17th ICSMGE 2009 - Alexandria

SOA-1: Geomaterial Behaviour and Testing

Mayne, Coop, Springman, Huang, and Zornberg (2009)

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SOA-1: Geomaterial Behaviour & Testing

- Paul W. Mayne
  - Georgia Tech, Atlanta, GA, USA
- Matthew Coop
  - Imperial College, London, UK
- Sarah Springman
  - ETH Swiss Federal Institute Tech, Zurich
- An-Bin Huang
  - National Chiao Tung University, Taiwan
- Jorge Zornberg
  - University of Texas at Austin, USA

ISSMGE Pres. Pedro Sêco e Pinto

and Master Orchestrator

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SOA-1: Geomaterial Behaviour & Testing

- Jorge G. Zornberg
  - 20 years in geotechnical engineering
  - Associate Professor – The University of Texas at Austin, USA
  - Expertise: geosynthetics, soil reinforcement, environmental geotechnics, unsaturated soils
  - Vice-President of the International Geosynthetics Society (IGS)
  - Chair of the International Activities Council (IAC) of Geo-Institute, ASCE

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SOA-1: Geomaterial Behaviour & Testing

- An-Bin Huang
  - 30 years in geotechnical engineering
  - Professor – National Chiao Tung University, Taiwan
  - Expertise: site characterization, in-situ testing, physical modeling, field instrumentation, liquefaction
  - Core Committee Member of TC16 - Ground property characterization by in-situ tests
  - Member: ISSMGE, TGS, SEAGS, ASCE, TRB

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SOA-1: Geomaterial Behaviour & Testing

- Sarah M. Springman
  - Active in geotechnical engineering since 1974
  - Professor – Eidgenössische Technische Hochschule, Zürich, Switzerland
  - Expertise: Soil Structure Interaction, Geohazards, Modelling
  - Chair of TC2 – Physical Modelling in Geotechnics
  - FREng, FICE, CEng, MInstRE, SIA

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SOA-1: Geomaterial Behaviour & Testing

- Matthew Coop
  - 28 years in geotechnical engineering
  - Professor, Imperial College, UK
  - Expertise: experimental soil mechanics, mechanics of sands, structured soils, weak rocks and transitional soils
  - 2003 Géotechnique lecture.
  - British Geotechnical Society Prize 1999
  - ICE Geotechnical Research Medal 1990
  - Telford Prize 2002
  - George Stephenson Medal 2005.

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SOA-1: Geomaterial Behaviour & Testing

- Paul W. Mayne
  - 33 years in geotechnical engineering
  - Professor - Georgia Institute of Technology, Atlanta, USA
  - Expertise: site characterization, soil property evaluation, in-situ testing, foundation systems
  - Chair of TC16 - Ground property characterization by in-situ tests
  - Member: ISSMGE, ASCE, ADSC, ASTM, CGS, DFI, MAEC, TRB, USUCGER

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SOA-1: Geomaterial Behaviour & Testing

- SOA-1 is 100 pages
- Total 76,776 words
- 749 references + 43 equations
- 5 tables + 228 figures, photos, and graphs
- Define 145 different parameters and symbols

SOA Record - Singapore 2003
225 pages + 110 p.
= 335 pages

Need 8+ hours for this presentation

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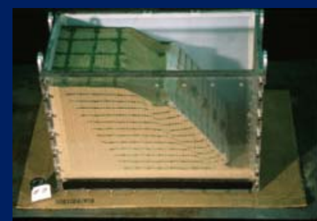
SOA-1: Geomaterial Behaviour & Testing

Six Sections:

- Introduction
- Soil Behaviour
- Physical Modelling
- In-Situ Testing
- Cyclic Response and Liquefaction
- Soil-Geosynthetic Interfaces



Geosynthetic-reinforced soil in a centrifuge. (Zornberg 1998)

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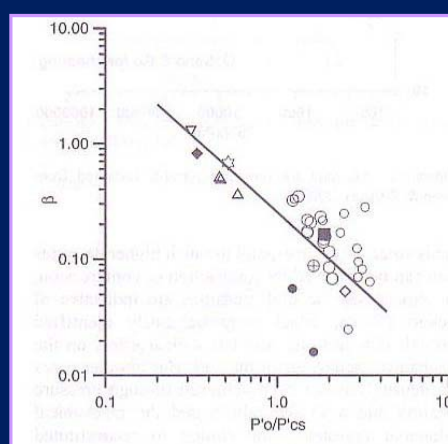
SOA-1 TOPICS: Geomaterial Behaviour & Testing

- Experimentation sites
- Methods of testing
- Interpretative framework
- Test modes
- Sample disturbance
- Local strain measurements
- Small-strain stiffness
- Critical-state soil mechanics
- Laboratory testing methods
- Yield surfaces
- Soil behaviour
- Particle behaviour
- Influence of fabric
- Intermediate grading
- Transitional geomaterials
- Rate effects



Shaft friction data for field pile tests (Coop, 2005 - IS-Lyon)

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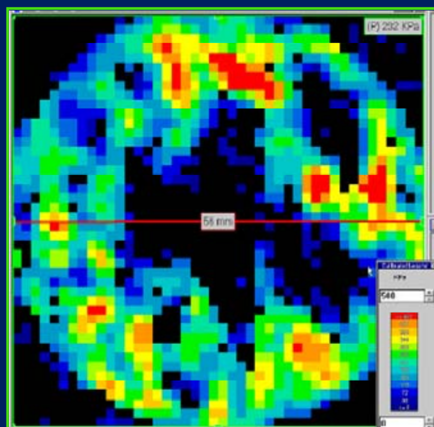
SOA-1 TOPICS: Geomaterial Behaviour & Testing



Contact stress measurements under an axisymmetric footing (Springman et al. 2002).

- Constitutive Modeling
- Physical Testing
- Numerical simulation
- 1-g tests
- Small scale model testing
- Shake tables
- Dimensional analysis
- Large scale testing
- Centrifuge modeling
- Mechatronics and robotics
- Installation devices
- Serviceability limit states
- Chamber boundary effects
- Beams and drums
- Environmental chambers
- Imaging

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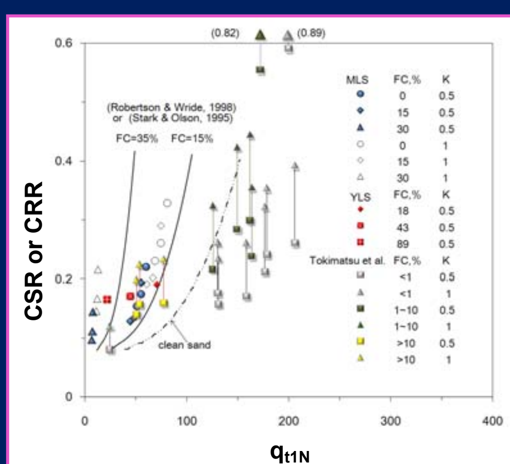
SOA-1 TOPICS: Geomaterial Behaviour & Testing



Soil Liquefaction Potential of sands with fines from CPT (Huang & Huang, 2007)

- Cyclic soil behaviour
- Liquefaction potential
- Undisturbed sampling of sands
- Stress-based procedures
- Cyclic resistance ratios (CRR)
- Evaluations from in-situ results: SPT $(N_1)_{60}$, CPT q_{t1}, DMT K_D, and stress-normalized shear wave velocity, V_{s1}
- Critical state lines for sands
- Effects of fines contents
- Porewater pressure influences
- Susceptibility to liquefaction
- State parameter approach
- Probabilistic liquefaction boundary

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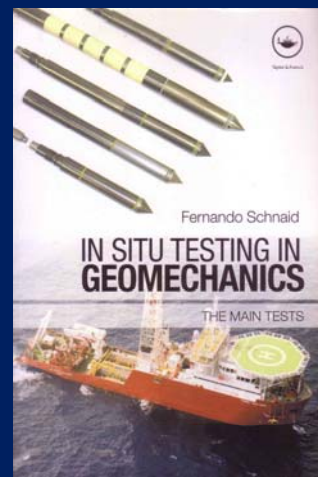
SOA-1 TOPICS: Geomaterial Behaviour & Testing

- In-situ testing
- Direct-push site characterization
- Interpretation of soil parameters
- Soil behavioural type
- Identification of cemented soils
- Geostatic stress state
- Intracorrelative trends
- Preconsolidation stresses
- Effective stress friction angle
- Stiffness of geomaterials
- Initial tangent shear modulus
- Modulus reduction curves
- New and advanced methods
- Twitch testing
- Full flow penetrometers
- Continuous V_s profiling



Schnaid (2009)

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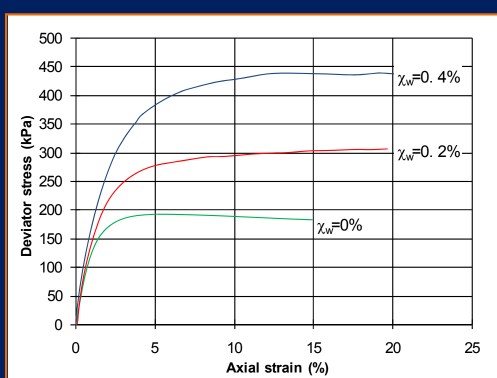
SOA-1 TOPICS: Geomaterial Behaviour & Testing



Stress-strain behavior of fiber-reinforced sand (Zornberg and Li, 2003)

