The Twenty-first Spencer Buchanan Lecture

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Friday, November 22, 2013
College Station Hilton
College Station, Texas, USA
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Importance of Undrained Behavior in the Analysis of Soil-Structure Interactions

The 2013 Spencer J. Buchanan Lecture
By Dr. Andrew Whittle

Geoenvironmental Engineering: Problems Solved and Challenges Remaining

The 2012 Karl Terzaghi Lecture
By Dr. David Daniel

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Biography

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”
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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”

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

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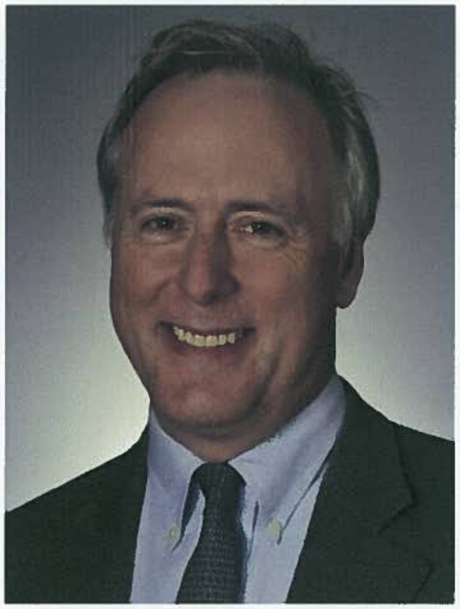
AGENDA

The Twenty-first Spencer J. Buchanan Lecture
Friday, November 22, 2013
College Station Hilton

2:00 p.m.	Introduction by Jean-Louis Briaud
2:15 p.m.	Katherine Banks – Dwight Look College of Engineering
2:25 p.m.	Introduction of David Daniel by Jean-Louis Briaud
2:30 p.m.	"Geoenvironmental Engineering: Problems Solved and Challenges Remaining" The 2012 Terzaghi Lecture by David E. Daniel
3:30 p.m.	Introduction of Andrew Whittle by Jean-Louis Briaud
3:35 p.m.	"Importance of Undrained Behavior in the Analysis of Soil-Structure Interactions" The 2013 Buchanan Lecture by Andrew J. Whittle
4:35 p.m.	Discussion
4:50 p.m.	Closure with Philip Buchanan
5:00 p.m.	Photos followed by a Reception at the home of Jean-Louis and Janet Briaud

Andrew J. Whittle, ScD

Edmund K. Turner Professor
Massachusetts Institute of Technology



Dr. Whittle earned his B.Sc. (Eng.) from the Imperial College of Science and Technology, London, in 1981 and the Sc.D. from the Massachusetts Institute of Technology (MIT) in 1987. While in graduate school, he was the MIT John F. Kennedy Scholar from 1982 to 1984. He was a postdoctoral research associate at the Institute in 1987-88. He joined the MIT faculty in 1988 and was promoted to full professor in 2000. From 2009 – 2013 he served as Head of the Department of Civil and Environmental Engineering. As of July 2013, he serves as the Edmund K. Turner Professor, in the Department of Civil and Environmental Engineering at MIT.

Much of Dr. Whittle's research deals with modeling soil behavior and predicting the performance of foundations and underground construction projects. His research has been widely used in the design of foundation systems for deepwater oil production facilities in the Gulf of Mexico. He has worked extensively on problems of soil-structure interaction for urban excavation and tunneling projects, including Boston's Central Artery-Third Harbor Tunnel and MBTA South Piers transit projects, as well as Tren Urbano, a subway system which began service in San Juan, Puerto Rico, in 2004. In 2008, Whittle established the Center for Environmental Sensing and Modeling (CENSAM), an interdisciplinary research program through the Singapore MIT Alliance for Research and Technology (SMART). Through this program he has led research efforts to develop wireless sensor networks for monitoring water distribution systems and is currently the Chief Scientific Advisor for an associated start-up company, Visenti Pte.

Dr. Whittle is Co-Editor of the International Journal of Numerical and Analytical Methods in Geomechanics (since 1999) and previously served on the editorial boards for the ASCE Journal of Geotechnical and Geoenvironmental Engineering (1993-2009) and the Canadian Geotechnical Journal (2000-2009). He is an active consultant who has worked on more than 40 major onshore and offshore construction projects. He has recently served on two major review panels; one for the National Research Council and National Academy of Engineering (NRC/NAE) investigating the performance of hurricane protection systems in New Orleans, and the second for the Governor of Massachusetts on a 'stem-to-stern' safety review of the Big Dig tunnels in Boston. He is currently a member of the Board of Directors for the Massachusetts Department of Transportation.

Dr. Whittle has published more than 150 papers in refereed journals and conferences, and received several awards for his work from the American Society of Civil Engineers, including the Casagrande Award (1994), the Croes Medal (1994), Middlebrooks Prize (1997, 2002, and 2005) and Huber Research Award (1998). He is a licensed professional engineer in New York State. In 2010, he was elected to the National Academy of Engineering.

David E. Daniel, PhD.

President of the University of Texas at Dallas

Dr. Daniel is the fourth president of The University of Texas at Dallas. He earned bachelor's, master's, and Ph.D. degrees in engineering from The University of Texas at Austin. Between his masters and PhD degrees, he worked for three years as a geotechnical engineer with Woodward-Clyde Consultants in the San Francisco Bay Area. He served on the faculty at UT Austin from 1980 to 1996. In 1996, he moved to the University of Illinois, first heading the Department of Civil and Environmental Engineering and then finishing his service as Dean of Engineering before being appointed UT Dallas' president in 2005.

Dr. Daniel's professional work has focused on geoenvironmental issues associated with waste containment and clean-up of contaminated sites with particular emphasis on low-permeability clay materials used in lining and capping systems. His work has been recognized by the American Society of Civil Engineers, which awarded him the Norman Medal and on two separate occasions the Croes Medal. He has also been awarded the ASCE Middlebrooks Award, Presidents' Award, Geotechnical Hero's Award, and the OPAL Award for Education. In 2000, he was elected to the National Academy of Engineering.

In 2005 through 2008, Dr. Daniel served as Chairman of the External Review Panel of the American Society of Civil Engineers, which reviewed causes for the failure of New Orleans' levees during Hurricane Katrina and recommended strategies for rebuilding the levee system. Dr. Daniel also served on the National Academy of Engineering panel that investigated the causes for the explosion, fire, and oil spill from Deepwater Horizon in the Gulf of Mexico.

In 2009, Dr. Daniel served as President of The Academy of Medicine, Engineering, and Science of Texas (TAMEST), which is comprised of all Texas residents who have won Nobel Prizes or been elected to one of the National Academies. Dr. Daniel serves on the Board of Directors for Sandia National Laboratory and numerous business and civic organizations in the Dallas area.

Importance of Undrained Behavior in the Analysis of Soil-Structure Interactions

The 2013 Spencer J. Buchanan Lecture

By Dr. Andrew Whittle

Importance of Undrained Behavior in the Analysis of Soil-Structure Interactions

Andrew J. Whittle
Massachusetts Institute of Technology

21st Spencer Buchanan Lecture
Texas A&M
November 2013

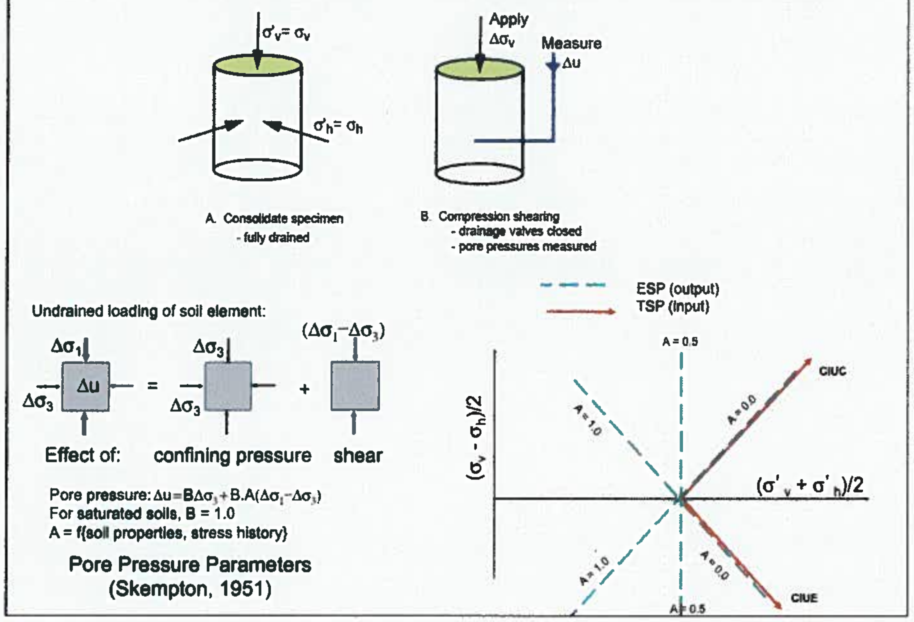
Outline

- **Undrained Shear Behavior**
  - Undrained shear strength
    - → Lab & field measurements
  - Constitutive models
    - → Simple vs complex
- **Applications**
  - Far field deformations
    - → Soil behavior secondary to volume constraints
  - Stability on soft ground
    - → Where s_u really matters
  - Performance of excavation support systems
    - → Where model limitations become apparent
- **Future issues**
  - Rate effects

Undrained Shear Behavior

- **Fully saturated soils - effective stresses control behavior**
    - ➔ Soil and water particles are relatively incompressible
    - ➔ $\sigma'_{ij} = \sigma_{ij} - p\delta_{ij}$
    - ➔ Soil deformations & strength controlled by changes in effective stresses
- **No migration of pore water**
    - ◆ within soil skeleton during timeframe of loading
- **Good approximation & common occurrence**
    - ◆ First loading of clays
        - ➔ Low permeability & relatively low stiffness
        - ➔ Shear strength governed by current water content
    - ◆ Partial drainage can occur close to drainage boundaries
- **May occur in sands under special conditions?**
    - ➔ Earthquake, wave loading etc.

Pore Pressures in Undrained Shearing



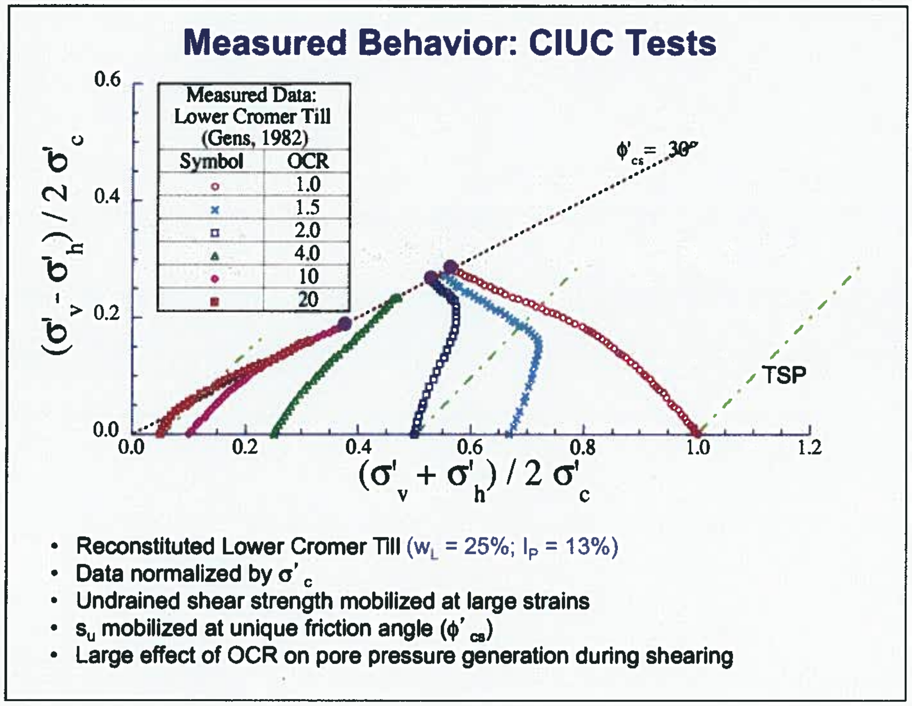
A. Consolidate specimen
- fully drained

B. Compression shearing
- drainage valves closed
- pore pressures measured

Undrained loading of soil element:

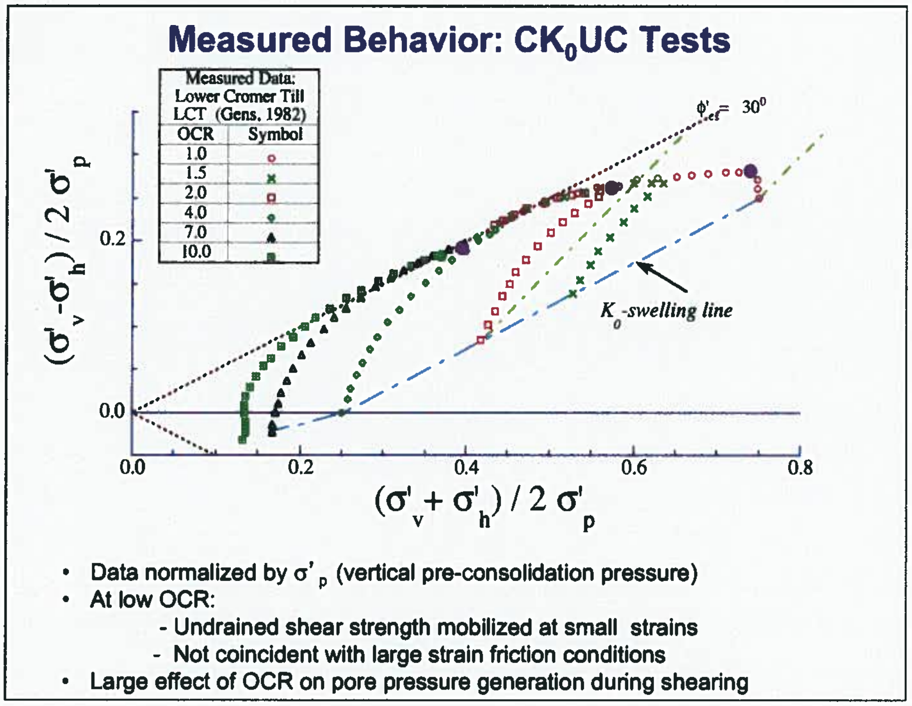
Pore pressure: $\Delta u = B\Delta\sigma_3 + B.A(\Delta\sigma_1 - \Delta\sigma_3)$
For saturated soils, B = 1.0
A = f(soil properties, stress history)

Pore Pressure Parameters
(Skempton, 1951)



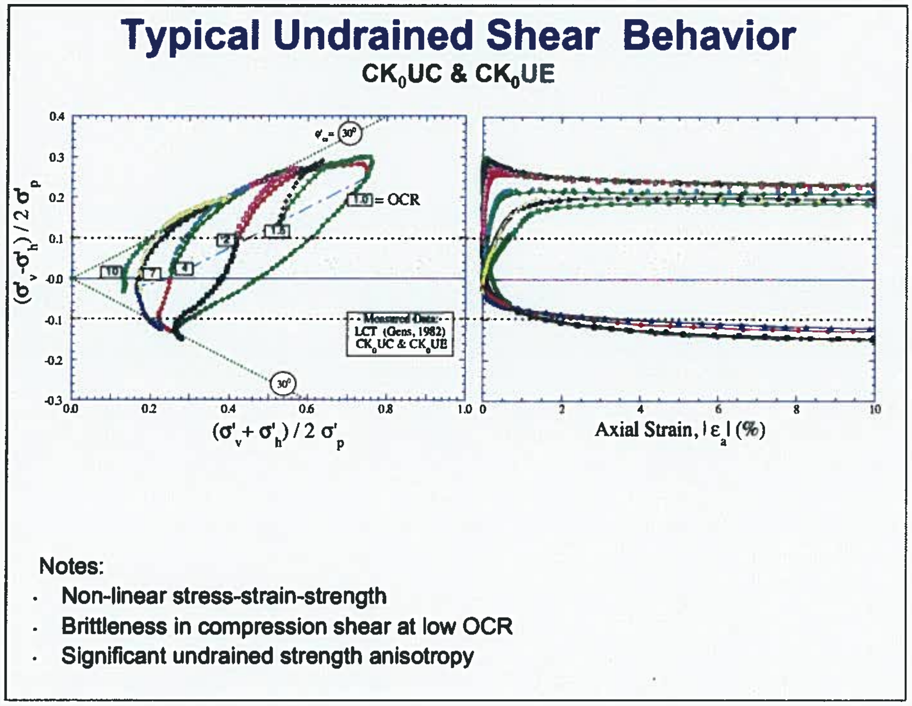
Measured Behavior: CIUC Tests

- Reconstituted Lower Cromer Till (w_L = 25%; I_P = 13%)
- Data normalized by σ'_c
- Undrained shear strength mobilized at large strains
- s_u mobilized at unique friction angle (ϕ'_{cs})
- Large effect of OCR on pore pressure generation during shearing



Measured Behavior: CK_0UC Tests

- Data normalized by σ'_p (vertical pre-consolidation pressure)
- At low OCR:
  - Undrained shear strength mobilized at small strains
  - Not coincident with large strain friction conditions
- Large effect of OCR on pore pressure generation during shearing

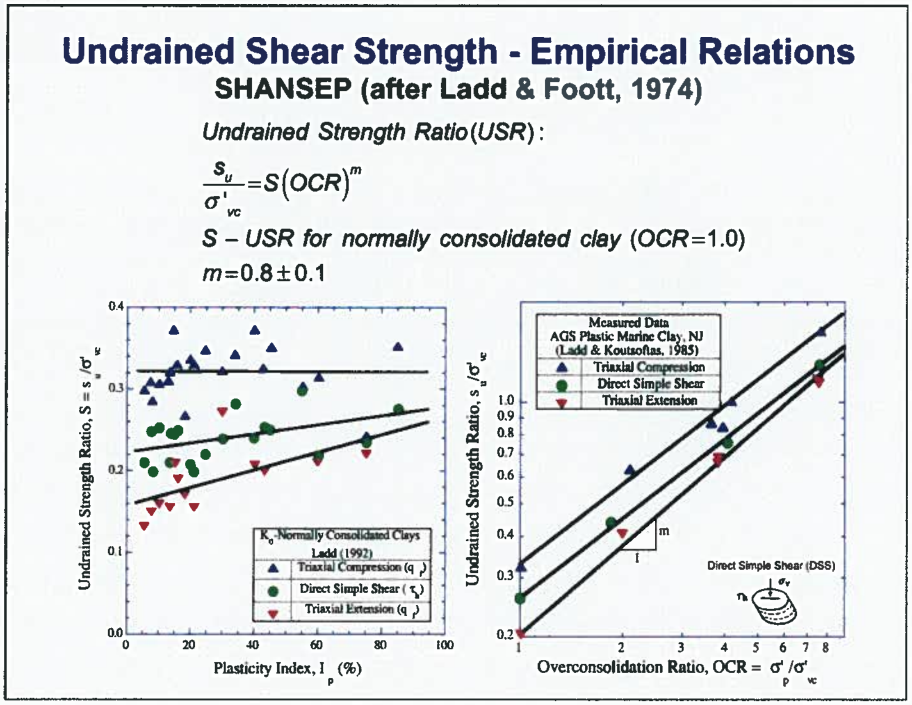


Typical Undrained Shear Behavior

CK_0UC & CK_0UE

Notes:

