models



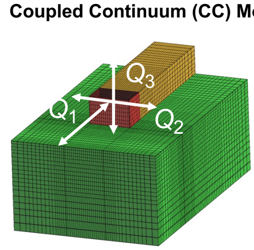
3D results for Tabas earthquake
CC – black; ME – red

Macro-Element (ME) Model

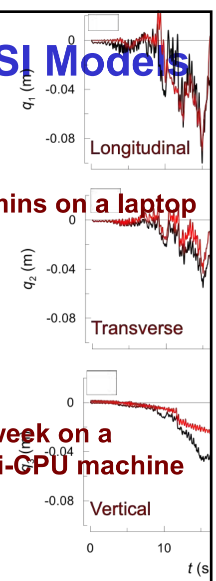


⇨ **< 5 mins on a laptop**

Coupled Continuum (CC) Model



⇨ **≈ 1 week on a multi-CPU machine**



Upscaling using Macro-Element:
highly computationally efficient
Discrepancies in vertical displacements:
reflect limitations in PDMY model (CC model)

(Gorini et al., 2022)

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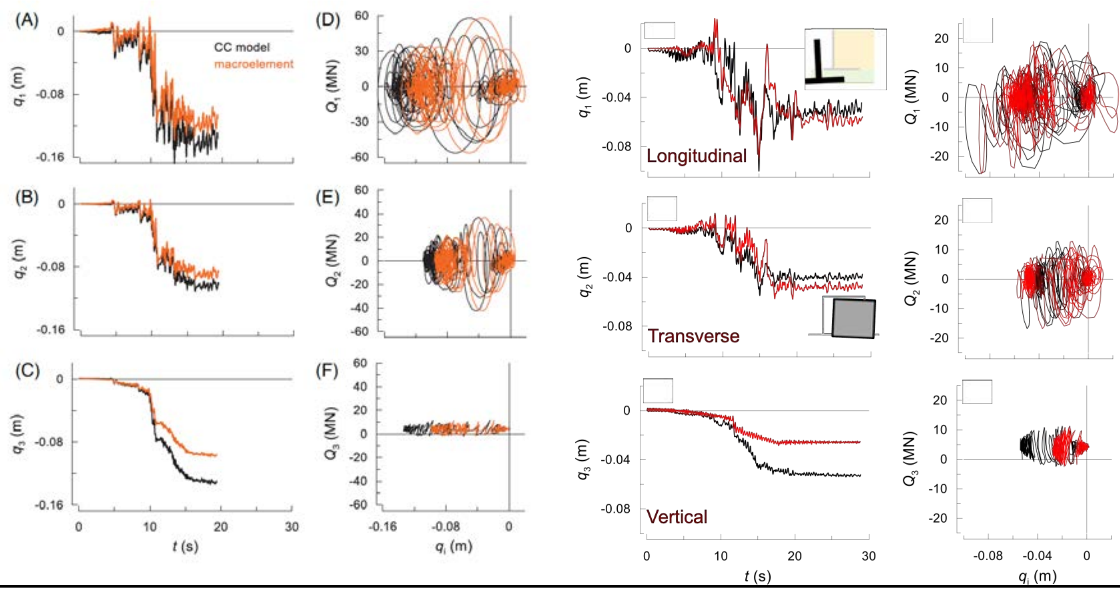

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Summary

- **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)***

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Acknowledgments

- **I owe special thanks to:**
  - Gretchen Young - for her continuous support
  - John Germaine – for teaching me all about laboratory methods & soil behavior
  - To those who assisted in preparing this lecture:
  - Sherif Akl, Giuseppe Buscarnera, Brendan Casey, Hayel El Naggar, Robert Fetell, Davide Gorini, Youssef Hashash, Rebecca John, Diego Lo Presti, Omar Mahdy, Maria Nikolinakou,Richard Kelly, Jiali Ma, Bob Palermo, Jubert Pineda, Mahdi Seyyeden, Yixing Yuan
- **Mentors who set me on this path:**
  - Mohsen Baligh, David Hight, Charles Ladd
- **The many brilliant research students who I've been privileged to work with:**
  - Naeem Abdulhadi, Mauricio Abramento, Sherif Akl, Domniki Asimaki, Charles Aubeny, Eng Sew Aw, Giuseppe Buscarnera, Doug Cauble, Yannis Chatzigianellis, Jialiang Chen, Gonzalo Corral, Samir Chauhan,Yuepeng Dong, Jianting Du, Davoud Ebrahimi, Majid Elghaib, Sonia Fortuna, Vasiliki Founta, Davide Gorini, Yo Ming Hsieh, Chu Eu Ho, Fu Shu Jeng, Youssef Hashash, Eva Ieronymaki, Lucy Jen, Kiyonobu Kasama, Yun Sung Kim, Dimitrios Konstantakos, Douglas Larson, Dante Legaspi, Michael Martello, Ivo Montenegro, Maria Nikolinakou, Zhandos Orazalin, Nina Panagiotidou, Jianyong Pei, Juan Pestana, Federico Pinto, Gonzalo Rellan, Marika Santagata, Alex Sanzeni, Ali Seiphoori, Mauro Sottile, Adnan Sufian, Twarath Sutabutr, Boonchai Ukritchon, Antonios Vytiniotis,Yixing Yuan, Guoping Zhang, Patrick Zhu, Despina Zymnis

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