- Geosynthetic materials
- Behaviour of interfaces
- Soil-geosynthetic interaction
- Geogrids and geotextiles
- Geonets
- Geomembranes
- Geocomposites
- Geopipes
- Geocells
- Fiber reinforcements
- Clay liner interfaces
- Roughness
- Shear displacement rate effects
- Resistance mechanisms
- Stress-strain-strength behaviour

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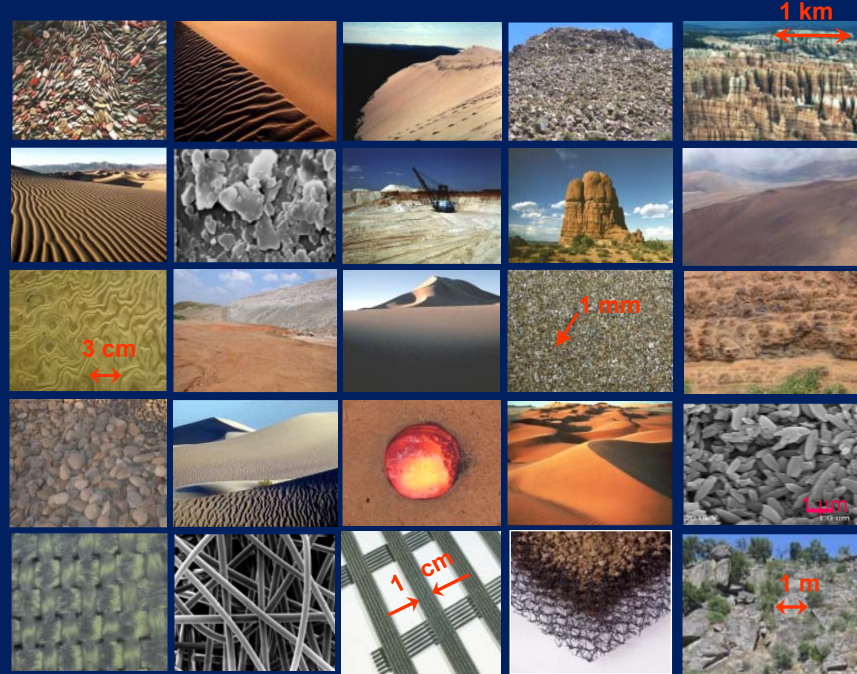

"...when you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind"

Lord Kelvin (1883)

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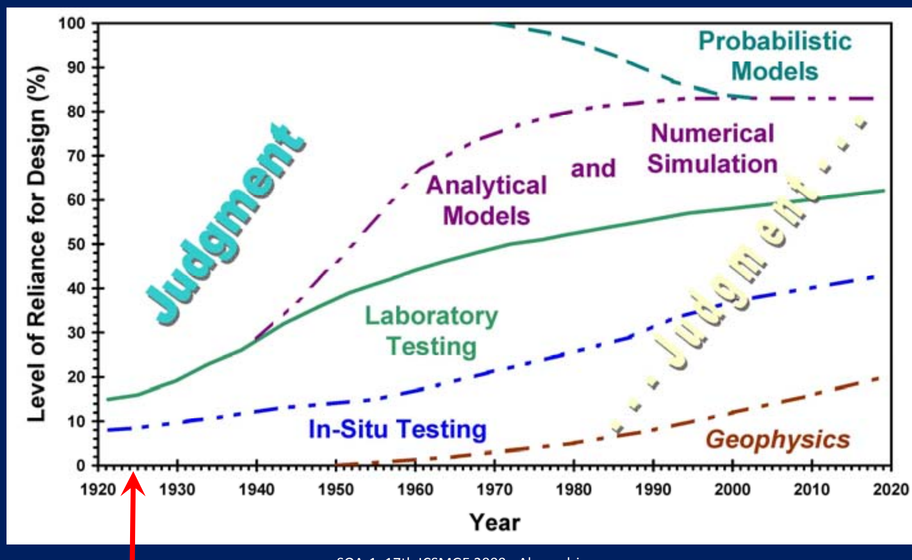
Evolution of Geotechnical Site Characterization

Modified after Lacasse (1985)



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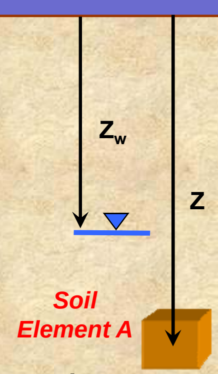
Initial Conditions

INDICES

- Origin
- Geologic Age, A_G
- Grain Sizes, D_{50}
- Mineralogy
- Plasticity, PI
- Shape (fractals)
- Sphericity, S_{ph}
- Roundness, R_n
- Angularity, A_{ng}
- Packing limits: e_{max} and e_{min}
- Grain Properties: strength, stiffness, roughness
- Geosynthetics:
  - resin type
  - carbon black



STATE

- Void Ratio, e_0
- Unit Weight, γ_T
- Relative Density, D_R
- Vertical Stress, σ_{vo}
- Hydrostatic, u_o
- Saturation, S (%)
- Geostatic $K_0 = \sigma_{ho}'/\sigma_{vo}'$
- Stiffness, $G_0 = G_{max}$
- State Parameter, ψ
- Cementation
- Fabric, void index I_{vo}
- Intact or Fissured
- Geosynthetics:
  - thickness
  - mass per unit area
  - melt index

Geomaterial Parameters and Properties

CONDUCTIVITY
- Hydraulic: k_v, k_h
- Thermal: k_e
- Electrical: Ω, ζ
- Chemical: D_f
- Transmissivity, T_m
- Permittivity, P_m

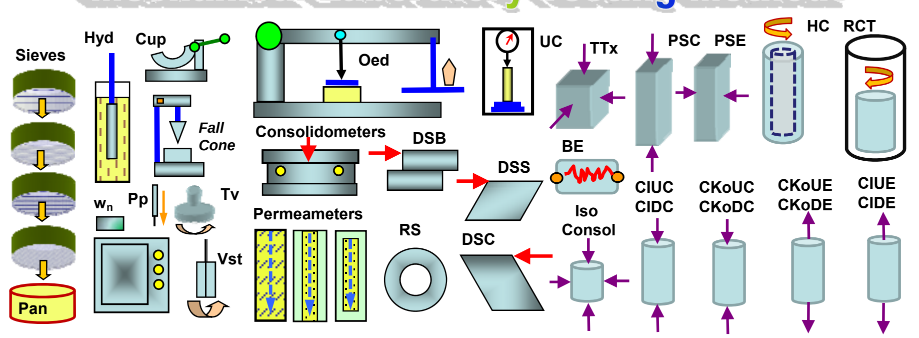
COMPRESSIBILITY
- Recompression index, C_r
- Yield Stress, σ_y' (and YSR)
- Preconsolidation, σ_p' (and OCR)
- Coefficient of Consolidation, c_v
- Virgin Compression index, C_c
- Swelling index, C_s

RHEOLOGICAL
- Coef. secondary comp, $C_{\alpha\varepsilon}$
- Strain rate, $\delta\varepsilon/\delta t$
- Age (T)
- Creep rate, α_R
- Time to creep rupture, t_{cr}

STIFFNESS
- Stiffness: $G_0 = G_{max}$
- Shear Modulus, G' and G_u
- Elastic Modulus, E' and E_u
- Bulk Modulus, K'
- Constrained Modulus, D'
- Tensile Stiffness, K_T
- Poisson's Ratio, ν
- Effects of Anisotropy (G_{vh}/G_{hh})
- Nonlinearity (G/G_{max} vs γ_s)

STRENGTH
- Drained and Undrained, τ_{max}
- Peak (s_u, c', ϕ')
- Post-peak, τ'
- Remolded/Softened/CS, $s_{u\ (rem)}$
- Residual (c_r', ϕ_r')
- Cyclic Behavior (τ_{cyc}/σ_{vo}')
- Geosynthetics: tensile strength, pullout resistance, interface shear strength.

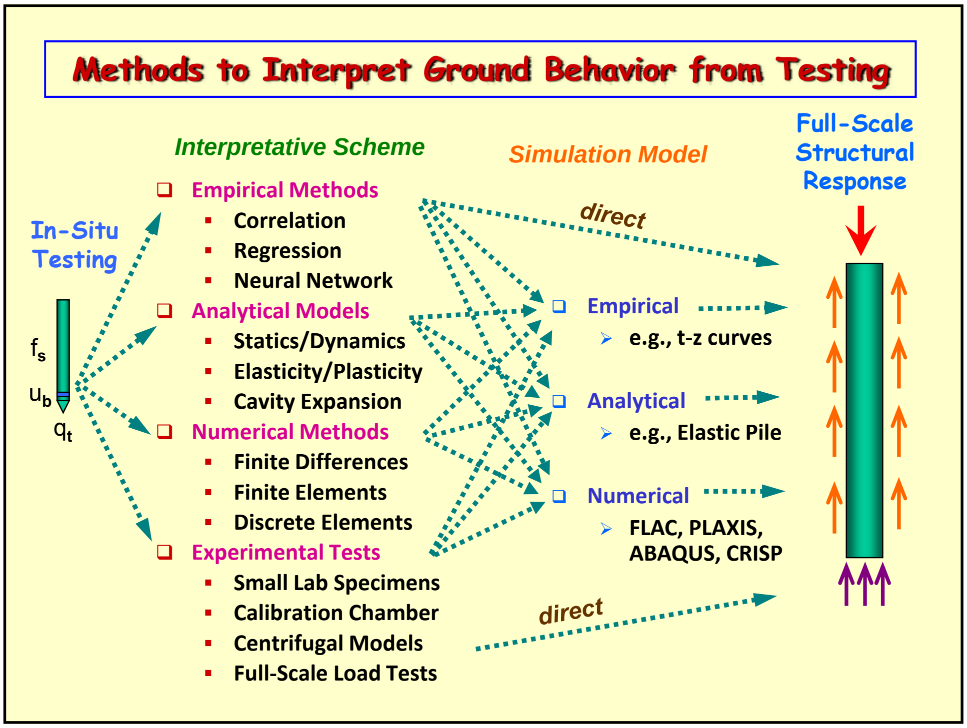
Mechanical Laboratory Testing Methods



Grain size analyses
Hydrometer
Water content by oven
Liquid limit cup
Plastic limit thread
Fall cone device
Pocket penetrometer
Torvane
Unconfined compression
Miniature vane
Digital image analysis