- Non-linear stress-strain-strength
- Brittleness in compression shear at low OCR
- Significant undrained strength anisotropy



Undrained Shear Strength - Empirical Relations

SHANSEP (after Ladd & Foott, 1974)

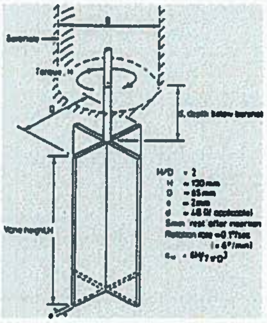
Undrained Strength Ratio (*USR*):

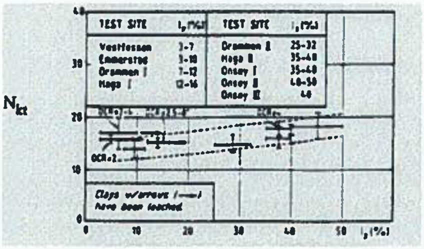
$$\frac{s_u}{\sigma'_{vc}} = S(OCR)^m$$

S – *USR for normally consolidated clay* ($OCR = 1.0$)

$m = 0.8 \pm 0.1$

Undrained Shear Strength - Field Tests





Calibrated to lab DSS tests

Field Vane Test:
M - measured torque
For H/D =2:

$$s_u = x\frac{M}{\pi D^3}$$

x = 0.85 - 0.95
Correction factors often used

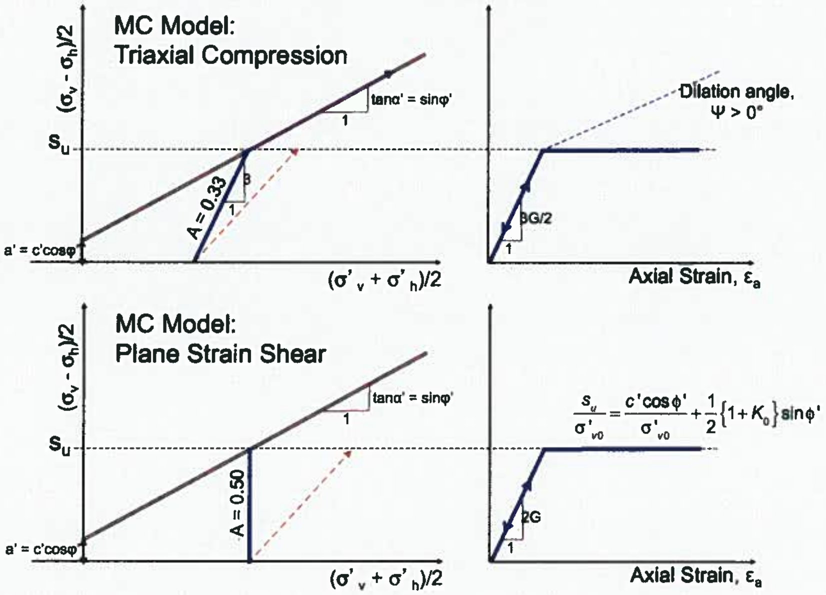
Piezocone:
q_T - Measured tip resistance

$$s_u = \frac{(q_T - \sigma_{v0})}{N_{kT}}$$

Empirical N_{kT} cone resistance factor
$N_{kT} = 15 \pm 2$ for s_{uDSS}
N_{kT} - needs site specific calibration

Linearly Elastic – Perfectly Plastic Model

[Mohr-Coulomb – MC]



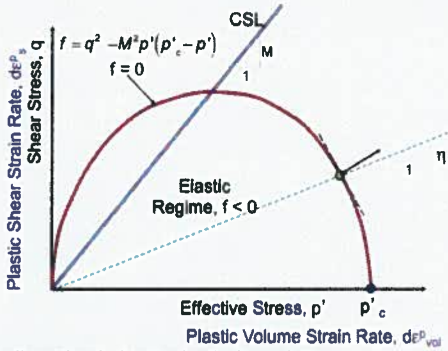
Two Methods for Using MC Model for Undrained Shearing

Input:	Method A		Method B
Deformation	(E', v')	or	(G, v')
Shear Strength	(c', φ')		φ' = 0°, c' -> s_u
Output Parameters:	Effective Stresses & pore pressures		
Undrained Shear Strength, s_u	$\frac{s_u}{\sigma'_{vo}} = \frac{c'\cos\phi'}{\sigma'_{vo}} + \frac{1}{2}\{1+K_0\}\sin\phi'$		Input $s_u(z)$
Limitations:	Inaccurate undrained behavior at low OCR		Unable to model effects of consolidation on undrained behavior

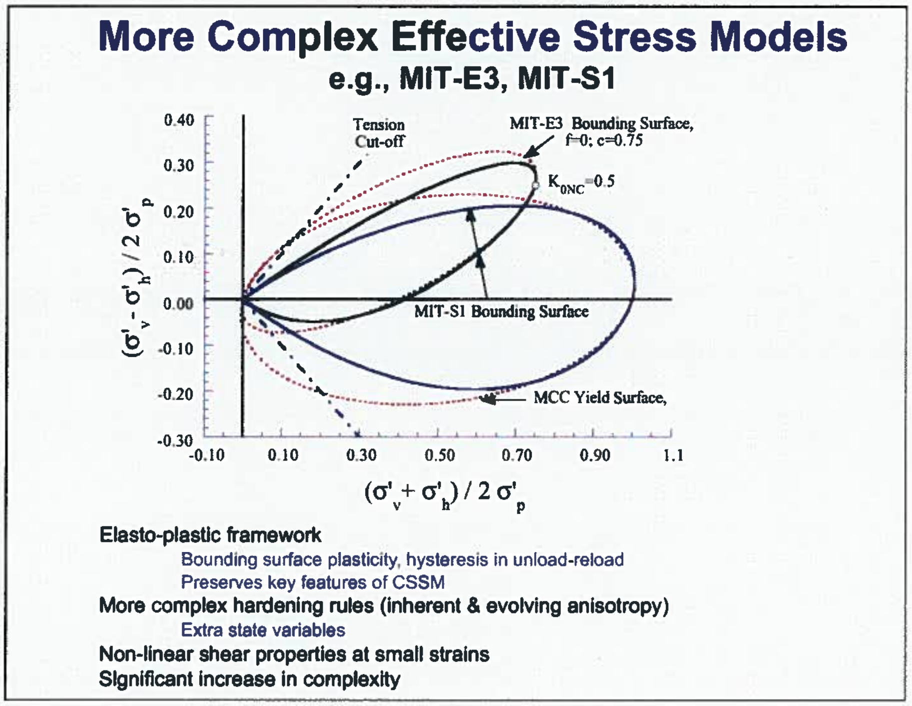
Terminology:
From Nicoll Highway Committee of Inquiry
Refers to application of MC model in Plaxis™ 2D program
Other methods assume clay is non-porous

Effective Stress Models

Modified Cam Clay (MCC) – Roscoe & Burland (1968)



Incrementally linearized elasto-plastic formulation
Linked to Critical State Soil Mechanics framework
    Unifies modeling of compression (e-logp') & shear behavior
Material Constants
    λ- slope of VCL (C_c)
    κ - slope of swelling line
    M – critical state friction coefficient [$M = 6\sin\phi'_{TC}/(3-\sin\phi'_{TC})$]
    ν' - Elastic Poisson's ratio
State Variables
    e - void ratio (updated through volume strain)
    p'_c - Isotropic pre-consolidation pressure



More Complex Effective Stress Models

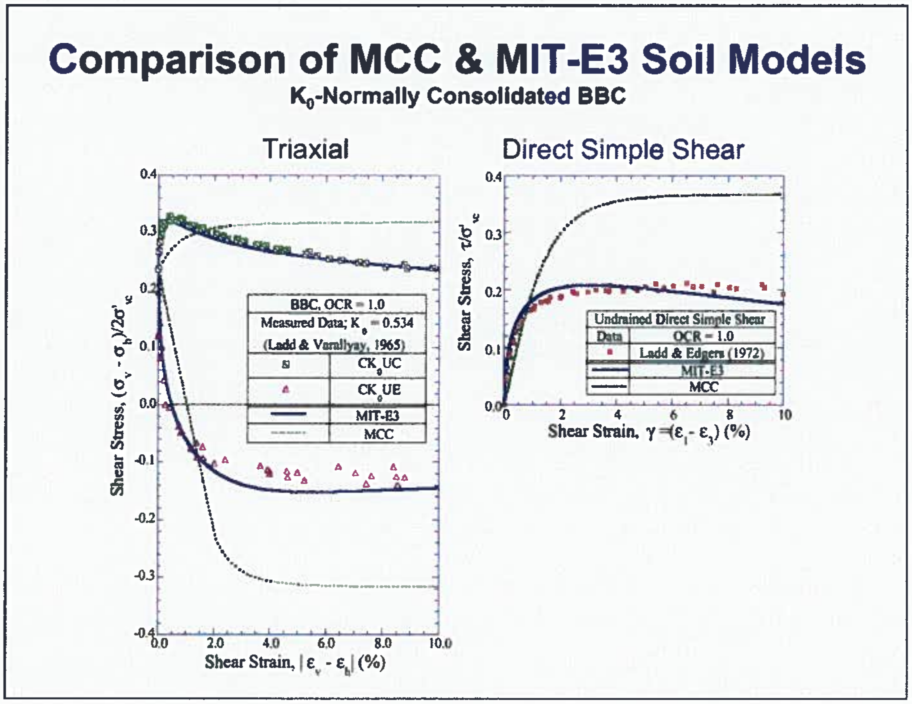
e.g., MIT-E3, MIT-S1

Elasto-plastic framework
- Bounding surface plasticity, hysteresis in unload-reload
- Preserves key features of CSSM

More complex hardening rules (inherent & evolving anisotropy)
- Extra state variables

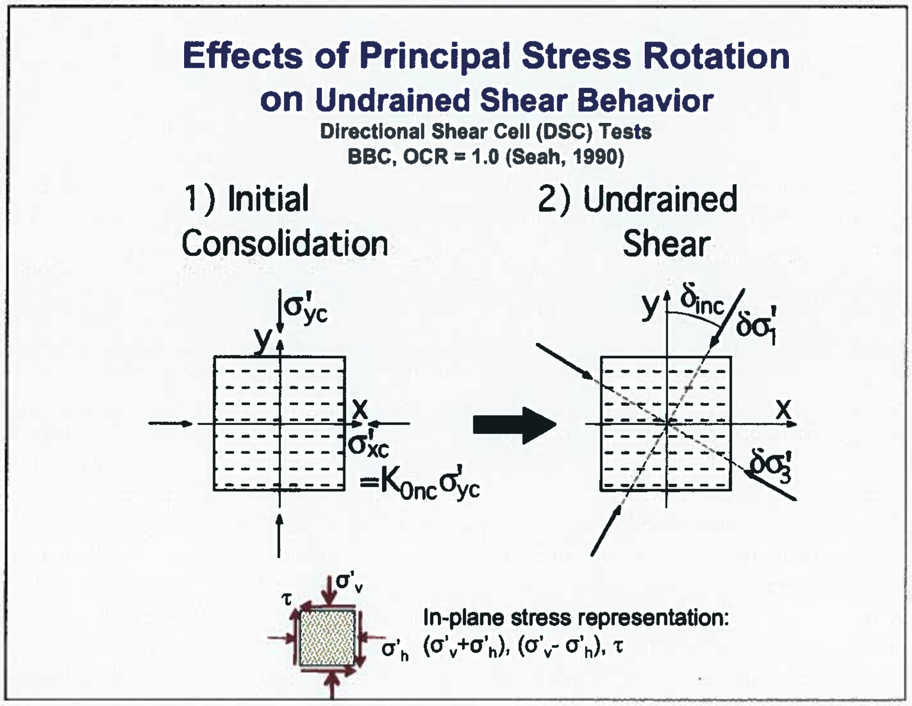
Non-linear shear properties at small strains

Significant increase in complexity



Comparison of MCC & MIT-E3 Soil Models

K_0-Normally Consolidated BBC



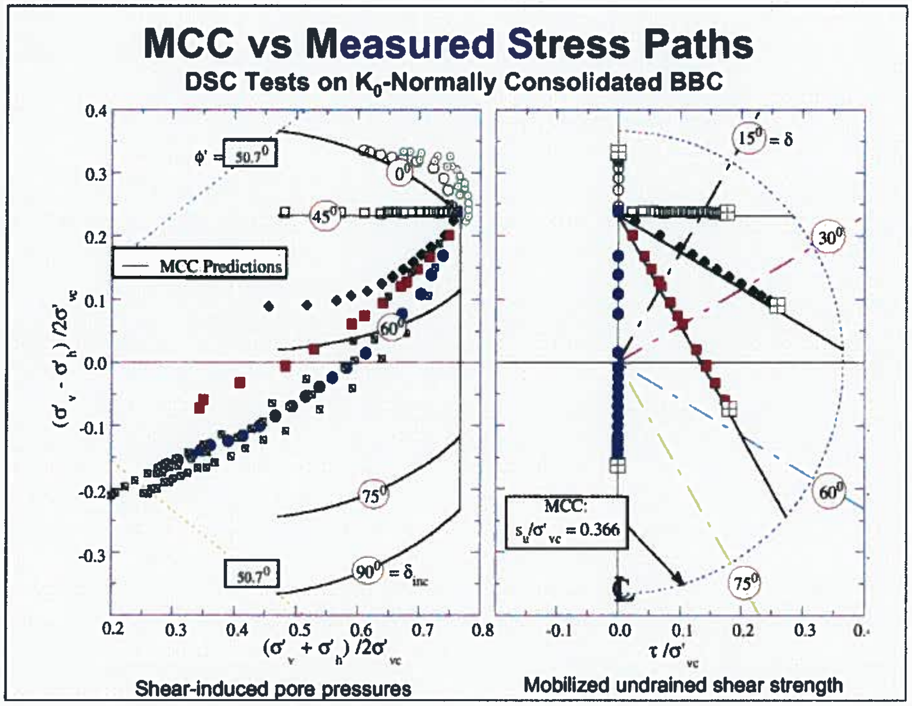
Effects of Principal Stress Rotation on Undrained Shear Behavior

Directional Shear Cell (DSC) Tests
BBC, OCR = 1.0 (Seah, 1990)

1) Initial Consolidation

2) Undrained Shear

In-plane stress representation: $(\sigma'_v+\sigma'_h)$, $(\sigma'_v-\sigma'_h)$, τ



MCC vs Measured Stress Paths

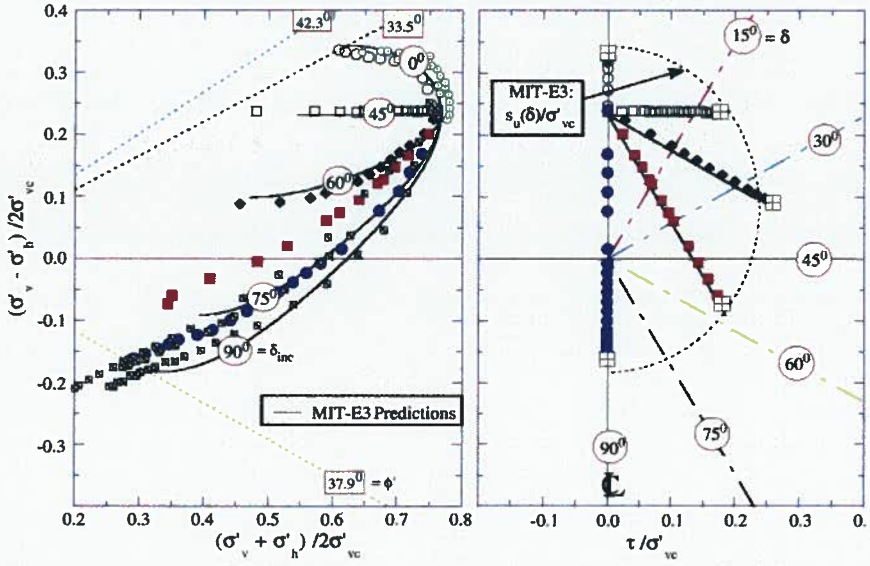
DSC Tests on K_0-Normally Consolidated BBC