Mechanical oedometer
Consolidometer
Constant rate of shear (CRS)
Falling-head permeameter
Constant-head permeameter
Flow permeameter
Direct shear box
Ring shear
Unconsolidated undrained Tx
Simple shear
Directional shear cell

Triaxial apparatus (iso-consols, CIUC, CKoUC, CAUC, CIUE, CAUE, CKoUE, stress path, CIDC, CKoDC, CIDE, CKoDE, constant P')
Plane strain apparatus (PSC, PSE)
True triaxial (cuboidal)
Hollow cylinder
Torsional Shear
Resonant Column Test device
Non-resonant column
Bender elements



State-of-the-Art ⇨ State-of-the-Practice

This SOA presentation versus SOA Technical Paper

What can be implemented to improve issues of forecasting, risk, economy, reliability by geotech community ?

How can our professional image be upgraded ?

Directed at 18,000 members of ISSMGE who are not here

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SOA-1: Selected Topics for Presentation

- Bad News
  - Undrained Shear Strength
  - Sample Disturbance
  - Reconstituted vs Undisturbed
- Good News
  - Critical State Soil Mechanics ←
  - Effective Friction Angle, ϕ'
  - Preconsolidation Stress, σ_p'
  - International Geotechnical Test Sites

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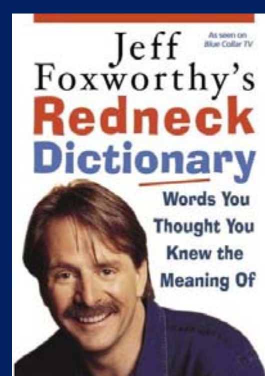
Geotech profession not using Critical State Soil Mechanics

Parody on "You might just be a redneck"



Comedian defines "redneck" as "a person who gloriously lacks of sophistication"

If you come home from the garbage dump with more than you went in with.......

....You might just be a redneck

Parody: Geotech Counterpart - - - - -
You might just need critical-state soil mechanics

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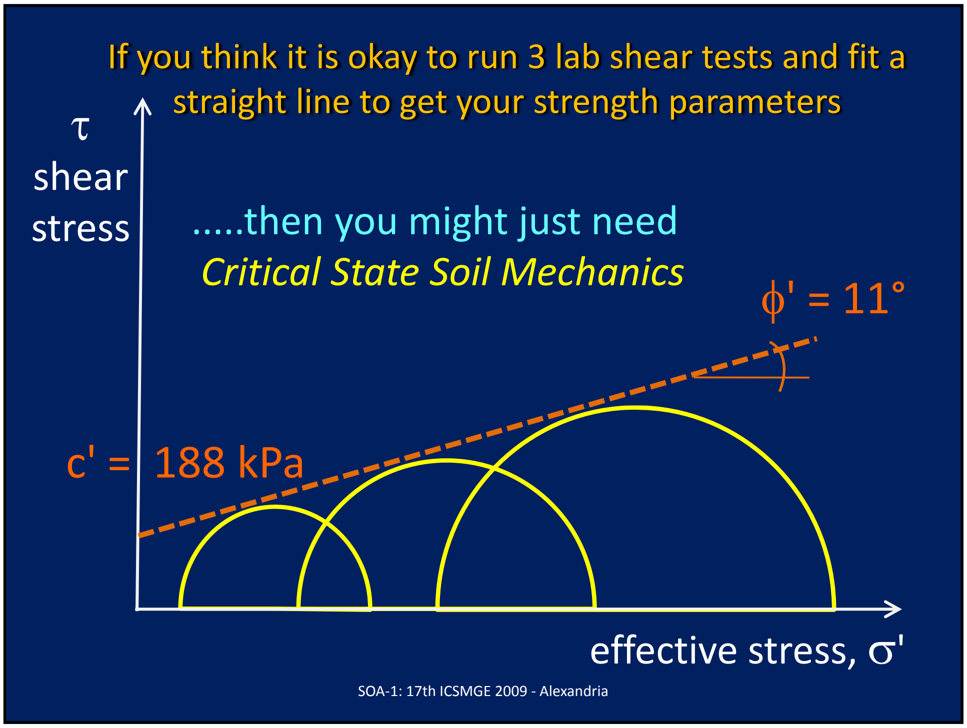

If you think it is okay to run 3 lab shear tests and fit a straight line to get your strength parameters
τ
shear stress
.....then you might just need
Critical State Soil Mechanics
ϕ' = 11°
c' = 188 kPa
effective stress, σ'
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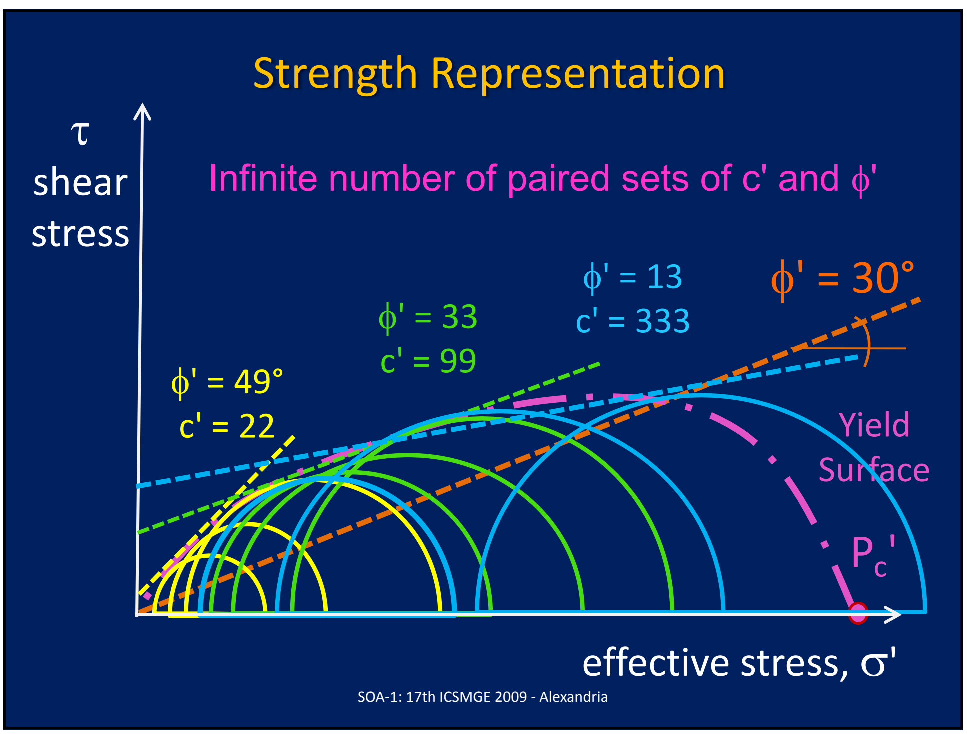