Shear-induced pore pressures

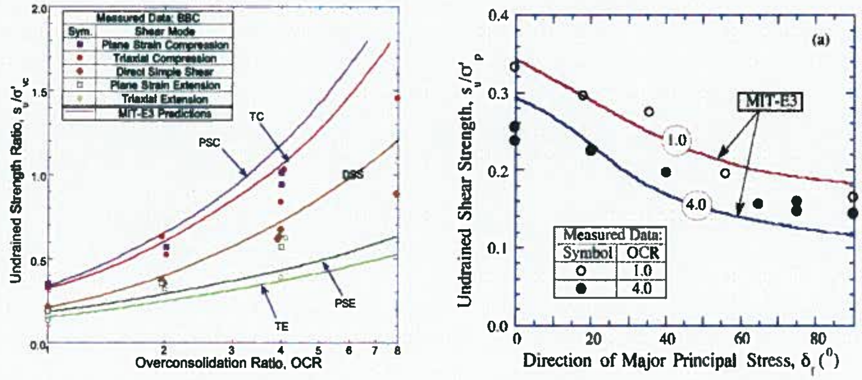
Mobilized undrained shear strength

MIT-E3 vs Measured Stress Paths

DSC Tests on K_0-Normally Consolidated BBC

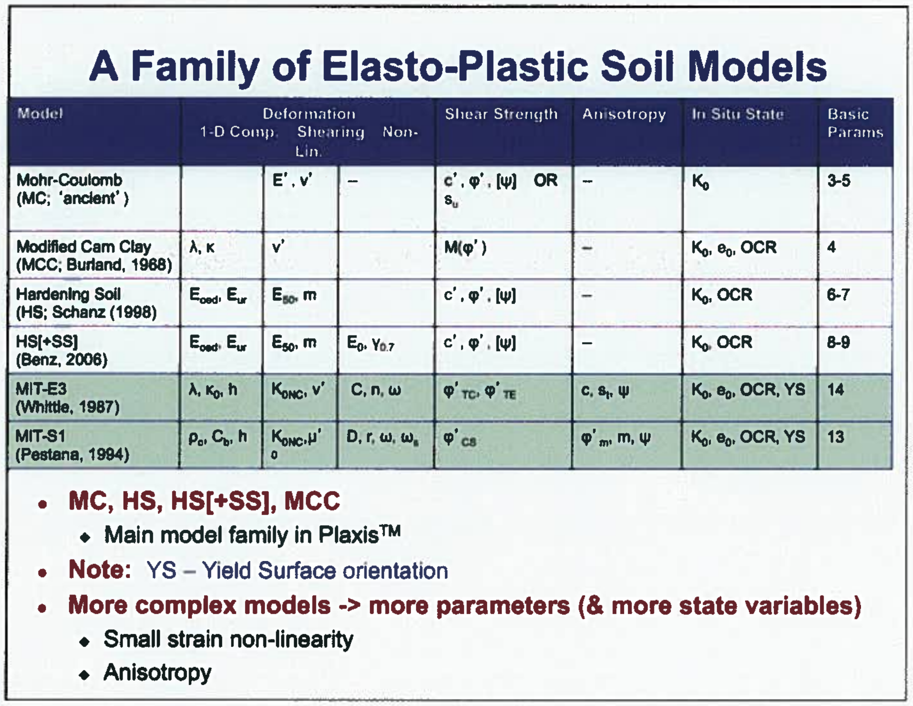


MIT-E3 Predictions of Stress History and Undrained Strength Anisotropy



Effect of OCR and Shear Mode

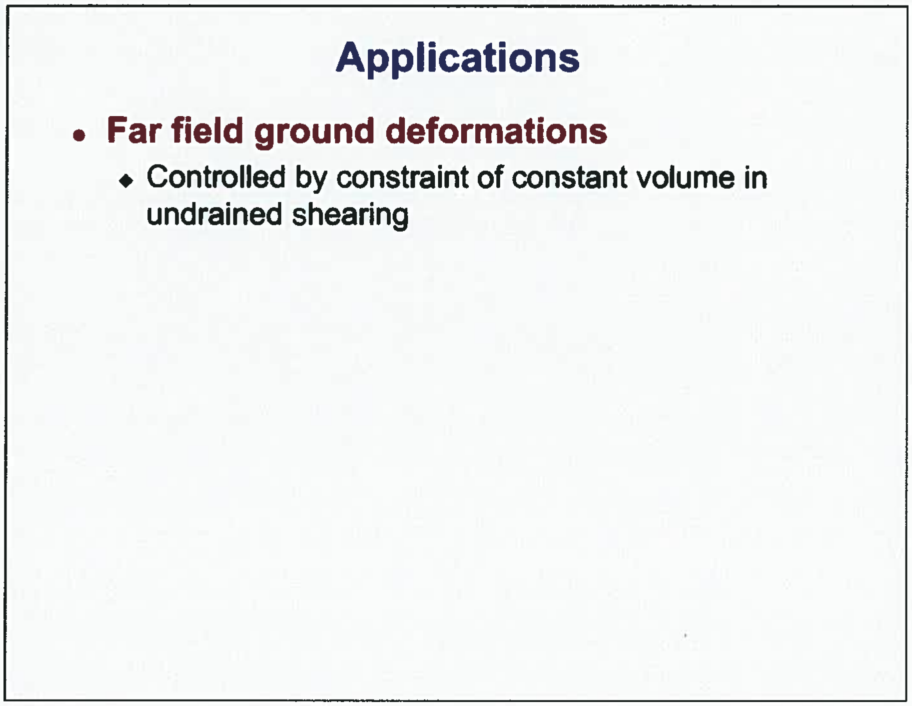
Effect of Principal Stress Orientation



A Family of Elasto-Plastic Soil Models

Model	Deformation 1-D Comp.	 Shearing	 Non-Lin.	Shear Strength	Anisotropy	In Situ State	Basic Params
Mohr-Coulomb (MC; 'ancient')		E', v'	–	c', φ', $[\psi]$ OR s_u	–	K_0	3-5
Modified Cam Clay (MCC; Burland, 1968)	λ, κ	v'		$M(\varphi')$	–	K_0, e_0, OCR	4
Hardening Soil (HS; Schanz (1998)	E_{oed}, E_{ur}	E_{50}, m		c', φ', $[\psi]$	–	K_0, OCR	6-7
HS[+SS] (Benz, 2006)	E_{oed}, E_{ur}	E_{50}, m	E_0, $\gamma_{0.7}$	c', φ', $[\psi]$	–	K_0, OCR	8-9
MIT-E3 (Whittle, 1987)	λ, κ_0, h	K_{0NC}, v'	C, n, ω	φ'_{TC}, φ'_{TE}	c, s_t, ψ	K_0, e_0, OCR, YS	14
MIT-S1 (Pestana, 1994)	ρ_c, C_b, h	K_{0NC}, μ'_0	D, r, ω, ω_s	φ'_{cs}	φ'_m, m, ψ	K_0, e_0, OCR, YS	13

- **MC, HS, HS[+SS], MCC**
  - Main model family in Plaxis™
- **Note:** YS – Yield Surface orientation
- **More complex models -> more parameters (& more state variables)**
  - Small strain non-linearity
  - Anisotropy



Applications

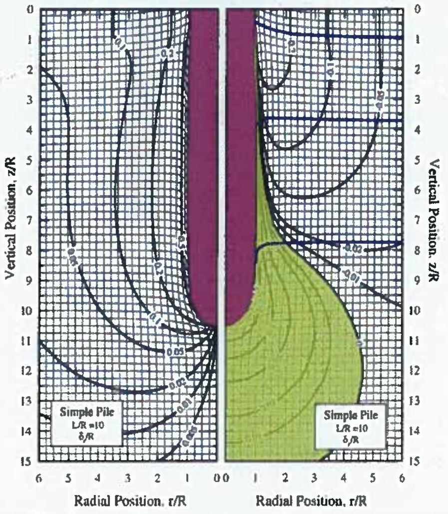
- **Far field ground deformations**
  - Controlled by constraint of constant volume in undrained shearing

Undrained Deformations Around Driven Piles

Shallow Strain Path Method (SSPM)

Assumes kinematics (deformations, strains & strain rates) are independent of constitutive behavior

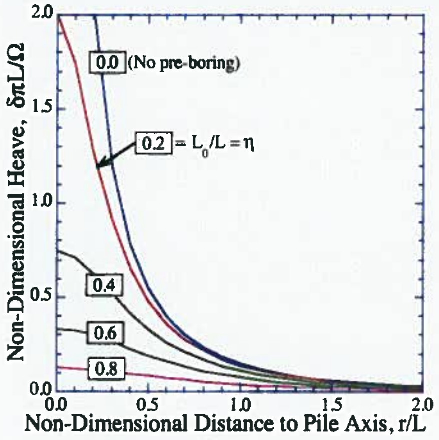
SSPM: Includes effects of stress-free ground surface



Simple pile:
Penetration to depth, z/R = 10

Sagaseta & Whittle (2001)

Ground Heave - SSPM Analytical Solutions



Surface Displacements :

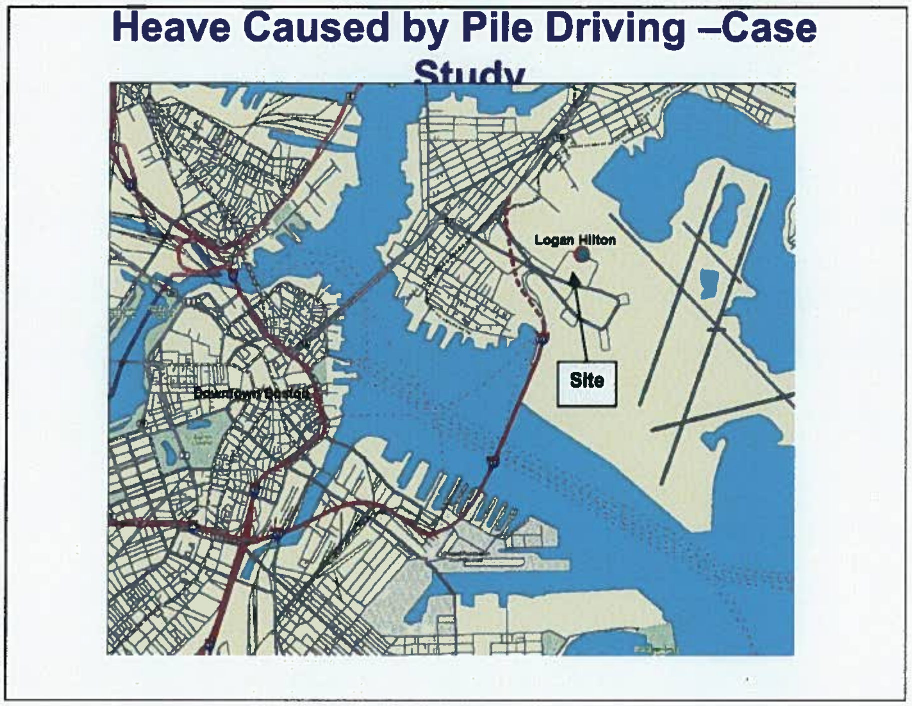
$$\delta_r = \frac{\Omega}{2\pi}\left(\frac{L}{r\sqrt{r^2+L^2}}\right)$$

$$\delta_z = \frac{\Omega}{2\pi}\left(\frac{1}{r}-\frac{1}{\sqrt{r^2+L^2}}\right)$$

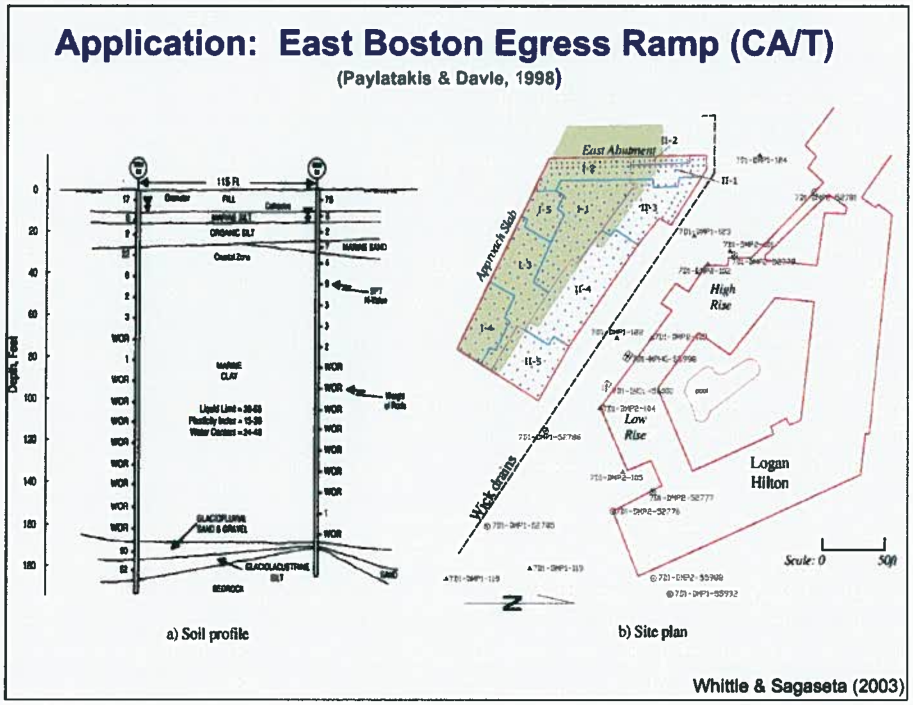
where : $\Omega = \pi R^2$

With Pre – Boring, η :

$$\delta_z = \frac{\Omega}{2\pi}\left(\frac{1}{\sqrt{r^2+(\eta L)^2}}-\frac{1}{\sqrt{r^2+L^2}}\right)$$



Heave Caused by Pile Driving –Case Study



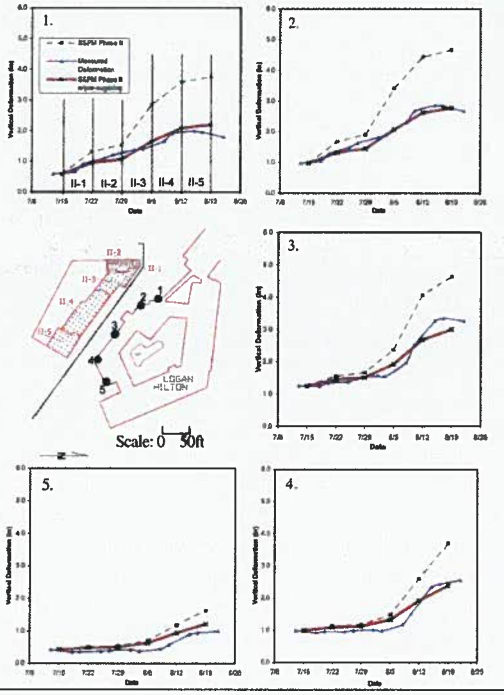
Application: East Boston Egress Ramp (CA/T)

(Paylatakis & Davie, 1998)

a) Soil profile

b) Site plan

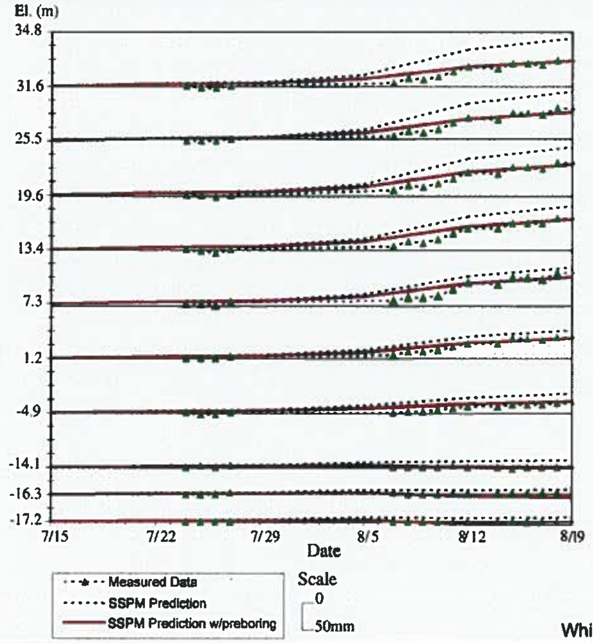
Whittle & Sagaseta (2003)



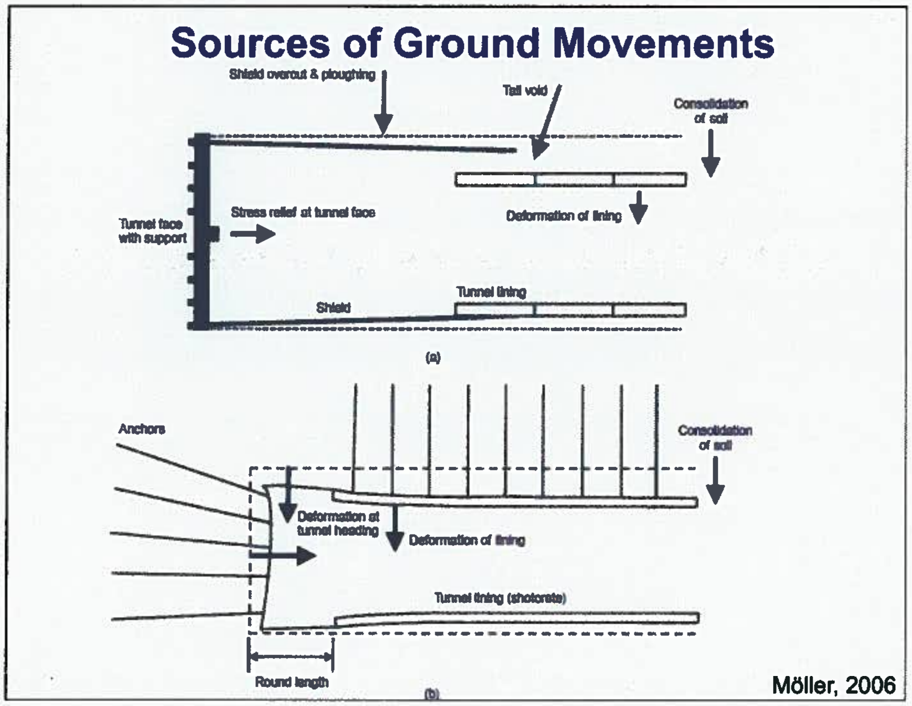
Comparison of Phase 2 Surface Settlements

Whittle & Sagaseta (2003)

Vertical Displacements within Clay

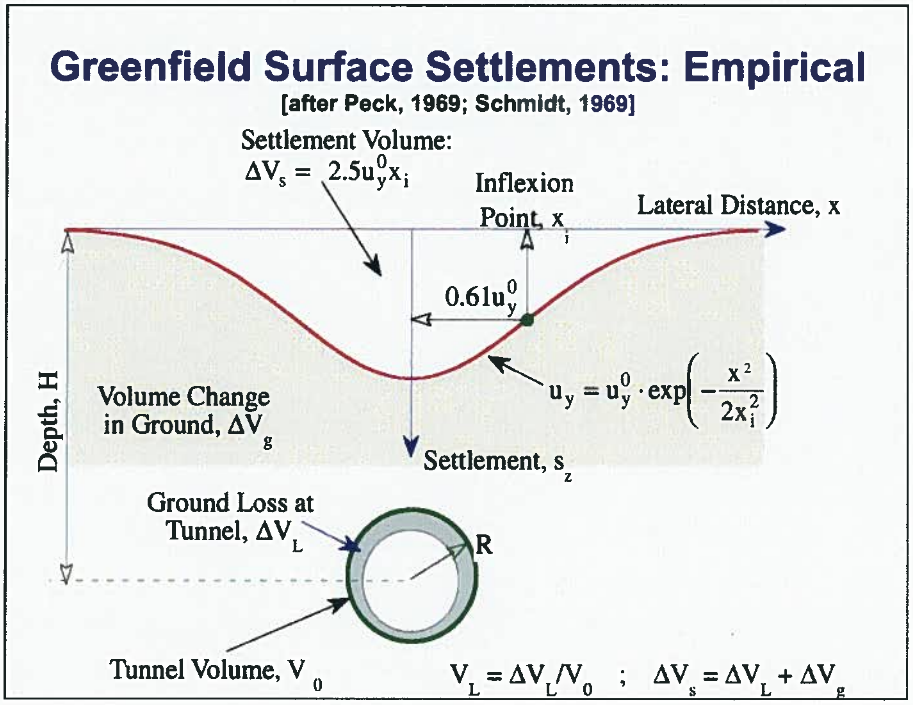


Whittle & Sagaseta (2003)



Sources of Ground Movements

Möller, 2006



Greenfield Surface Settlements: Empirical

[after Peck, 1969; Schmidt, 1969]

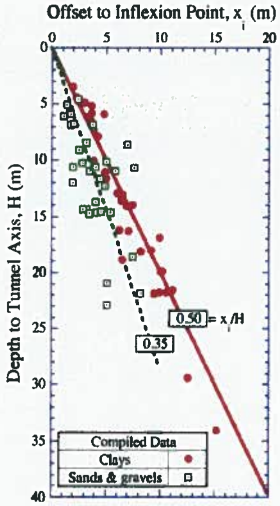
Settlement Volume:
$\Delta V_s = 2.5 u_y^0 x_i$

$$u_y = u_y^0 \cdot \exp\left(-\frac{x^2}{2x_i^2}\right)$$

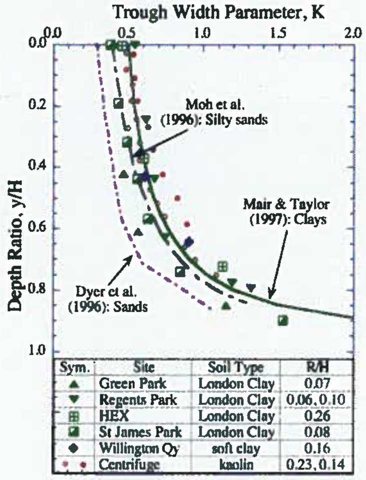
$V_L = \Delta V_L / V_0$; $\Delta V_s = \Delta V_L + \Delta V_g$

Empirical Interpretation of Sub-Surface Settlements

(Mair & Taylor, 1997)



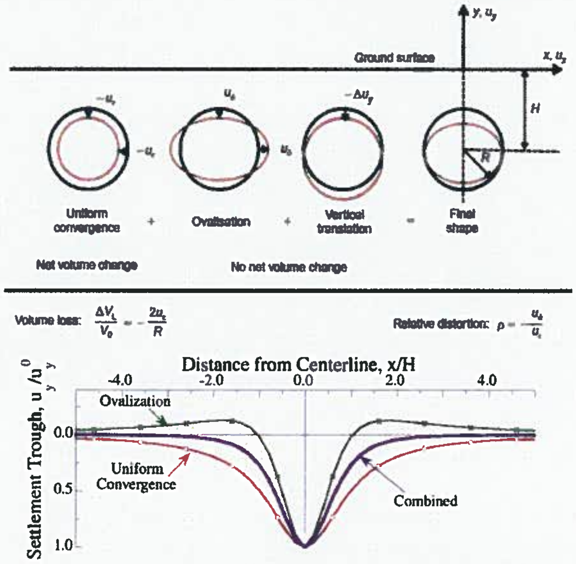
Surface Settlements



Sym.	Site	Soil Type	R/H
▲	Green Park	London Clay	0.07
▼	Regents Park	London Clay	0.06, 0.10
⊞	HEX	London Clay	0.26
◪	St James Park	London Clay	0.08
◆	Willington Qy	soft clay	0.16
● ●	Centrifuge	kaolin	0.23, 0.14

Subsurface settlements:
$x_i/H = K(1-y/H)$

Modes of Deformation Around Tunnel Cavity

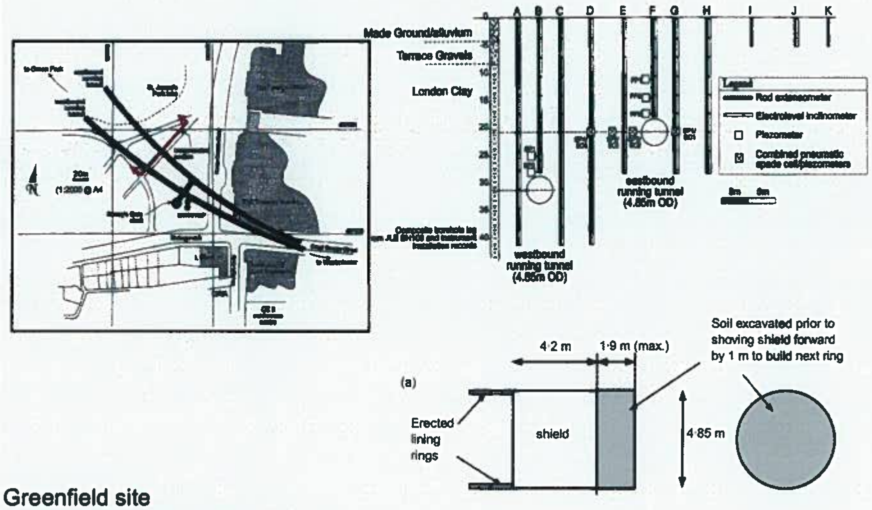


b) Component contributions to surface settlement trough

Pinto &Whittle (2013)

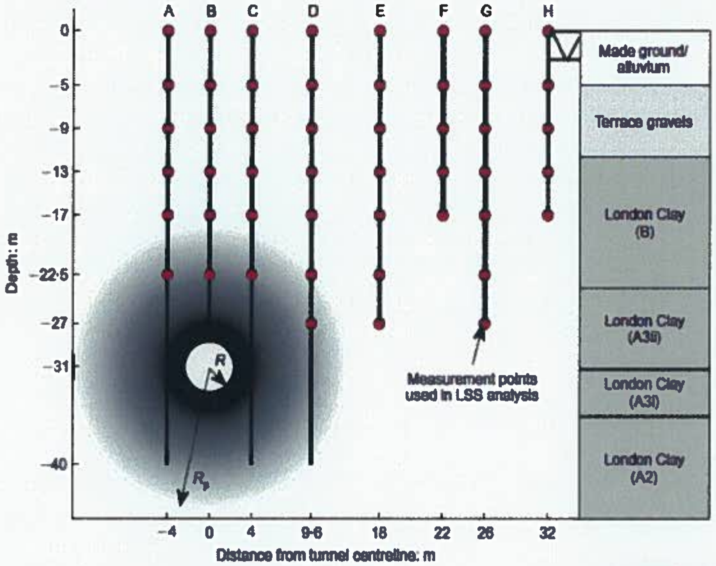
JLE St. James Park

(Nyren, 1998; Standing & Burland, 2006)

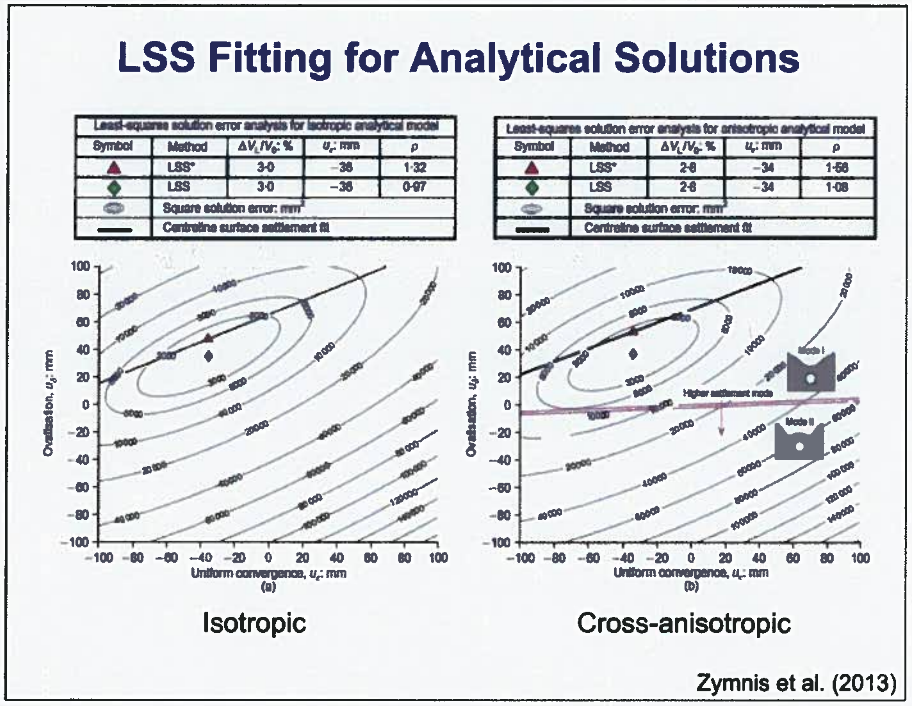


Greenfield site
Open-face shield construction
Relatively uniform ground conditions

Interpretation of Analytical Solutions



Zymnis et al. (2013)



LSS Fitting for Analytical Solutions

Least-squares solution error analysis for isotropic analytical model

Symbol	Method	$\Delta V_L/V_0$: %	u_ε: mm	ρ
▲	LSS*	3·0	−36	1·32
◆	LSS	3·0	−36	0·97
⬭	Square solution error: mm²			
—	Centreline surface settlement fit			

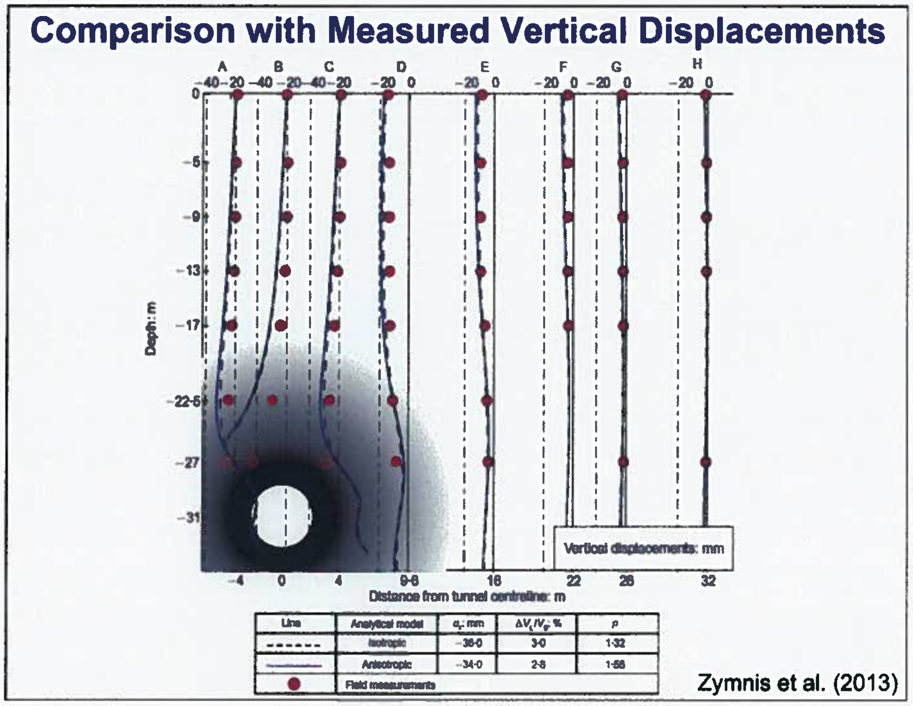
Least-squares solution error analysis for anisotropic analytical model

Symbol	Method	$\Delta V_L/V_0$: %	u_ε: mm	ρ
▲	LSS*	2·6	−34	1·56
◆	LSS	2·6	−34	1·08
⬭	Square solution error: mm²			
—	Centreline surface settlement fit			

Isotropic

Cross-anisotropic

Zymnis et al. (2013)

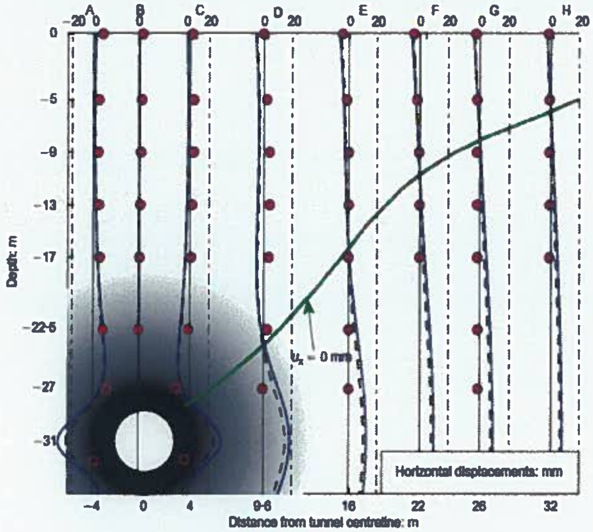


Comparison with Measured Vertical Displacements

Line	Analytical model	u_ε: mm	$\Delta V_L/V_0$: %	ρ
- - - - - -	Isotropic	−36·0	3·0	1·32
——	Anisotropic	−34·0	2·6	1·66
●	Field measurements			

Zymnis et al. (2013)

vs Measured Horizontal Displacements

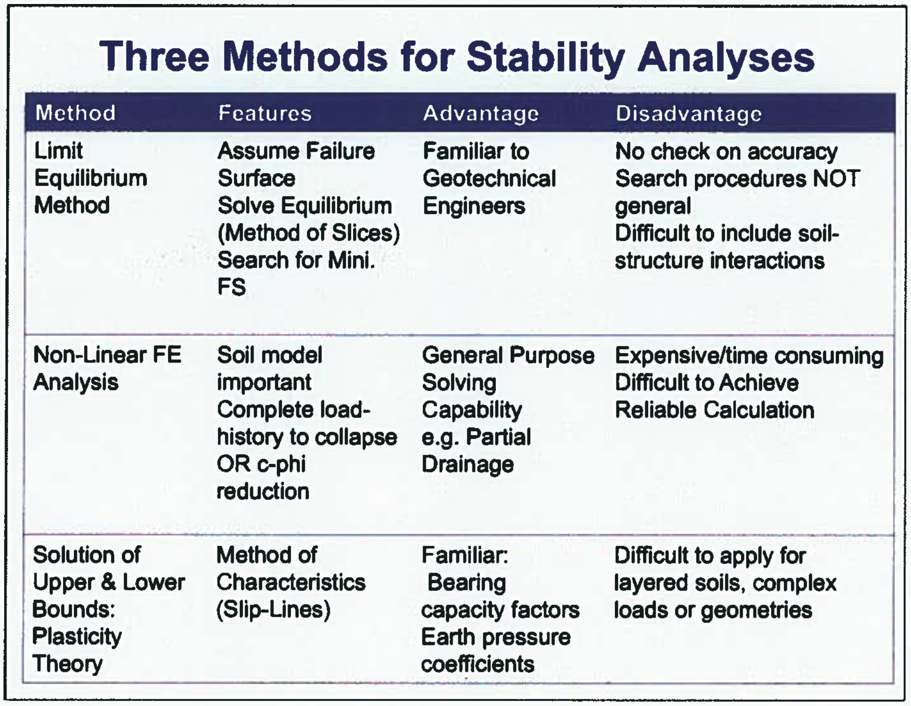


Line	Analytical model	u_ε: mm	$\Delta V_L/V_0$: %	ρ
- - - - - -	Isotropic	−38·0	3·0	1·32
———	Anisotropic	−34·0	2·8	1·66
●	Field measurements			

Zymnis et al. (2013)

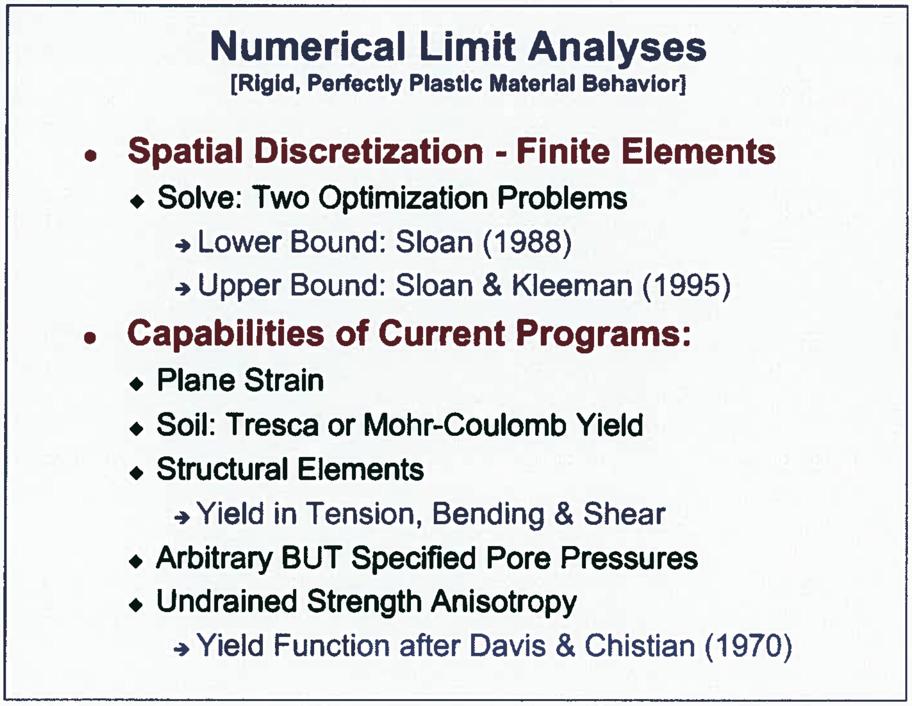
Applications

- Far field ground deformations
    - Controlled by constraint of constant volume in undrained shearing
- **Undrained stability problems**
    - Undrained shear strength is critical



Three Methods for Stability Analyses

Method	Features	Advantage	Disadvantage
Limit Equilibrium Method	Assume Failure Surface Solve Equilibrium (Method of Slices) Search for Mini. FS	Familiar to Geotechnical Engineers	No check on accuracy Search procedures NOT general Difficult to include soil-structure interactions
Non-Linear FE Analysis	Soil model important Complete load-history to collapse OR c-phi reduction	General Purpose Solving Capability e.g. Partial Drainage	Expensive/time consuming Difficult to Achieve Reliable Calculation
Solution of Upper & Lower Bounds: Plasticity Theory	Method of Characteristics (Slip-Lines)	Familiar: Bearing capacity factors Earth pressure coefficients	Difficult to apply for layered soils, complex loads or geometries

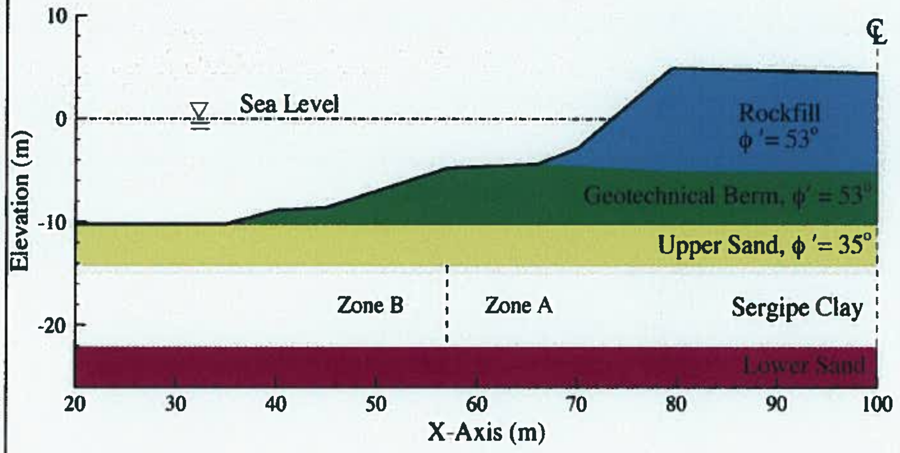


Numerical Limit Analyses

[Rigid, Perfectly Plastic Material Behavior]

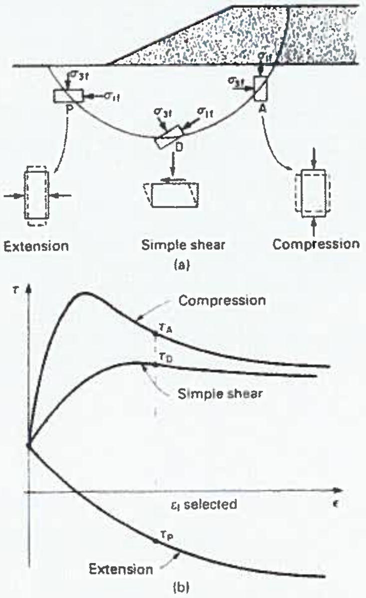
- **Spatial Discretization - Finite Elements**
  - Solve: Two Optimization Problems
    - Lower Bound: Sloan (1988)
    - Upper Bound: Sloan & Kleeman (1995)
- **Capabilities of Current Programs:**
  - Plane Strain
  - Soil: Tresca or Mohr-Coulomb Yield
  - Structural Elements
    - Yield in Tension, Bending & Shear
  - Arbitrary BUT Specified Pore Pressures
  - Undrained Strength Anisotropy
    - Yield Function after Davis & Chistian (1970)