Strength Representation
τ
shear stress
Infinite number of paired sets of c' and ϕ'
ϕ' = 13
c' = 333
ϕ' = 30°
ϕ' = 33
c' = 99
ϕ' = 49°
c' = 22
Yield Surface
Pc'
effective stress, σ'
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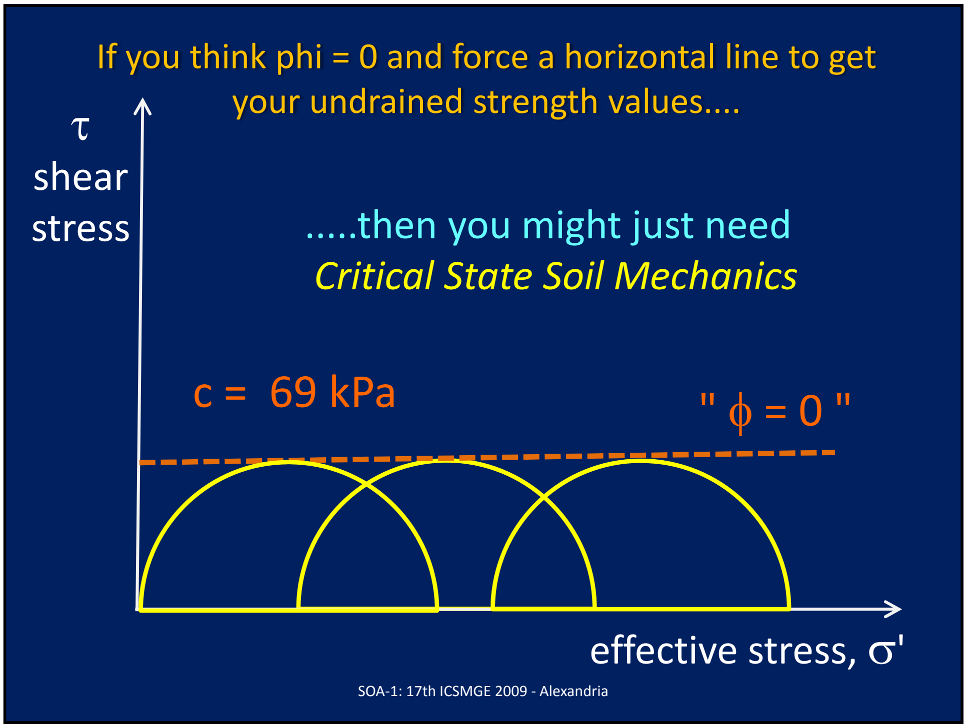
If you think phi = 0 and force a horizontal line to get
your undrained strength values....
τ
shear
stress
.....then you might just need
Critical State Soil Mechanics
c = 69 kPa
" ϕ = 0 "
effective stress, σ'
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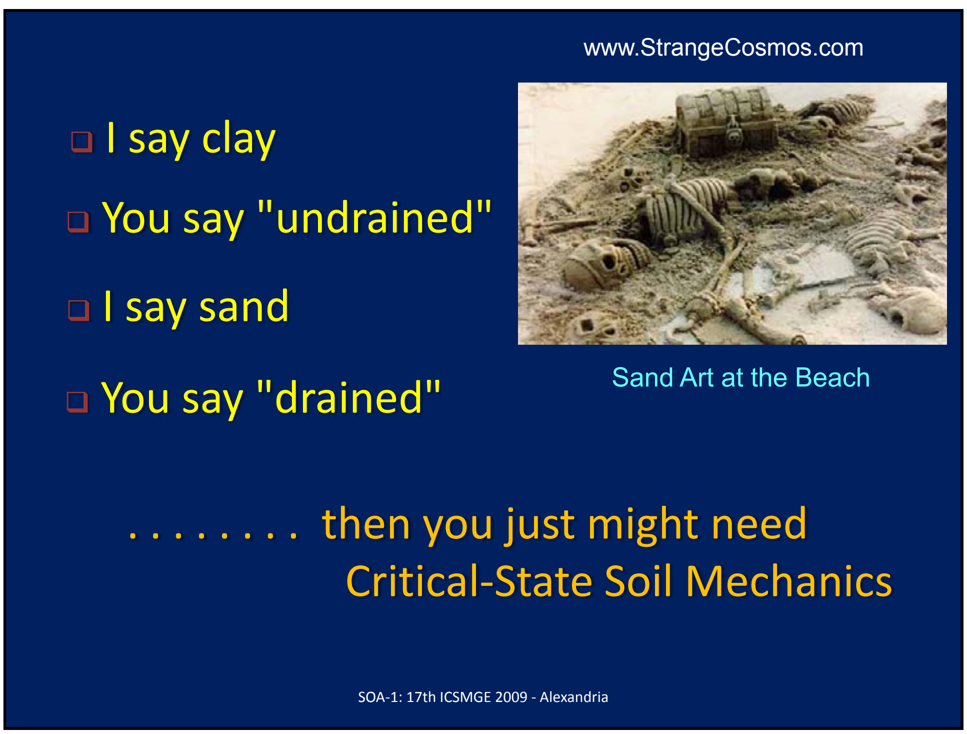
www.StrangeCosmos.com
I say clay
You say "undrained"
I say sand
You say "drained"
Sand Art at the Beach
. . . . then you just might need
Critical-State Soil Mechanics
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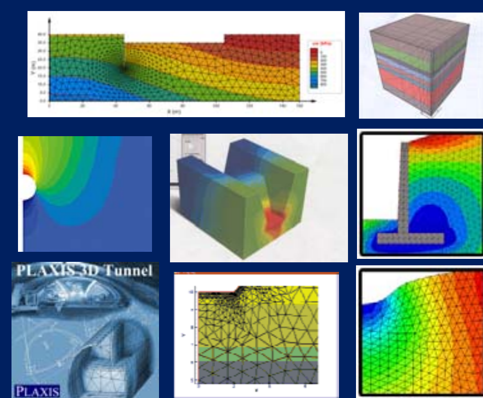
If you are using any of the following software

- PLAXIS
- FLAC
- TNO Diana
- ABAQUS
- CRISP
- ADINA
- GEOSLOPE
- FLEA
- Soilvision3d
- GeoFEAS
- ZSOIL
- Seep3d
- WANFE
- GEO5
- OASYS
- SIGMA/W
- SETTLE
- GFAS
- OpenSees

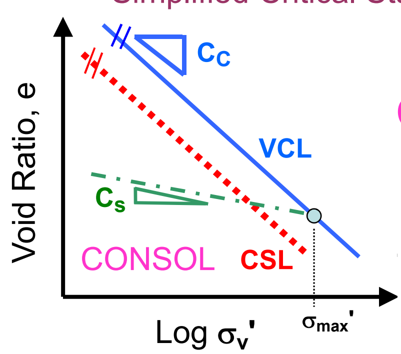
then you just might need CSSM

Numerical Simulations

- Finite Elements
- Finite Differences



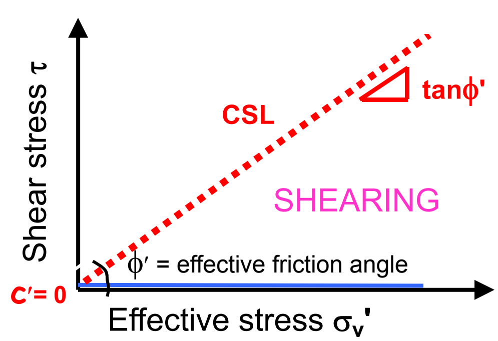
Simplified Critical State Soil Mechanics (CSSM)

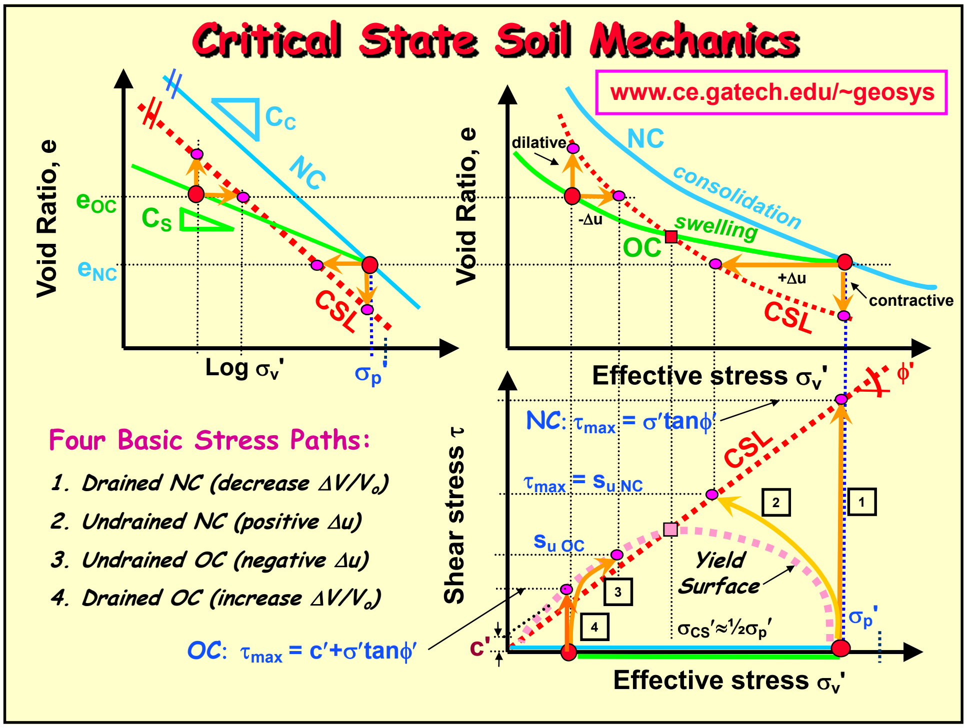


CSSM = Link between Consolidation, Swelling, and Shear

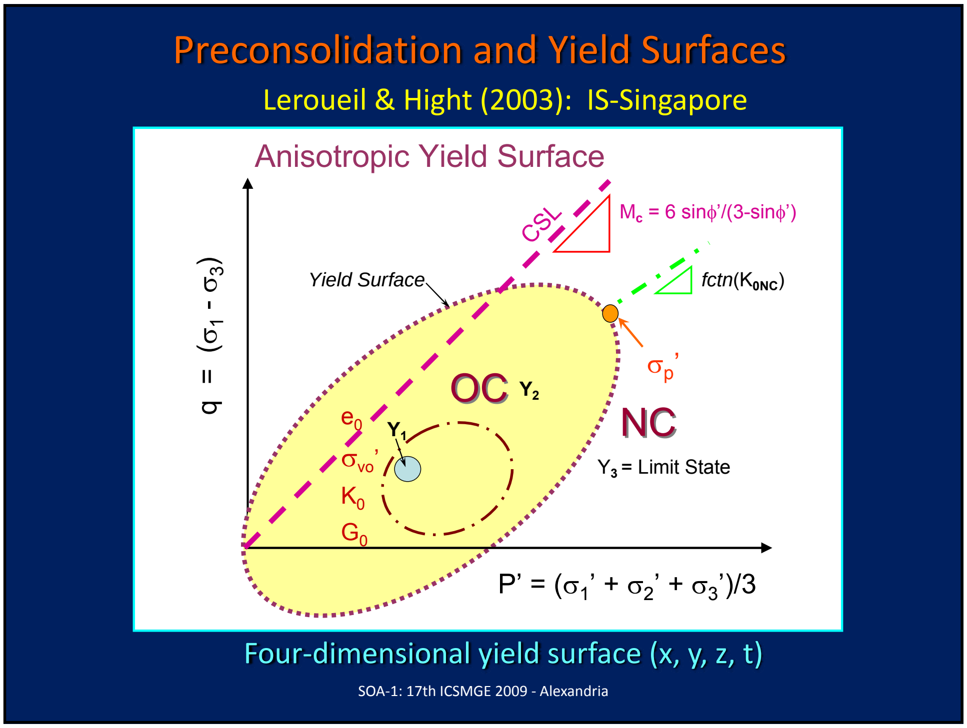
Critical State Soil Mechanics for Dummies