Failure of Offshore Breakwater, Sergipe, Brazil



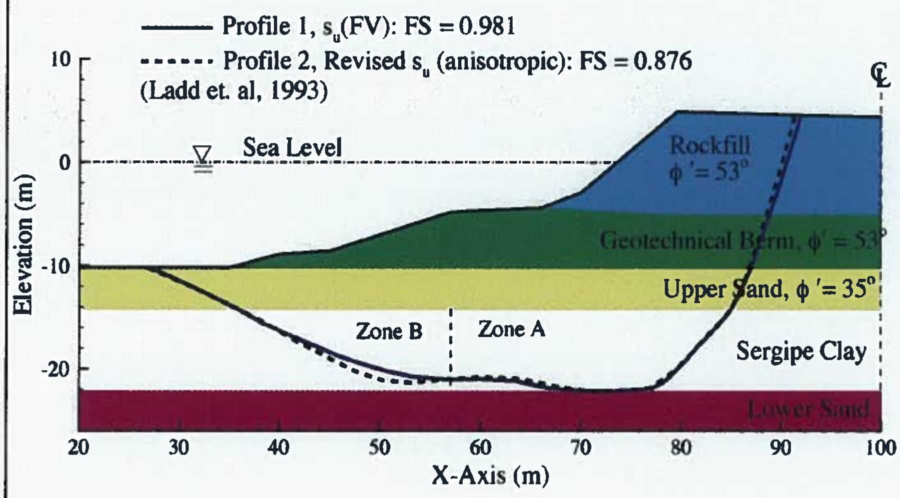
Ladd et al. (1993)

Undrained Strength Anisotropy

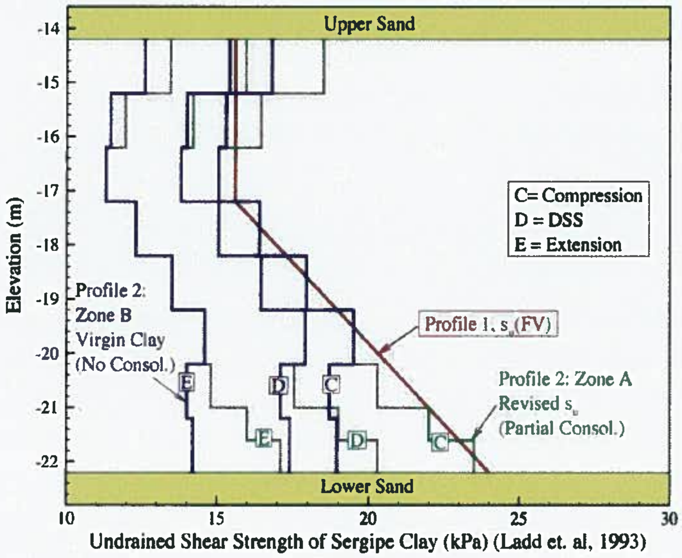


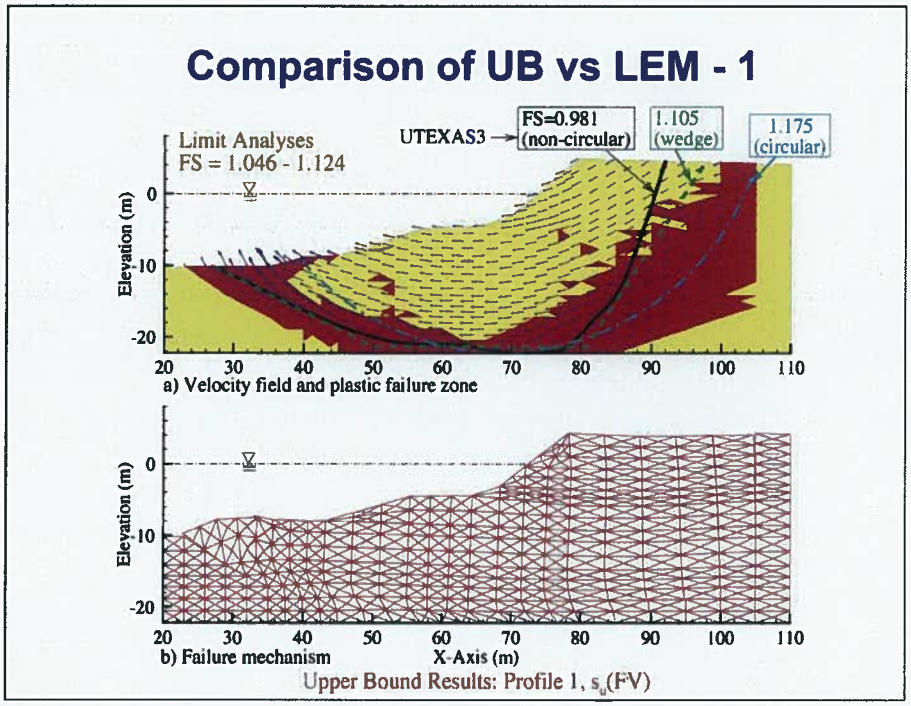
Importance of shear modes in stability analyses

Limit Equilibrium Results



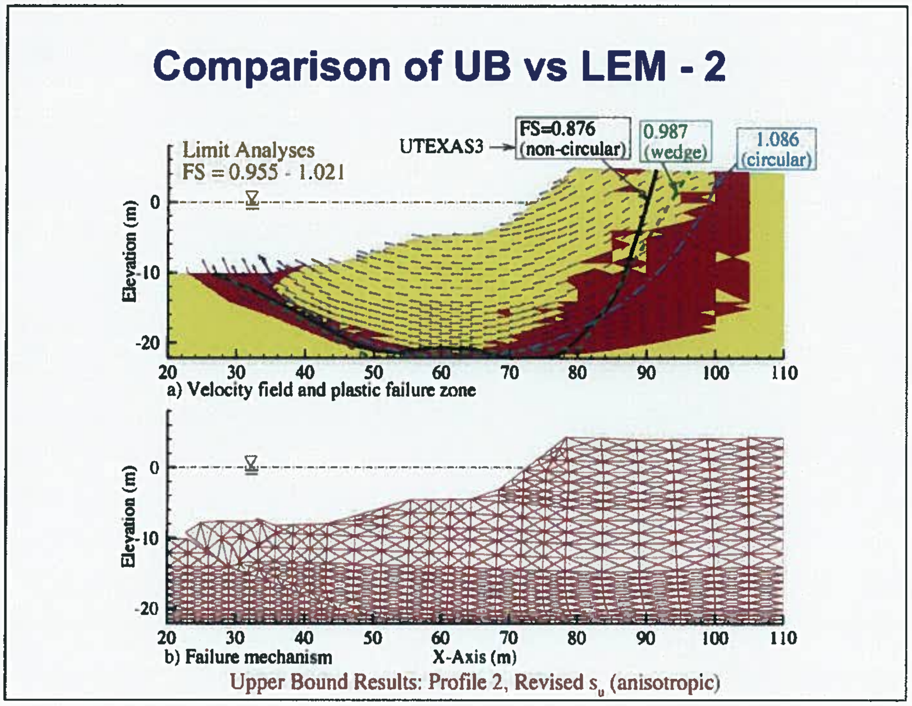
Undrained Strength - Sergipe Clay





Comparison of UB vs LEM - 1

Upper Bound Results: Profile 1, s_u(FV)

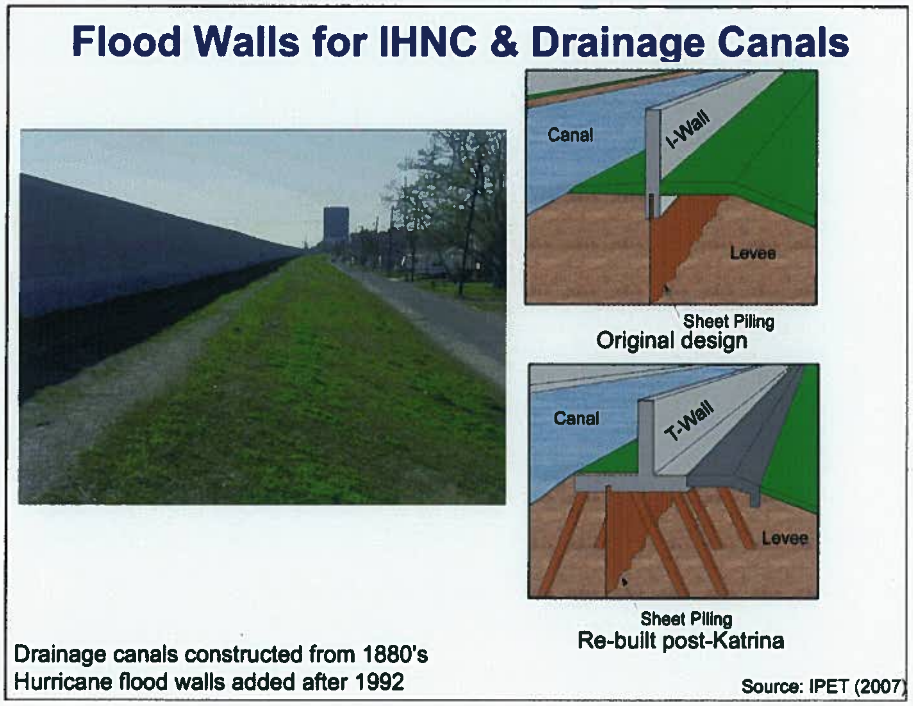


Comparison of UB vs LEM - 2

Upper Bound Results: Profile 2, Revised s_u (anisotropic)

Breach at 17th Street Canal

Source: IPET



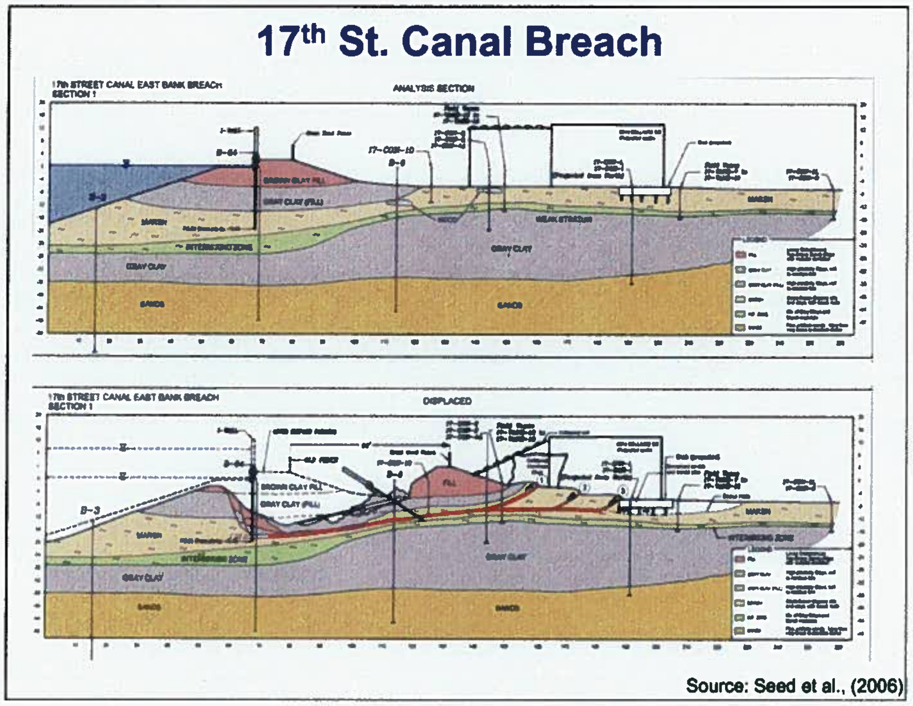
Flood Walls for IHNC & Drainage Canals

Original design

Re-built post-Katrina

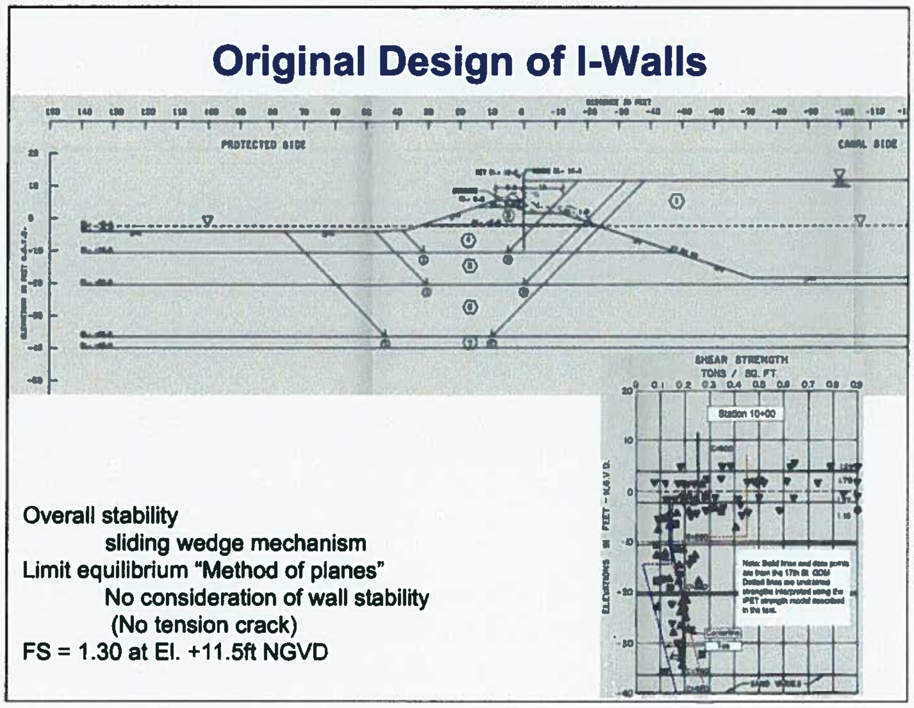
Drainage canals constructed from 1880's
Hurricane flood walls added after 1992

Source: IPET (2007)



17th St. Canal Breach

Source: Seed et al., (2006)



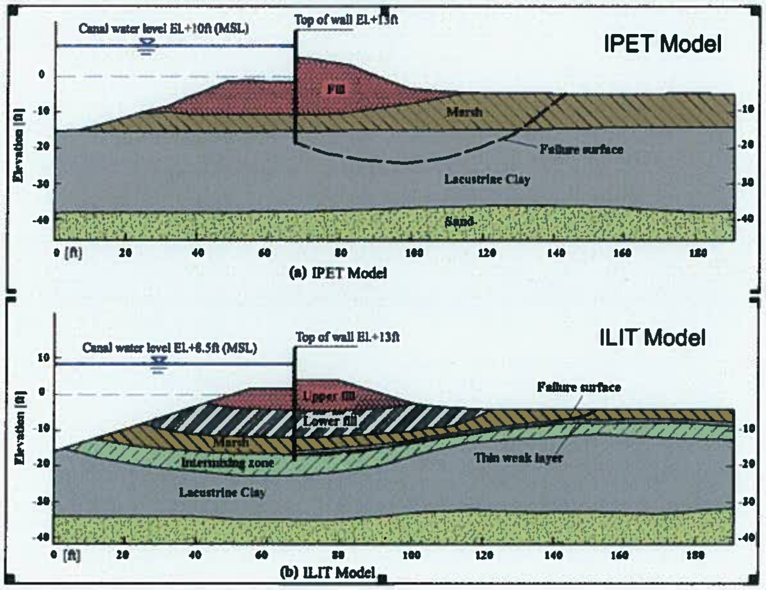
Original Design of I-Walls

Overall stability
- sliding wedge mechanism

Limit equilibrium "Method of planes"
- No consideration of wall stability
- (No tension crack)

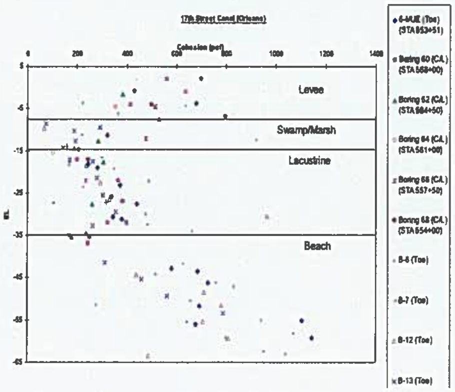
FS = 1.30 at El. +11.5ft NGVD

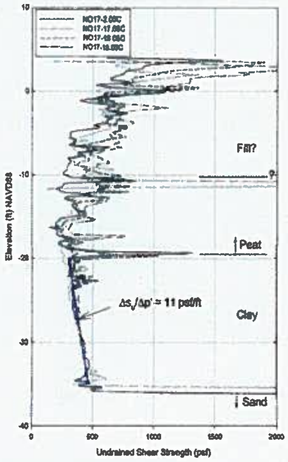
17th Street Canal: Stratigraphy – Two Versions



(Yuan & Whittle, 2013)

Undrained Shear Strength – Spatial Variability vs Noisy Data





Lab:

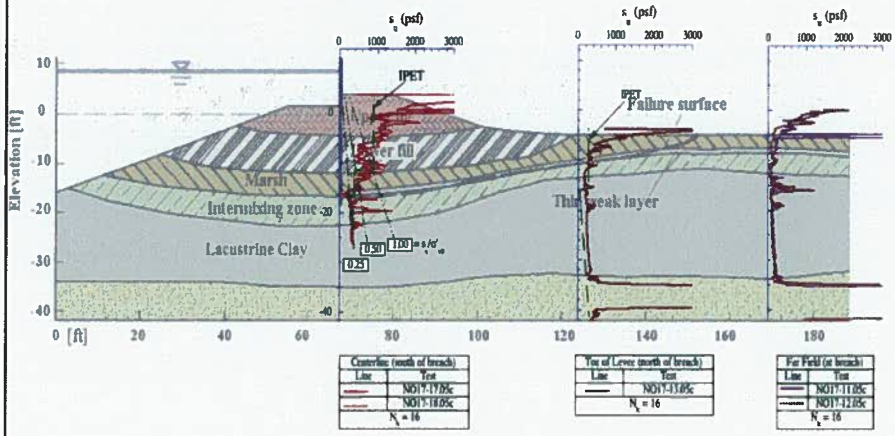
- Data scatter mainly attributable to sample disturbance
- Improved sample protocols and testing essential

Piezocone:

- Highlights uniformity of underlying lacustrine clays

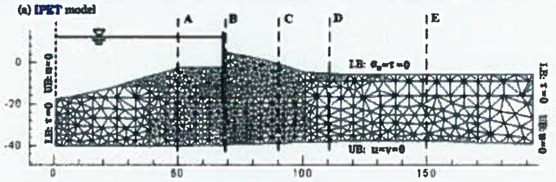
Undrained Stability – 17th Street Canal

[unpublished – Whittle, 2006]