www.webforum.com/tc16





Critical State Soil Mechanics
www.ce.gatech.edu/~geosys
Void Ratio, e
Cc
NC
eOC
Cs
eNC
CSL
Log σv'
σp'
Void Ratio, e
dilative
NC
consolidation
swelling
OC
-Δu
+Δu
contractive
CSL
Effective stress σv'
Four Basic Stress Paths:
1. Drained NC (decrease ΔV/Vo)
2. Undrained NC (positive Δu)
3. Undrained OC (negative Δu)
4. Drained OC (increase ΔV/Vo)
OC: τmax = c'+σ'tanφ'
Shear stress τ
NC: τmax = σ'tanφ'
τmax = su NC
su OC
CSL
φ'
Yield Surface
σCS'≈½σp'
σp'
c'
Effective stress σv'



Preconsolidation and Yield Surfaces
Leroueil & Hight (2003): IS-Singapore
Anisotropic Yield Surface
CSL
Mc = 6 sinφ'/(3-sinφ')
Yield Surface
fctn(K0NC)
σp'
q = (σ1 - σ3)
OC
Y2
NC
e0
Y1
σvo'
K0
G0
Y3 = Limit State
P' = (σ1' + σ2' + σ3')/3
Four-dimensional yield surface (x, y, z, t)
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Undrained Shear Strength

- Undrained Shear Strength of Clays = c = c_u = s_u = τ_{max}
- Classical interpretation of CPT and VST in clays:

$$s_{uCPT} = \frac{q_t - \sigma_{vo}}{N_{kt}}$$

$$s_{u-Mobilized} = \mu_v \cdot \frac{6T}{7\pi d^3}$$

- **Which s_u ?**

$N_{kCPT} \approx 15 \pm 5$

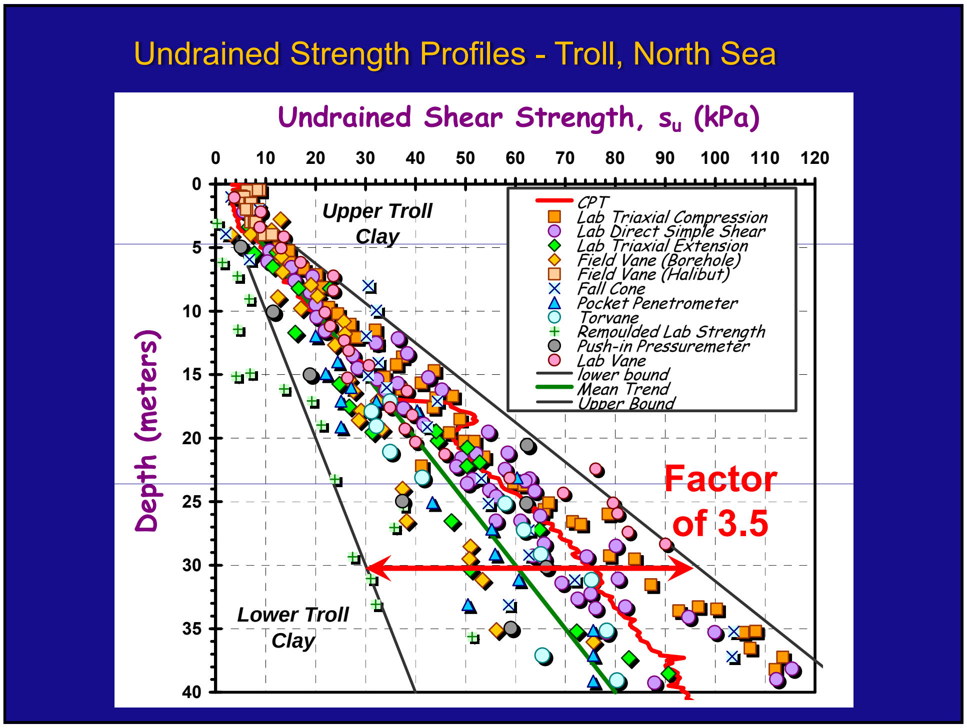
μ_{vane} decreases with *PI*

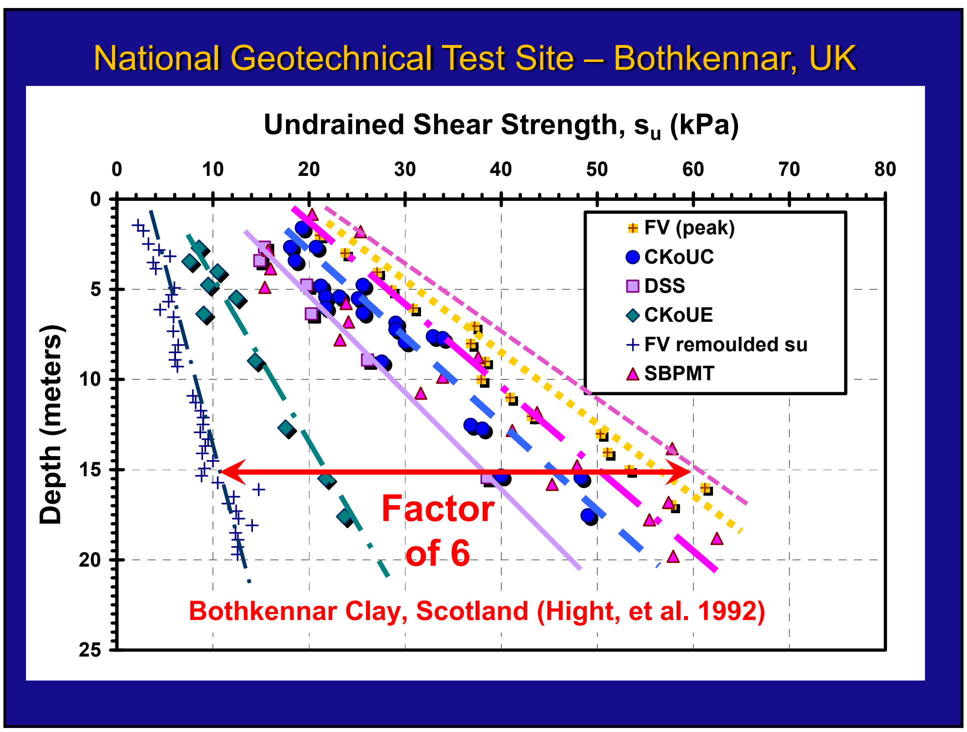
Undrained Shear Strengths for Boston Blue Clay

Test Method/Mode	$S = s_u/\sigma_{vo}'_{NC}$
Self-boring pressuremeter (SBPMT)	0.42
Plane strain compression (PSC)	0.34
Triaxial compression (CK_0UC)	0.33
Unconsolidated Undrained (UU)	0.275
Field vane shear test (FV)	0.21
Direct simple shear (DSS)	0.20
Plane strain extension (PSE)	0.19
Triaxial extension (CK_0UE)	0.16
Unconfined compression (UC)	0.14

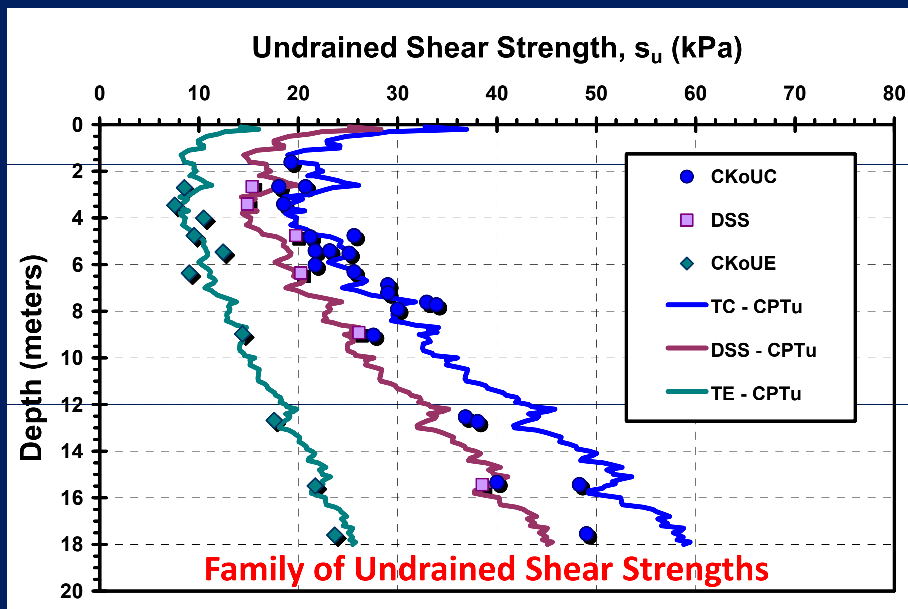
Factor of 3

Ref: MIT Reports; Ladd (1991); Ladd, et al. (1980), Whittle (1993)