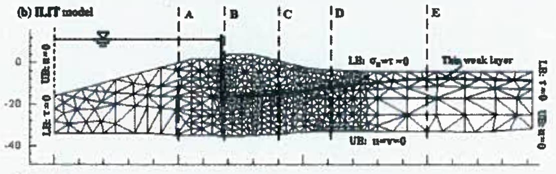


17th Street Canal: Shear Strength Profiles

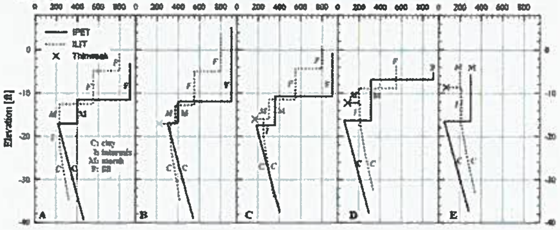
(a) IPET model

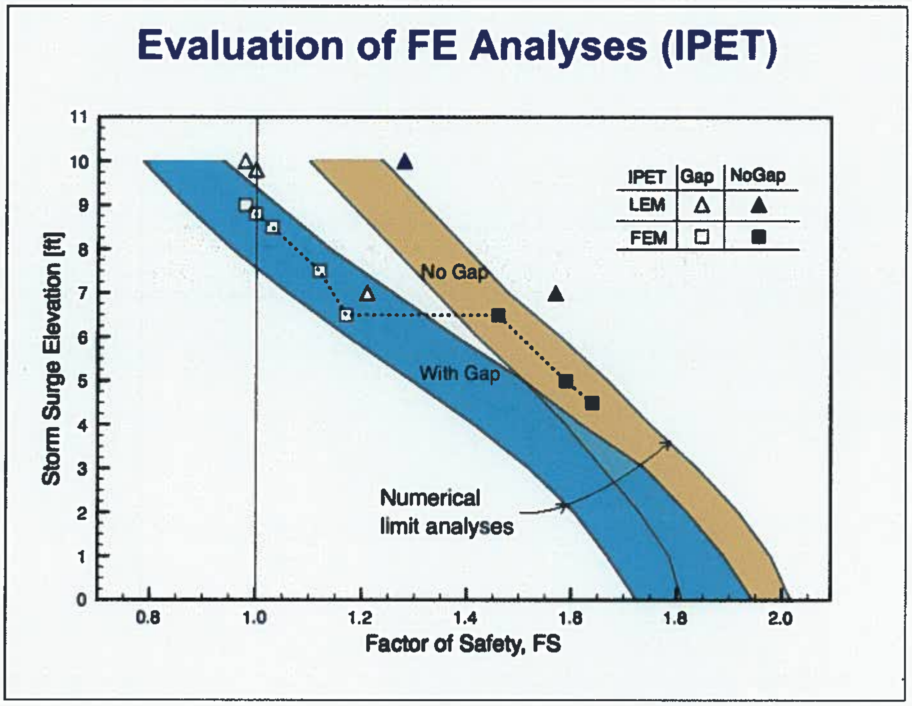


(b) ILIT model



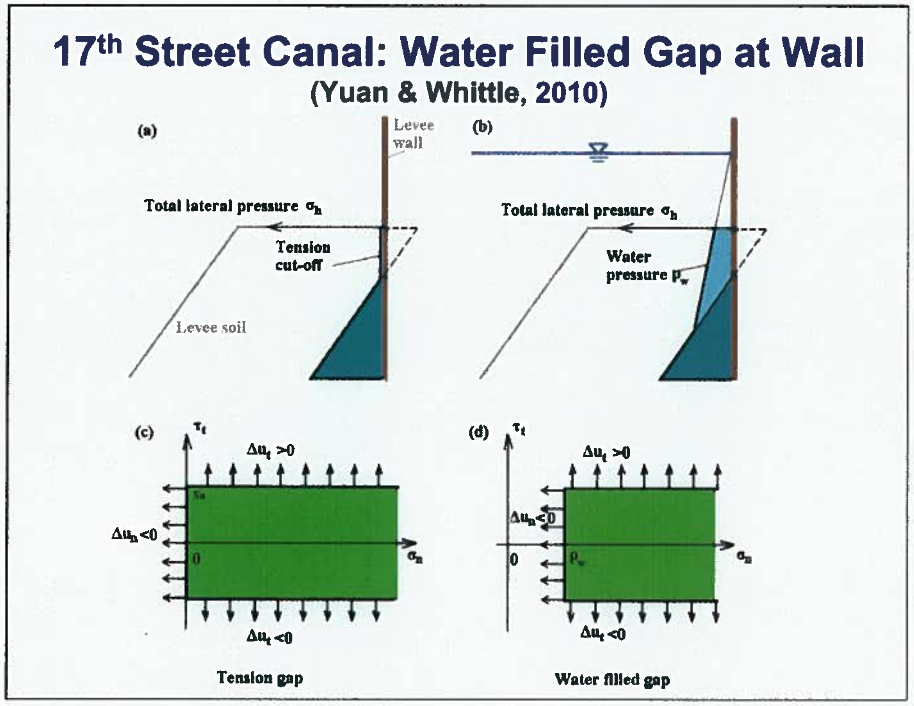
(c) Su [psf]





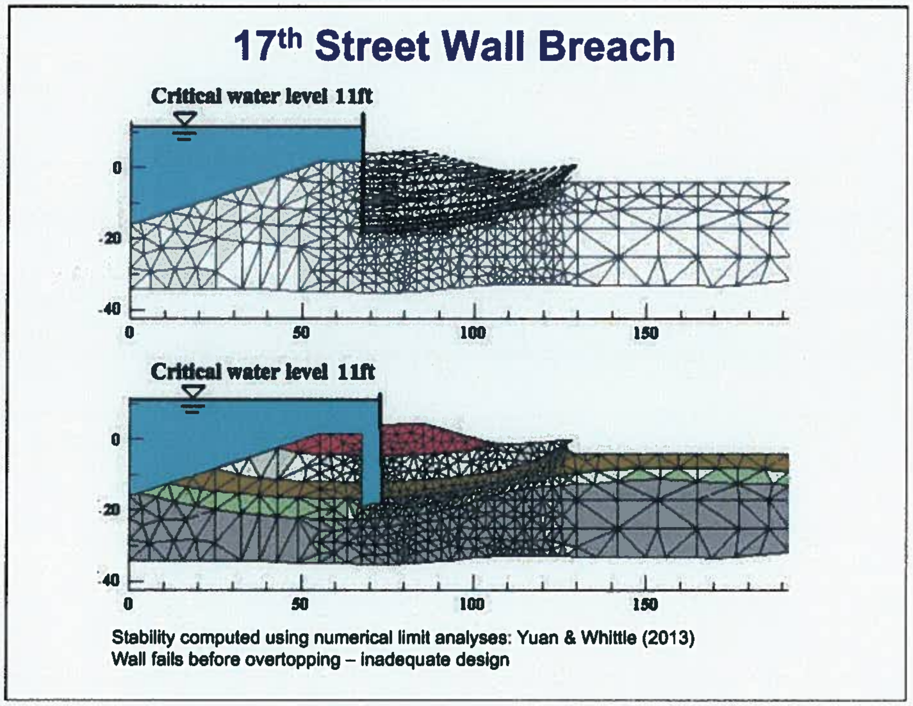
Evaluation of FE Analyses (IPET)

IPET	Gap	NoGap
LEM	△	▲
FEM	□	■



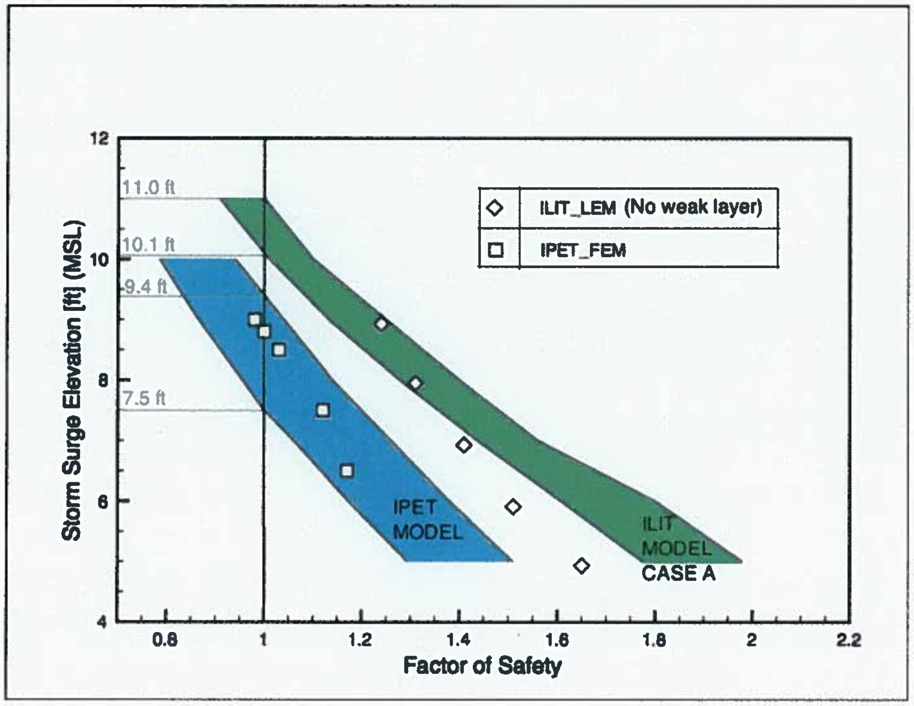
17th Street Canal: Water Filled Gap at Wall

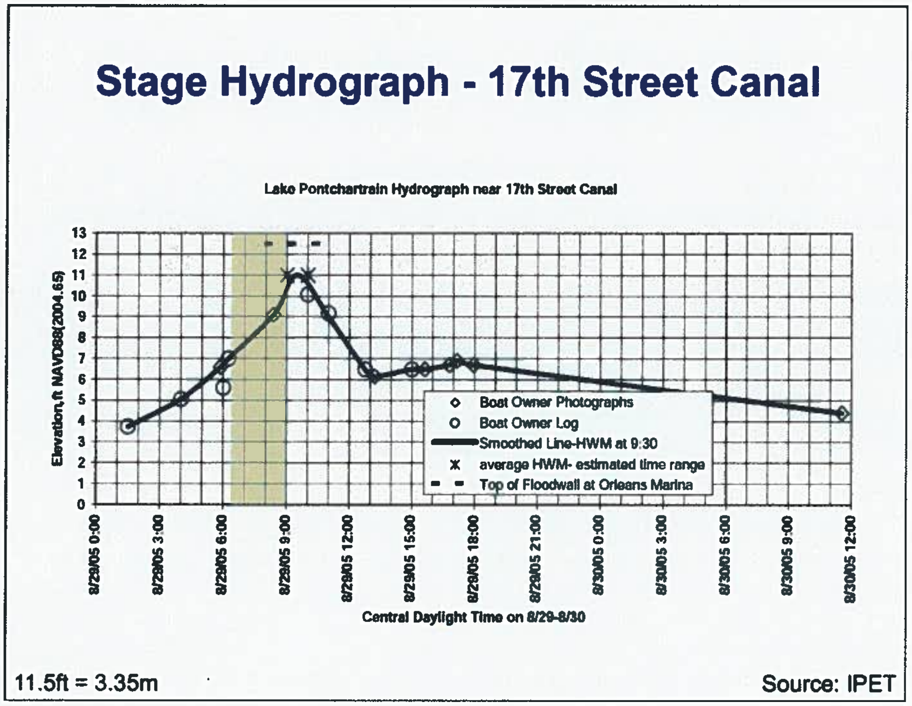
(Yuan & Whittle, 2010)



17th Street Wall Breach

Stability computed using numerical limit analyses: Yuan & Whittle (2013)
Wall fails before overtopping – inadequate design

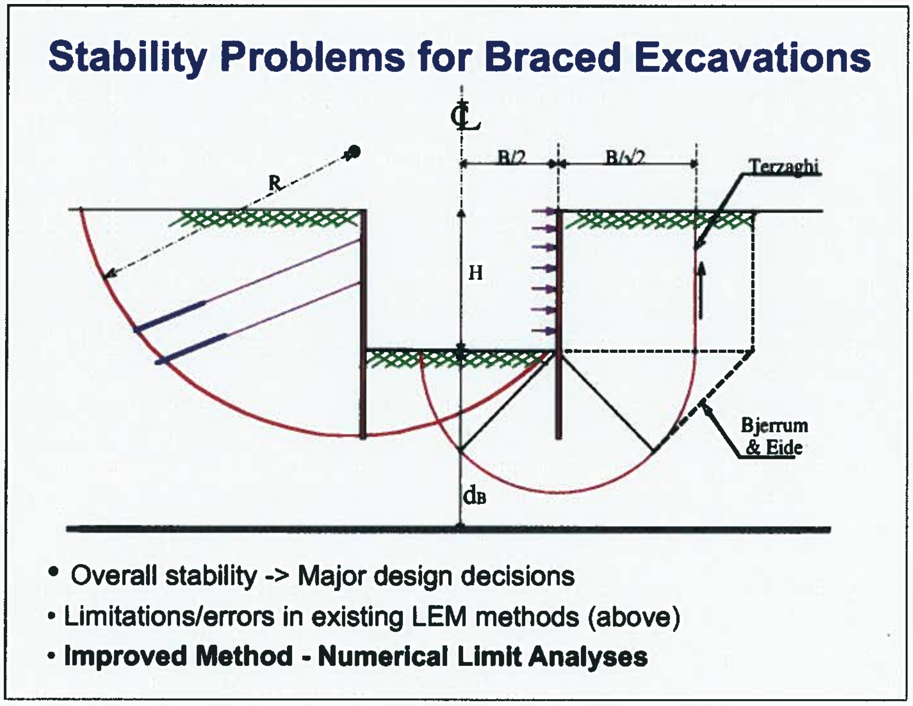




Stage Hydrograph - 17th Street Canal

11.5ft = 3.35m

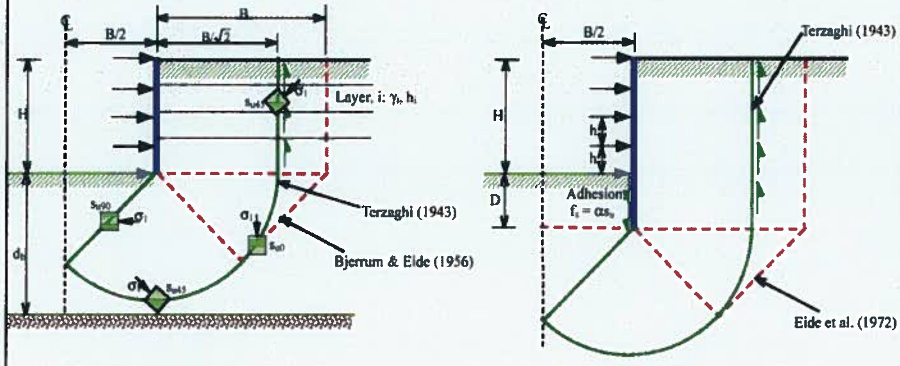
Source: IPET



Stability Problems for Braced Excavations

- Overall stability -> Major design decisions
- Limitations/errors in existing LEM methods (above)
- **Improved Method - Numerical Limit Analyses**

Existing Methods for Basal Stability

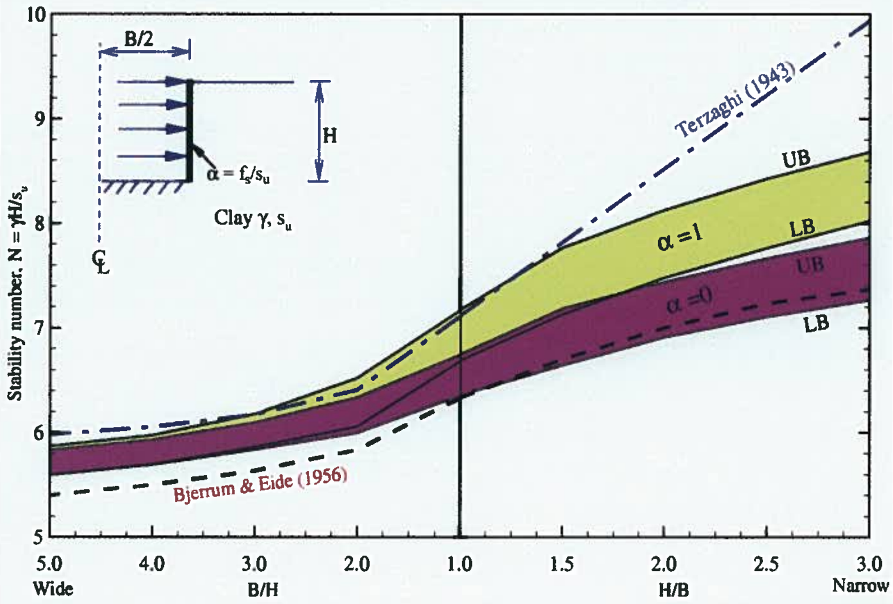


a) Without wall embedment
(principal stress directions after Clough & Hansen, 1981)

b) With wall embedment

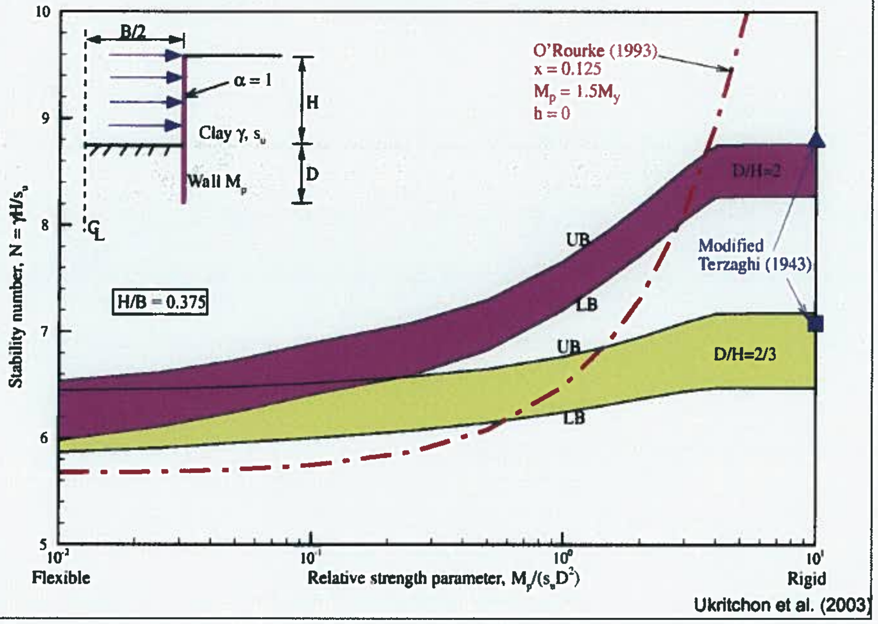
Ukritchon et al. (2003)

Braced Vertical Cut in Clay



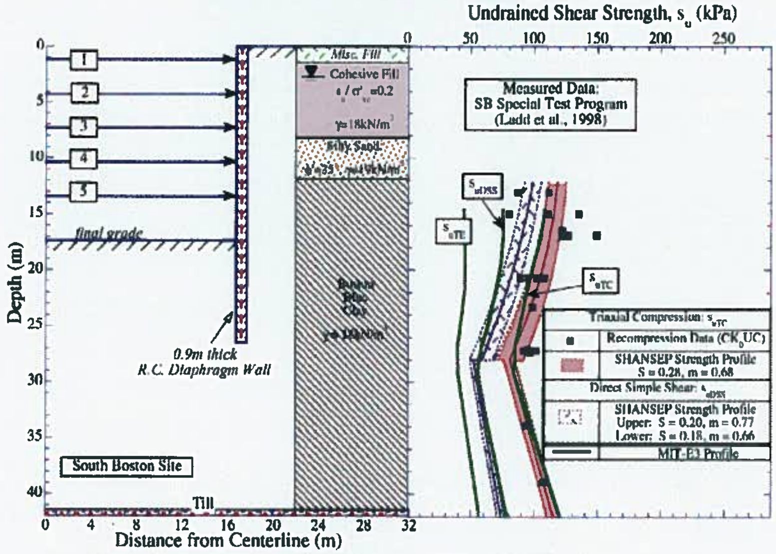
Ukritchon et al. (2003)

Effect of Wall Embedment



Ukritchon et al. (2003)

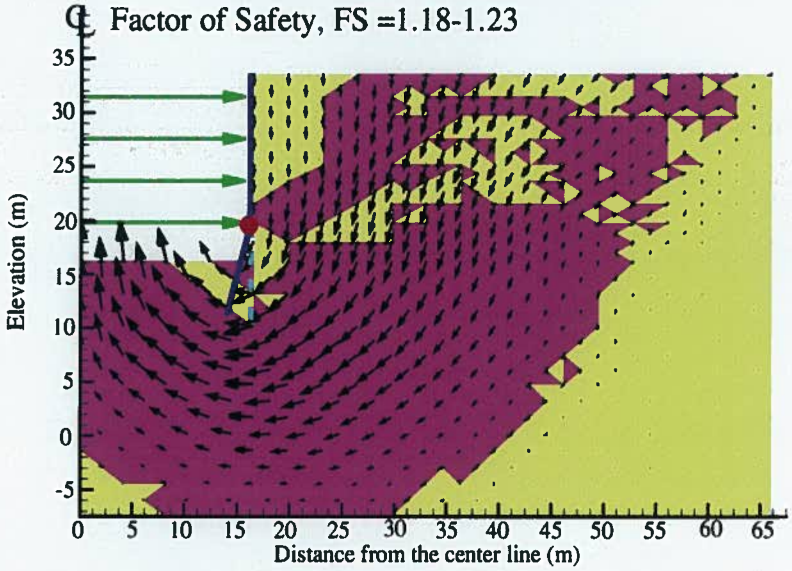
Braced Excavation in South Boston MBTA Transitway



- Very low margin of safety on basal stability

Stability of Excavation:

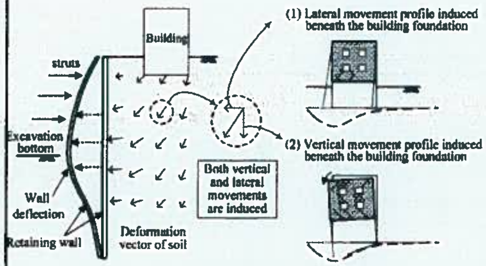
MBTA Transitway South Boston

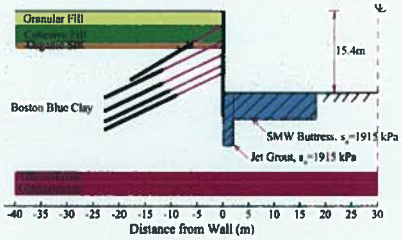


Applications

- Far field ground deformations
  - Controlled by constraint of constant volume in undrained shearing
- Undrained stability problems
  - Undrained shear strength is critical
- **Performance of excavation support systems**
  - **Role of soil modeling**

Performance of Excavation Support Systems





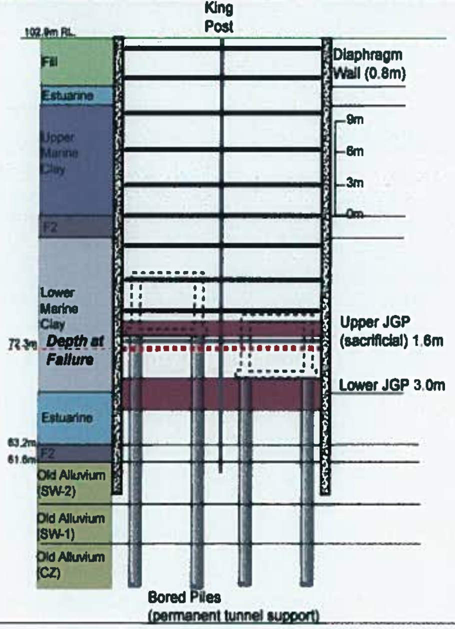
- **Key Components**
  - Ground Deformations -> Adjacent Facilities
  - Structural Design (Wall & Bracing System)
  - Construction Procedures
  - Groundwater Control, Ground Improvement

Collapse of Nicoll Highway, Singapore

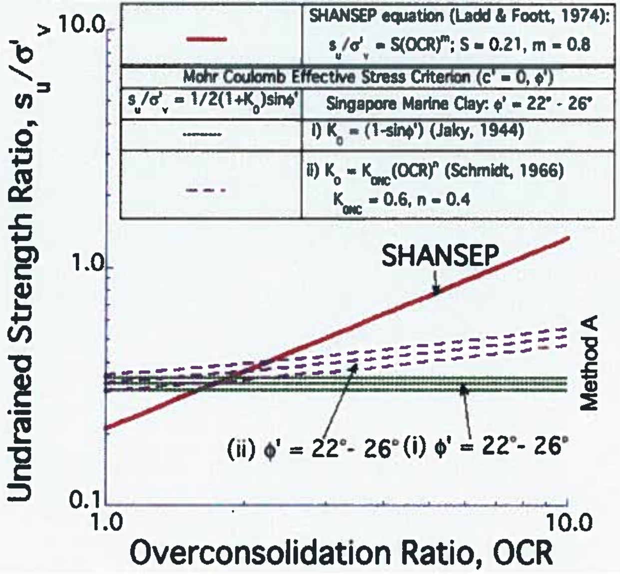
April 2004

Court of Inquiry Report (COI; May 2005)
Causes of failure investigated by 18 experts
Back-analyses and diagnoses of collapse mechanism
All done with MC model & limited field strength data

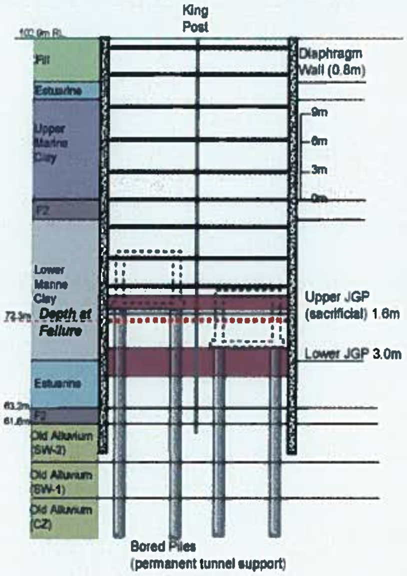
Excavation Support - Section M3

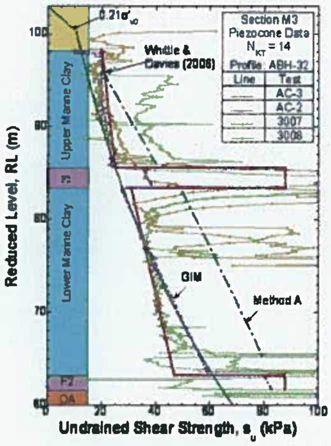


Overestimation of Undrained Shear Strength in Design
Limitations of MC Model (Method A)



Nicoll Highway: Design Section & Soil Profile

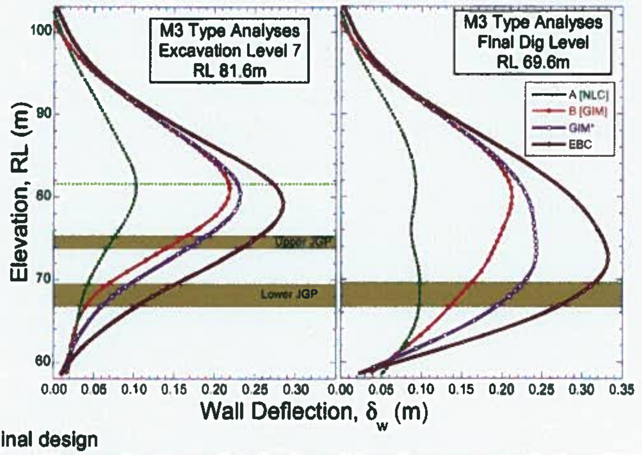




Piezocone strength data
(no reliable lab data)
Method A – overestimates s_u
GIM – Method B (design profile)
Lower Marine Clay - underconsolidated

Whittle & Davies (2006)

Wall Deflections - M3 Design Section

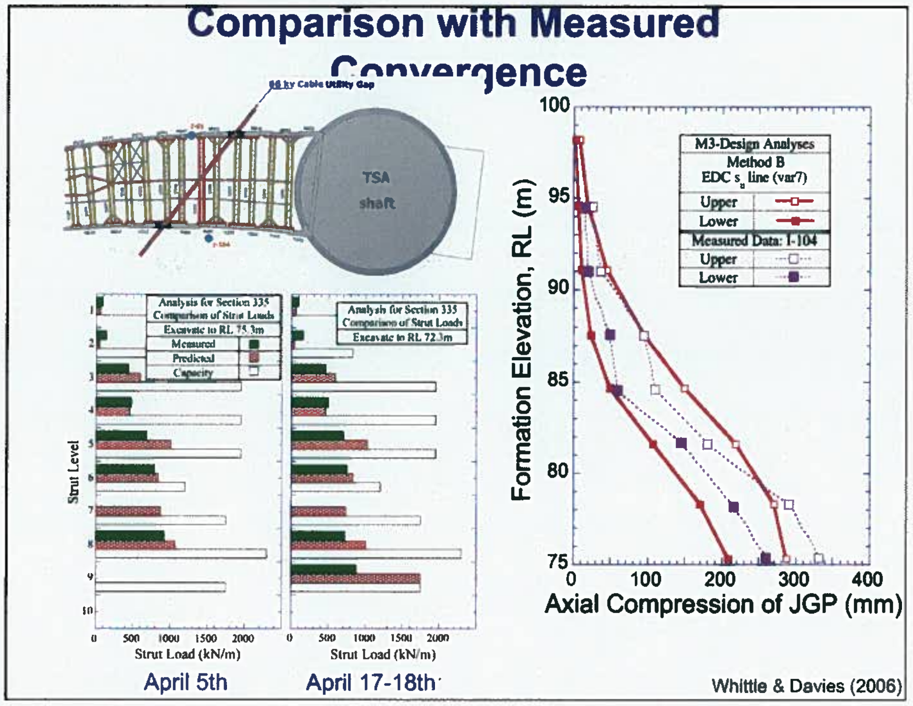


Original design
- Underestimates wall deflections & bending moments (factor of 2)

Consequence
- Wall under-designed (bending capacity)
- JGP rafts under-sized

During construction
- Performance mis-interpreted

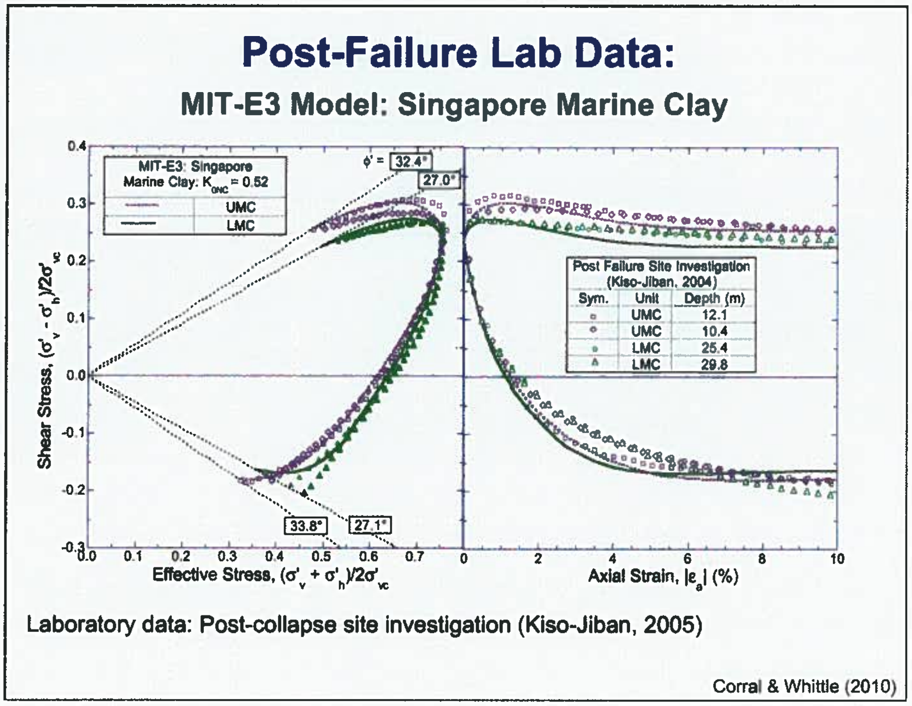
Whittle & Davies (2006)



Comparison with Measured Convergence

April 5th April 17-18th

Whittle & Davies (2006)

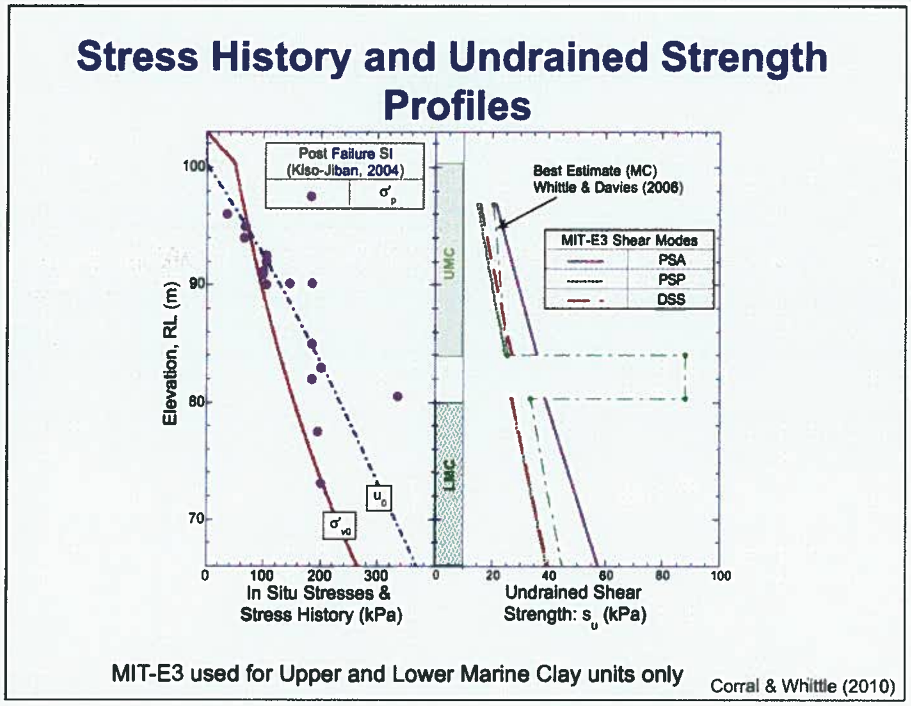


Post-Failure Lab Data:

MIT-E3 Model: Singapore Marine Clay

Laboratory data: Post-collapse site investigation (Kiso-Jiban, 2005)

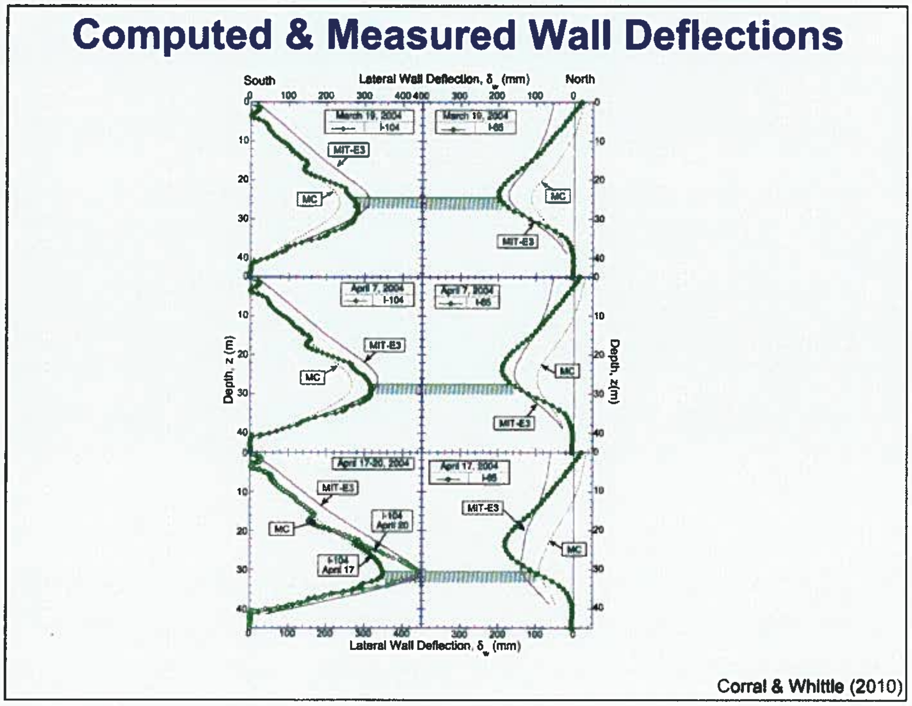
Corral & Whittle (2010)