Undrained Strength Profiles - Troll, North Sea
Undrained Shear Strength, s_u (kPa)
Depth (meters)
Upper Troll Clay
Lower Troll Clay
CPT
Lab Triaxial Compression
Lab Direct Simple Shear
Lab Triaxial Extension
Field Vane (Borehole)
Field Vane (Halibut)
Fall Cone
Pocket Penetrometer
Torvane
Remoulded Lab Strength
Push-in Pressuremeter
Lab Vane
lower bound
Mean Trend
Upper Bound
Factor of 3.5


National Geotechnical Test Site – Bothkennar, UK
Undrained Shear Strength, s_u (kPa)
Depth (meters)
FV (peak)
CKoUC
DSS
CKoUE
FV remoulded su
SBPMT
Factor of 6
Bothkennar Clay, Scotland (Hight, et al. 1992)

CPTu Profiles of s_u in Bothkennar Clay, UK



Undrained Shear Strength of Clays

- 1. Critical-state soil mechanics for intact clays (Cambridge and Oxford Universities):

  $s_u/\sigma_{vo}'_{DSS} = \frac{1}{2} \sin\phi' OCR^{\Lambda}$ — Wroth (1984)

  where $\Lambda \approx 1 - C_s/C_c$

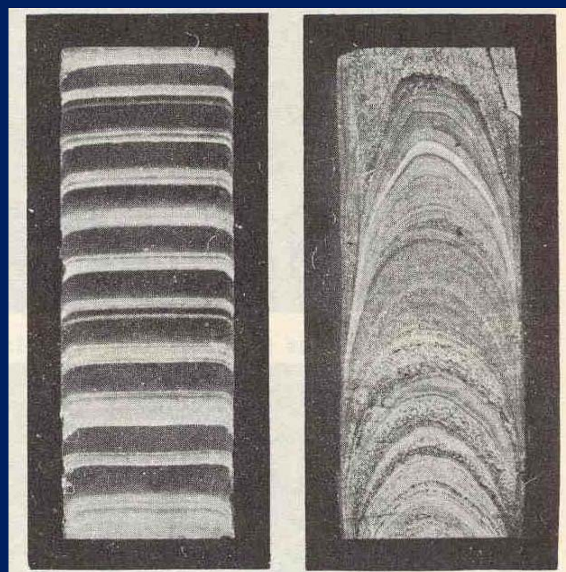
- 2. Experimental lab work by MIT:

  $s_u/\sigma_{vo}'_{DSS} = 0.23\ OCR^{0.8}$ — Ladd (1991)

- 3. Vane Shear Tests calibrated with failure case studies of embankments, footings, & excavations:

  $s_{u\ Mobilized} \approx 0.22\ \sigma_p'$ — Mesri (1975)

Sampling Disturbance



Sampler A Sampler B

Hvorslev (1949)

Issue of Sample Disturbance

I say "Undisturbed Sampling"

You say "Shelby Tube"

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Sample Disturbance Effects

(after Tanaka, 2000)

Sampler	O.D. (mm)	I.D. (mm)	Length (mm)	Wall t (mm)	Piston
JPN	78	75	1000	1.5	Yes
Laval	216	208	660	4.0	No
Shelby	75.3	72	610	1.65	No
NGI-54	80	54	768	13	Yes
ELE100	104.4	101	500	1.7	Yes
Sherbrooke	N/A	350	250	N/A	No
NGI-95	105.6	95	1000	5.3	Yes
Split-Barrel	51.1	34.9	600	8.1	No

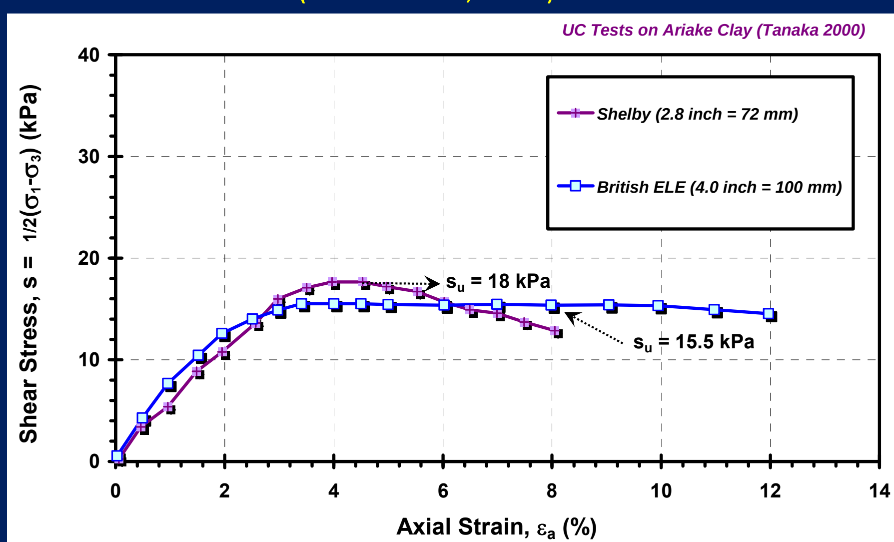
Gel Sampler (Huang 2007)
Mazier Tube
Dames & Moore

NGI Block Sampler
Gus Sampler
Osterberg Sampler

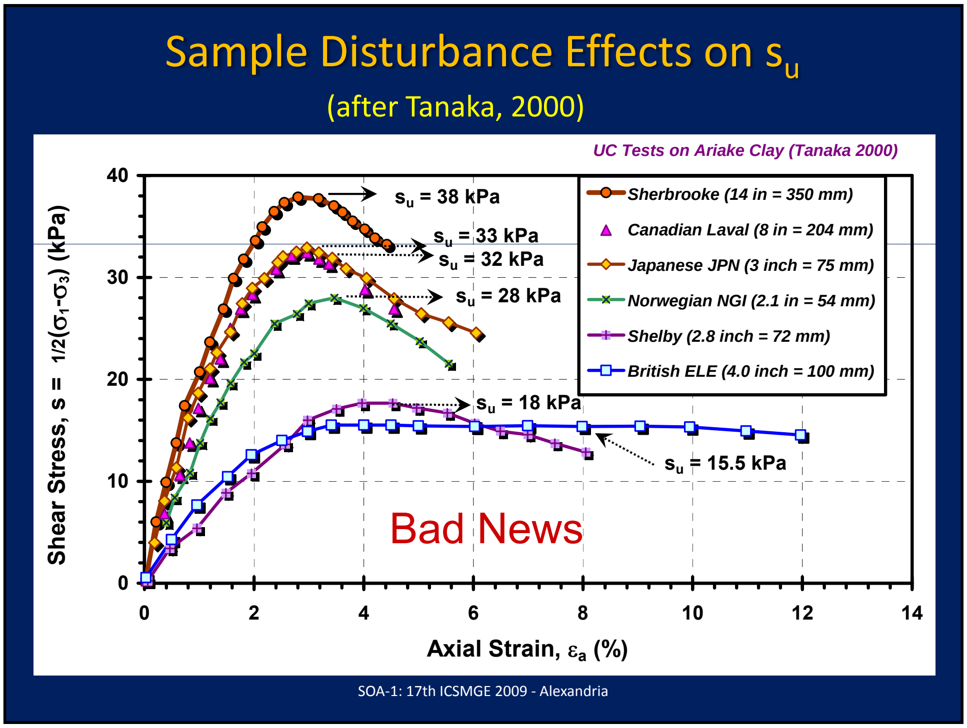
SOA-1 (2009)

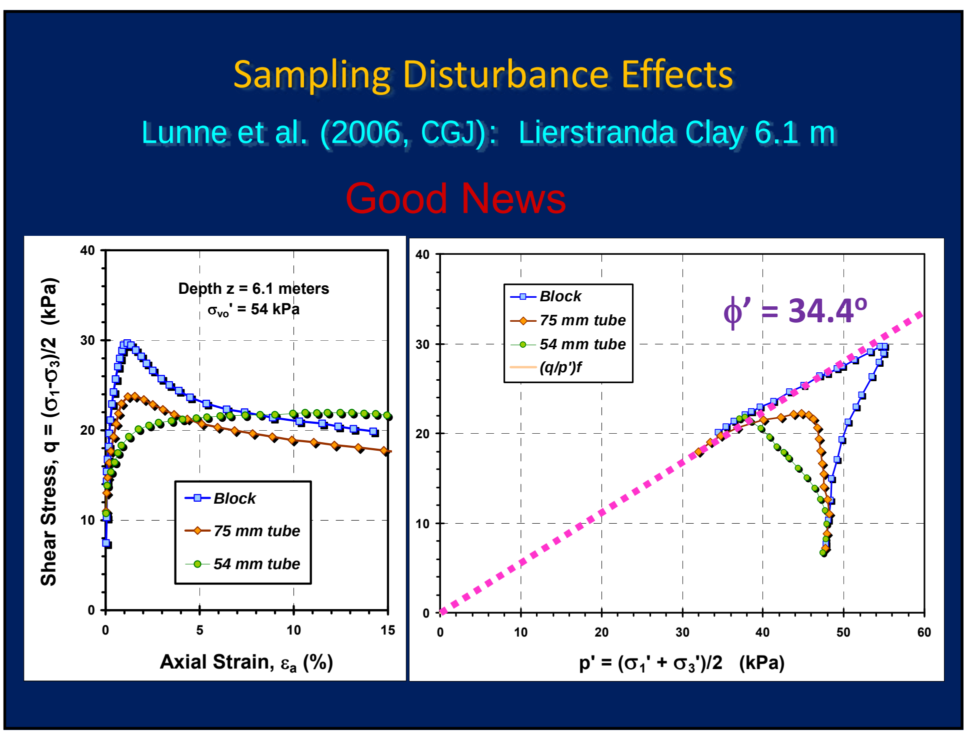
Sample Disturbance Effects on s_u

(after Tanaka, 2000)



SOA-1: 17th ICSMGE 2009 - Alexandria


Sample Disturbance Effects on s_u
(after Tanaka, 2000)
UC Tests on Ariake Clay (Tanaka 2000)
Sherbrooke (14 in = 350 mm)
Canadian Laval (8 in = 204 mm)
Japanese JPN (3 inch = 75 mm)
Norwegian NGI (2.1 in = 54 mm)
Shelby (2.8 inch = 72 mm)
British ELE (4.0 inch = 100 mm)
s_u = 38 kPa
s_u = 33 kPa
s_u = 32 kPa
s_u = 28 kPa
s_u = 18 kPa
s_u = 15.5 kPa
Bad News
Shear Stress, s = 1/2(σ_1-σ_3) (kPa)
Axial Strain, ε_a (%)
SOA-1: 17th ICSMGE 2009 - Alexandria


Sampling Disturbance Effects
Lunne et al. (2006, CGJ): Lierstranda Clay 6.1 m
Good News
Depth z = 6.1 meters
σ_{vo}' = 54 kPa
Block
75 mm tube
54 mm tube
(q/p')f
ϕ' = 34.4°
Shear Stress, q = (σ_1-σ_3)/2 (kPa)
Axial Strain, ε_a (%)
p' = (σ_1' + σ_3')/2 (kPa)

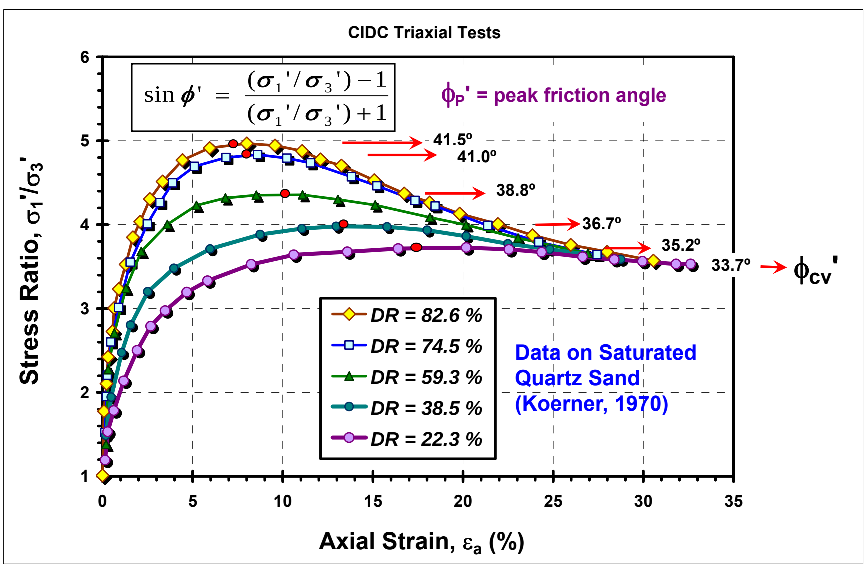
Quantification of Lab Sample Disturbance

Lunne, et al. (2006, Canadian Geot. Journal)

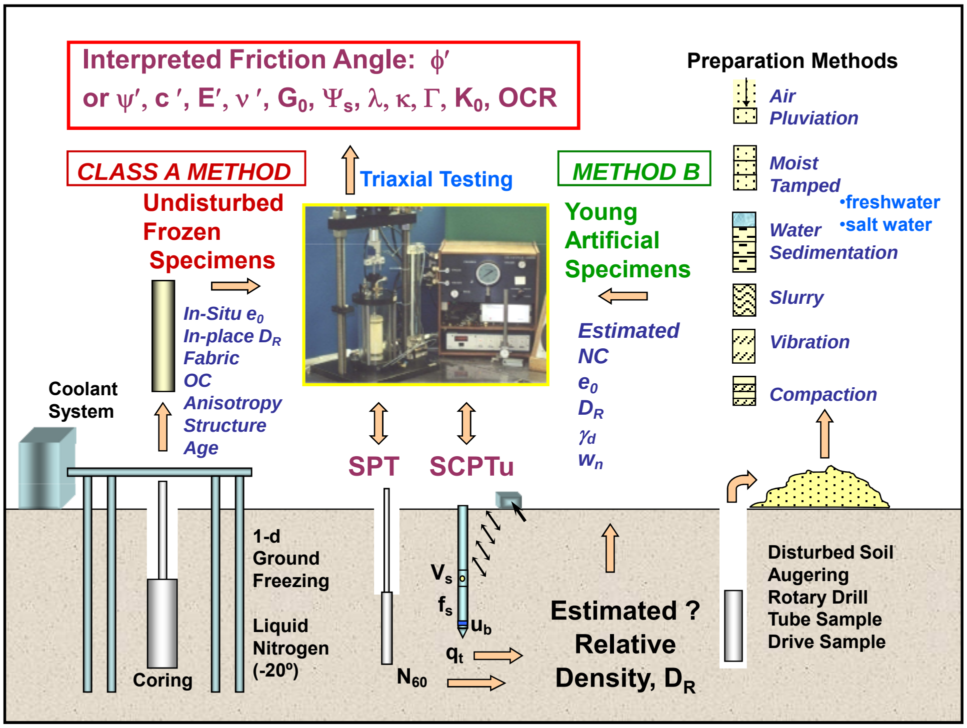
RATE SPECIMEN QUALITY: Ratio of $\Delta e/e_0$ to attain σ_{vo}'

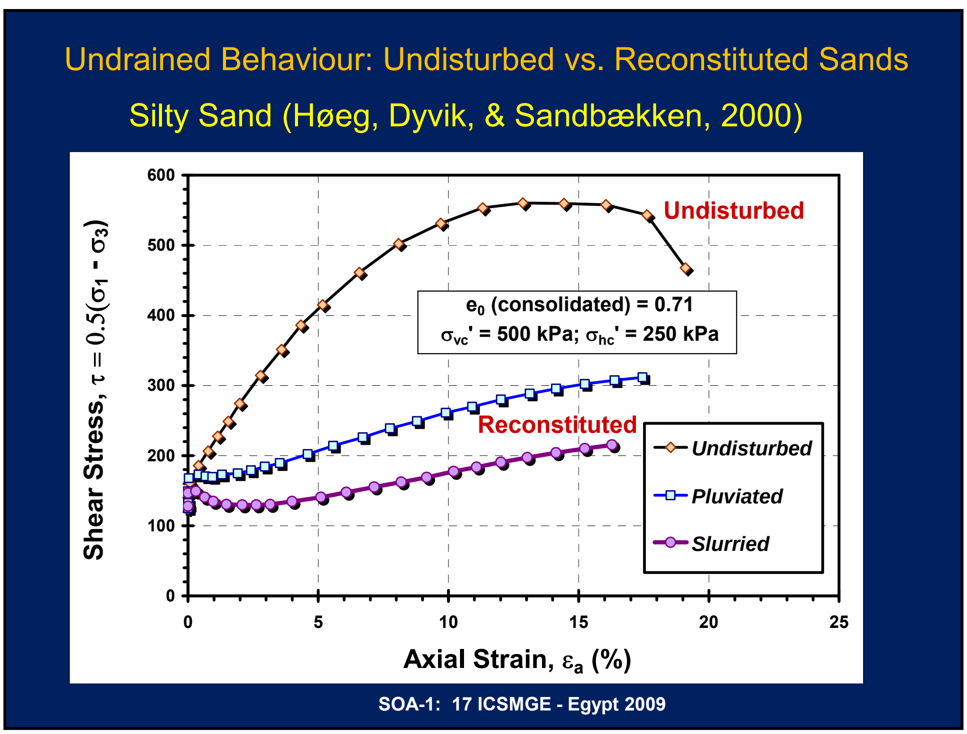
OCR	*Excellent to Very Good*	*Good to Fair*	*Poor*	*Very Poor*
1 to 2	**< 0.04**	**0.04 to 0.07**	**0.07 to 0.14**	**> 0.14**
2 to 4	**< 0.03**	**0.03 to 0.05**	**0.05 to 0.10**	**> 0.10**