Stress History and Undrained Strength Profiles

MIT-E3 used for Upper and Lower Marine Clay units only

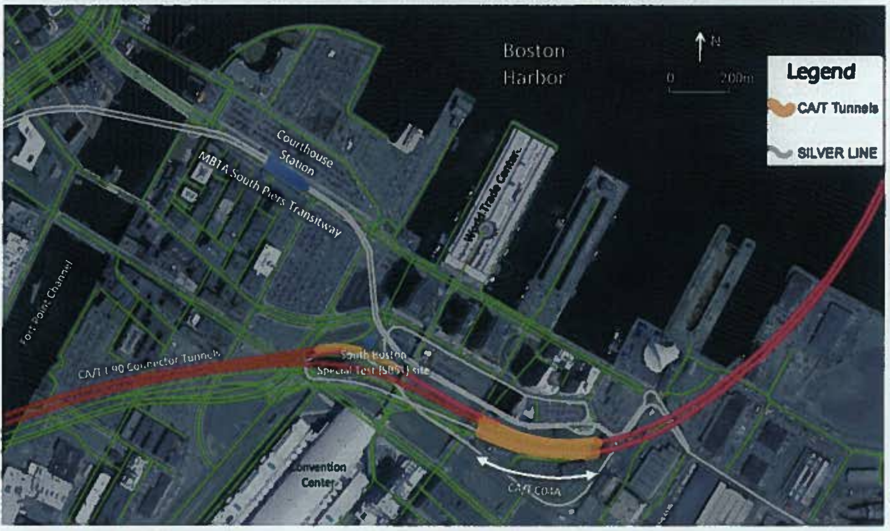
Corral & Whittle (2010)



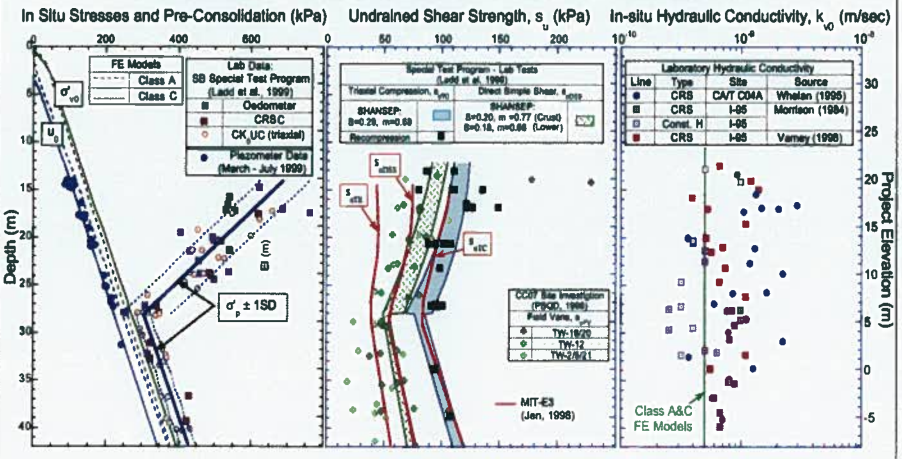
Computed & Measured Wall Deflections

Corral & Whittle (2010)

CA/T & Transitway Projects – South Boston

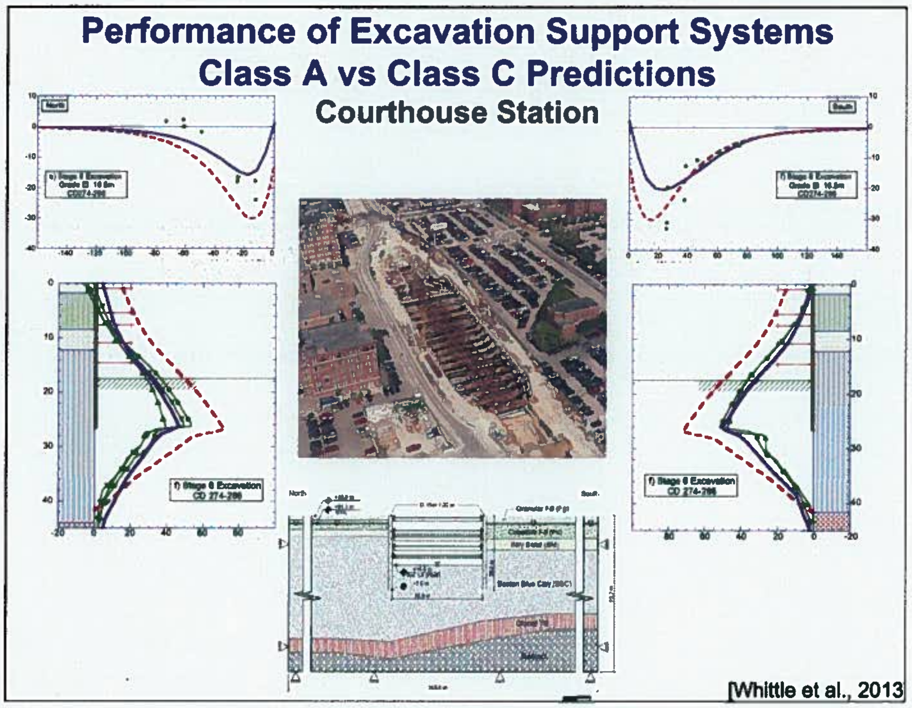


In Situ Properties South Boston



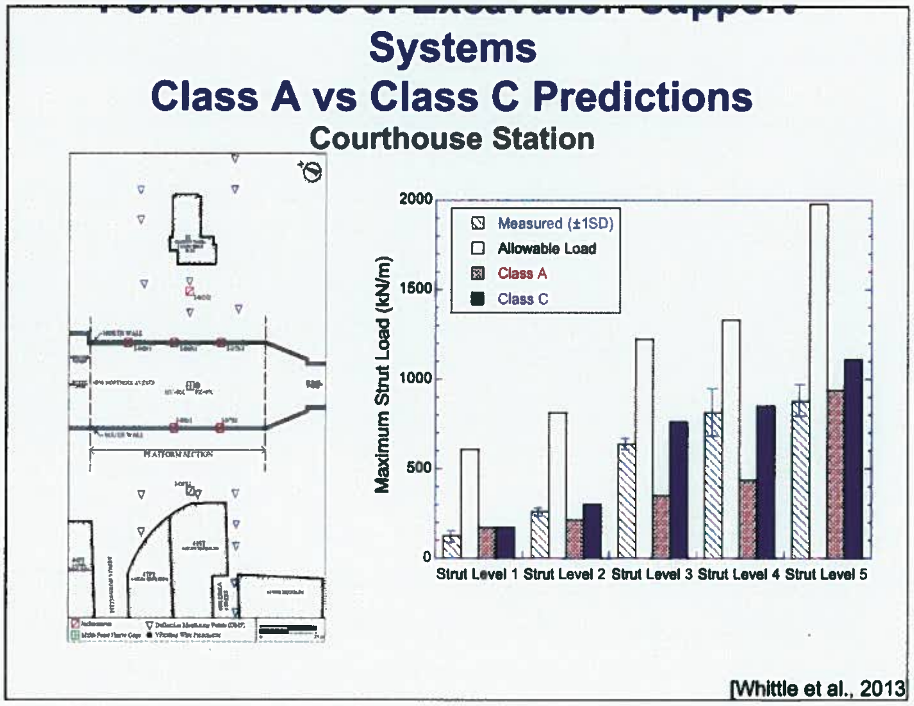
Analyses assume coupled consolidation in clay
Based on expected construction sequence

[Whittle et al., 2013]



Performance of Excavation Support Systems
Class A vs Class C Predictions
Courthouse Station

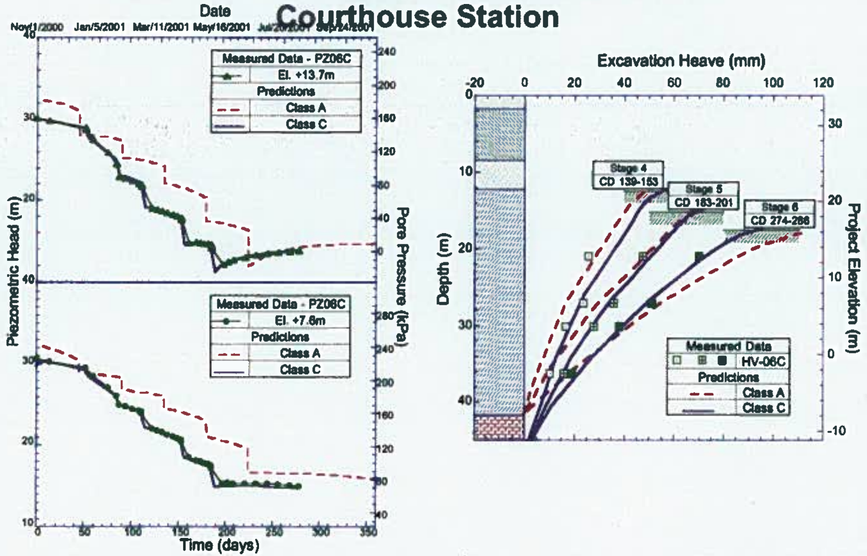
[Whittle et al., 2013]



Systems
Class A vs Class C Predictions
Courthouse Station

[Whittle et al., 2013]

Performance of Excavation Support Systems
Class A vs Class C Predictions
Courthouse Station

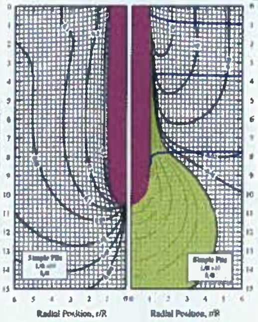


[Whittle et al., 2013]

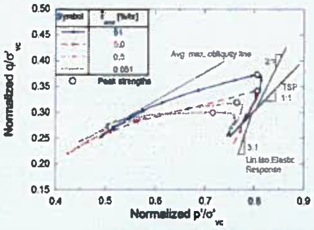
Applications

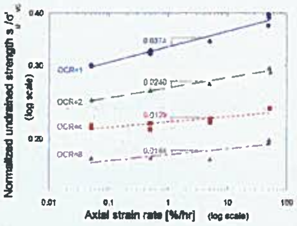
- **Far field ground deformations**
  - Controlled by constraint of constant volume in undrained shearing
- **Undrained stability problems**
  - Undrained shear strength is critical
- **Performance of excavation support systems**
  - Role of soil modeling
- **Future research on undrained behavior**

Rate Effects in Normally & Lightly Overconsolidated Clays



High strain rates associated with pile installation





Measured data (Sheahan, 1991):

Strain rate principally affects peak shear resistance

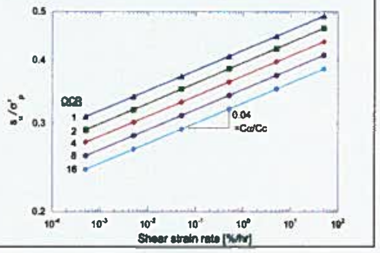
Strain rate effects significantly reduce with OCR

Limitations of current viscoplastic models:

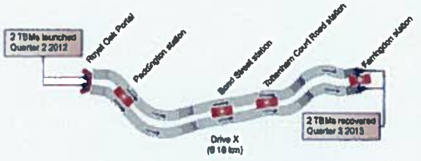
- Strain rate effect same at all OCR's
- Affects critical state conditions

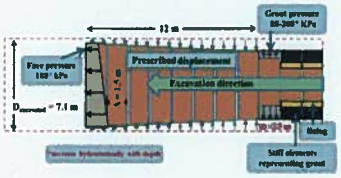
Major upgrade of MIT soil models (Yuan, 2013)

- Unifies modeling of creep-relaxation-shear rate



Behavior of Highly OC Clays



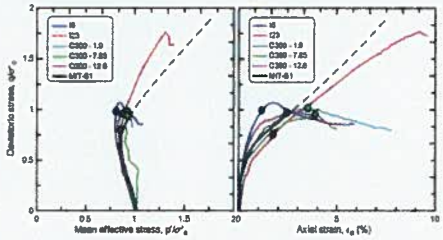


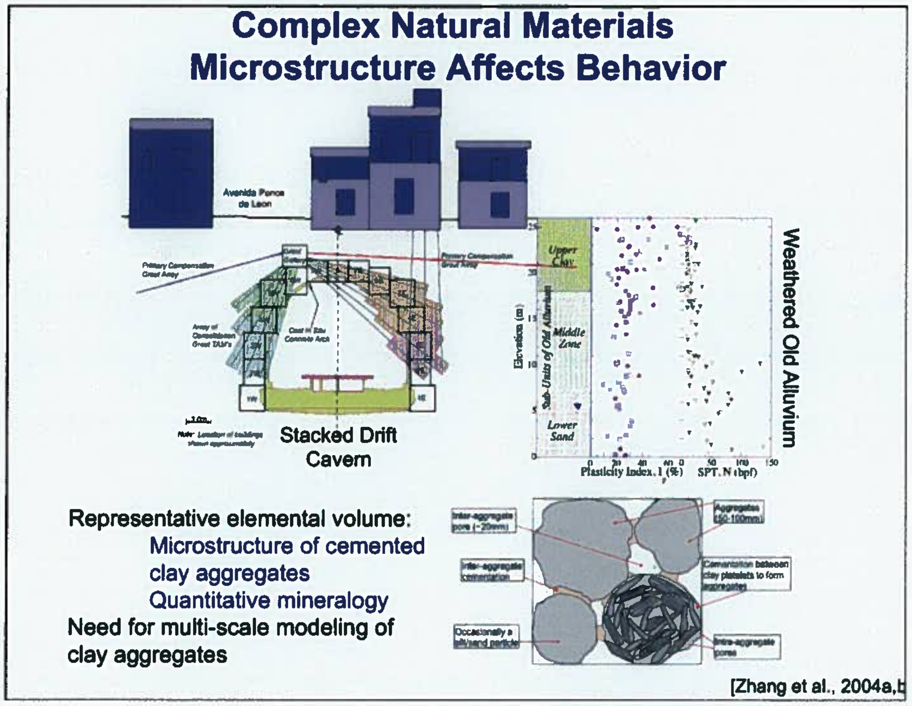
Stiff high OC London Clay

$w < w_p$ (Ductile-brittle transition)

Localization observed in undrained shear tests

Impacts on near field conditions & control Of EPB parameters





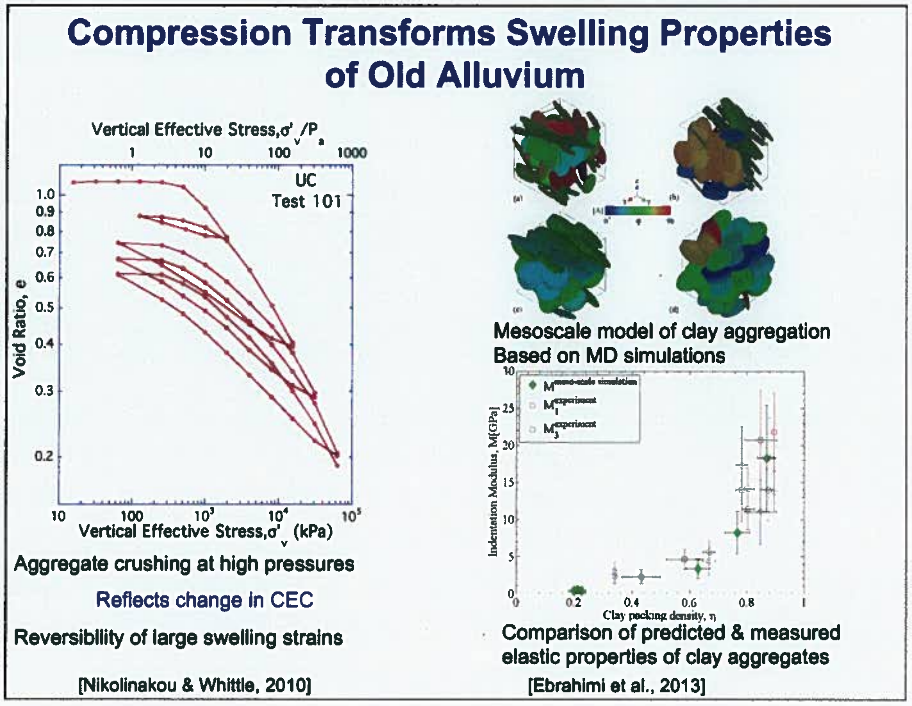
Complex Natural Materials
Microstructure Affects Behavior

Representative elemental volume:

- Microstructure of cemented clay aggregates
- Quantitative mineralogy

Need for multi-scale modeling of clay aggregates

[Zhang et al., 2004a,b



Compression Transforms Swelling Properties of Old Alluvium

Aggregate crushing at high pressures

- Reflects change in CEC

Reversibility of large swelling strains

[Nikolinakou & Whittle, 2010]

Mesoscale model of clay aggregation Based on MD simulations

Comparison of predicted & measured elastic properties of clay aggregates

[Ebrahimi et al., 2013]

Summary

- **Undrained shear behavior**
  - Stress history
  - Non-linear, anisotropic stress-strain-strength
  - Limitations in conventional elasto-plastic models

Applications

- **Far Field Deformations**
  - Effect of pile driving, ground movements due to tunneling
  - Largely independent of constitutive behavior
- **Stability Problems**
  - Importance of undrained shear strength, s_u
    - → Properties based on lab vs field tests
  - Advantages of numerical limit analyses
    - → In comparisons with Limit Equilibrium & FE Methods
- **Predictions of performance – excavation support**
  - Importance of undrained properties in design
  - Demonstrated predictive capabilities of advanced effective stress models

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Yixing Yuan
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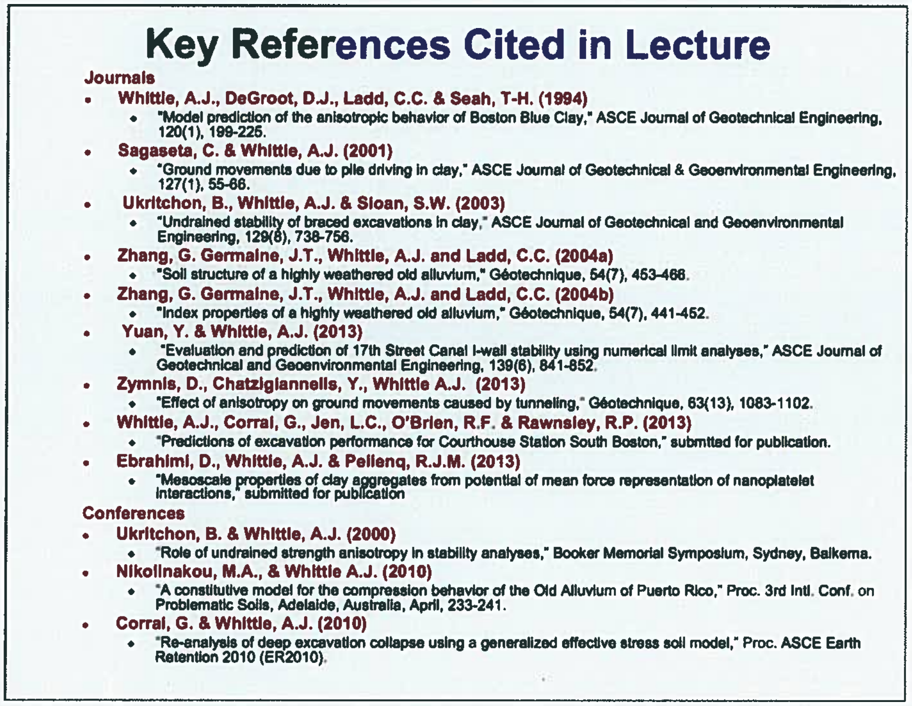

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  - "Mesoscale properties of clay aggregates from potential of mean force representation of nanoplatelet interactions," submitted for publication

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