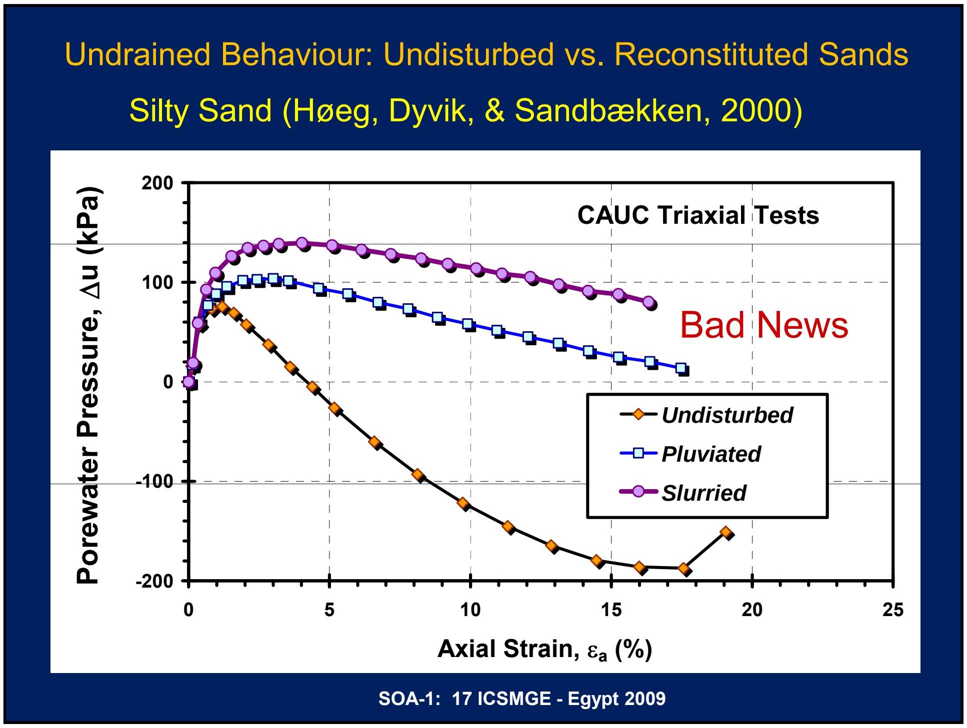
Friction Angle of Sands

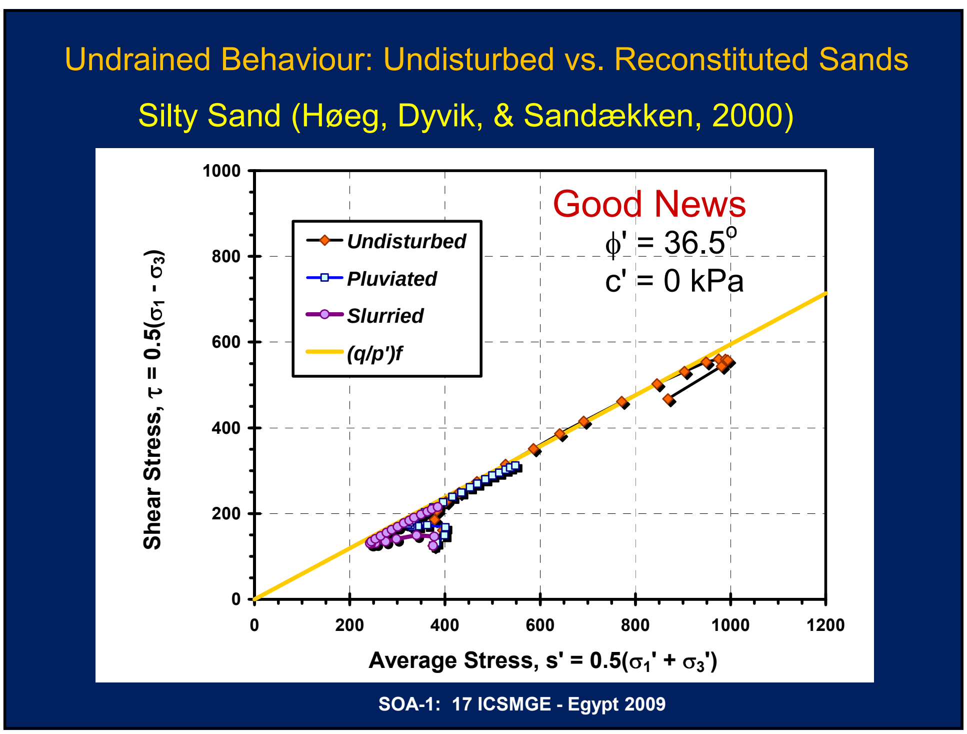


Georgia Tech


Interpreted Friction Angle: φ′
or ψ′, c ′, E′, ν ′, G0, Ψs, λ, κ, Γ, K0, OCR
Preparation Methods
Air Pluviation
Moist Tamped
Water Sedimentation
•freshwater
•salt water
Slurry
Vibration
Compaction
CLASS A METHOD
Undisturbed Frozen Specimens
Triaxial Testing
METHOD B
Young Artificial Specimens
In-Situ e0
In-place DR
Fabric
OC
Anisotropy
Structure
Age
Estimated
NC
e0
DR
γd
wn
Coolant System
SPT
SCPTu
1-d Ground Freezing
Liquid Nitrogen (-20º)
Coring
Vs
fs
ub
qt
N60
Estimated ? Relative Density, DR
Disturbed Soil
Augering
Rotary Drill
Tube Sample
Drive Sample

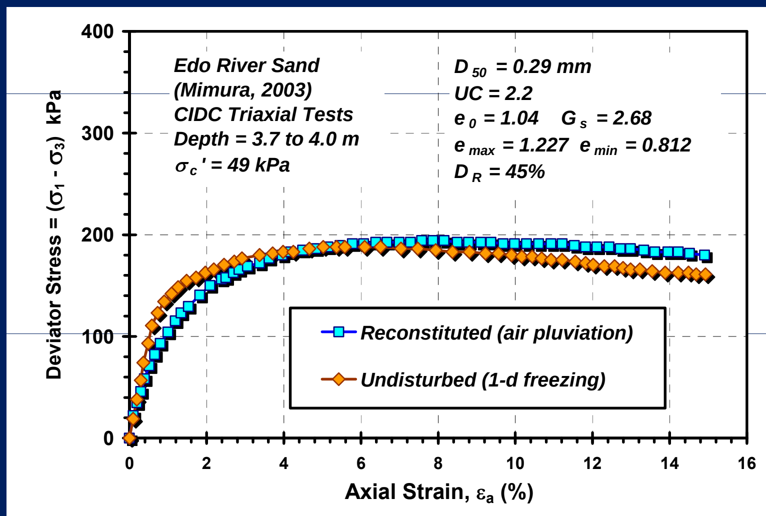

Undrained Behaviour: Undisturbed vs. Reconstituted Sands
Silty Sand (Høeg, Dyvik, & Sandbækken, 2000)
Shear Stress, τ = 0.5(σ1 - σ3)
Axial Strain, εa (%)
0
100
200
300
400
500
600
0
5
10
15
20
25
Undisturbed
Reconstituted
e0 (consolidated) = 0.71
σvc' = 500 kPa; σhc' = 250 kPa
Undisturbed
Pluviated
Slurried
SOA-1: 17 ICSMGE - Egypt 2009


Undrained Behaviour: Undisturbed vs. Reconstituted Sands
Silty Sand (Høeg, Dyvik, & Sandbækken, 2000)
CAUC Triaxial Tests
Bad News
Undisturbed
Pluviated
Slurried
Porewater Pressure, Δu (kPa)
Axial Strain, εa (%)
200
100
0
-100
-200
0
5
10
15
20
25
SOA-1: 17 ICSMGE - Egypt 2009


Undrained Behaviour: Undisturbed vs. Reconstituted Sands
Silty Sand (Høeg, Dyvik, & Sandækken, 2000)
Good News
ϕ' = 36.5°
c' = 0 kPa
Undisturbed
Pluviated
Slurried
(q/p')f
Shear Stress, τ = 0.5(σ1 - σ3)
Average Stress, s' = 0.5(σ1' + σ3')
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
SOA-1: 17 ICSMGE - Egypt 2009

Undisturbed vs Reconstituted Sand

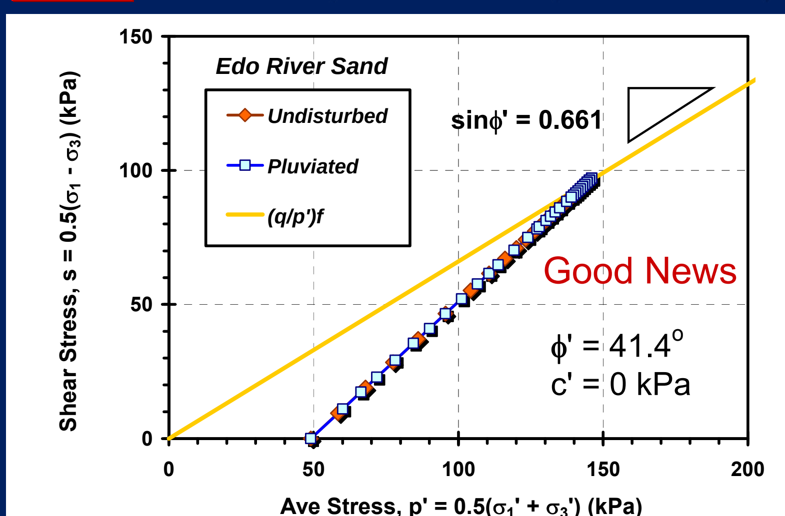
Drained Triaxial Compression Tests (Mimura 2003)



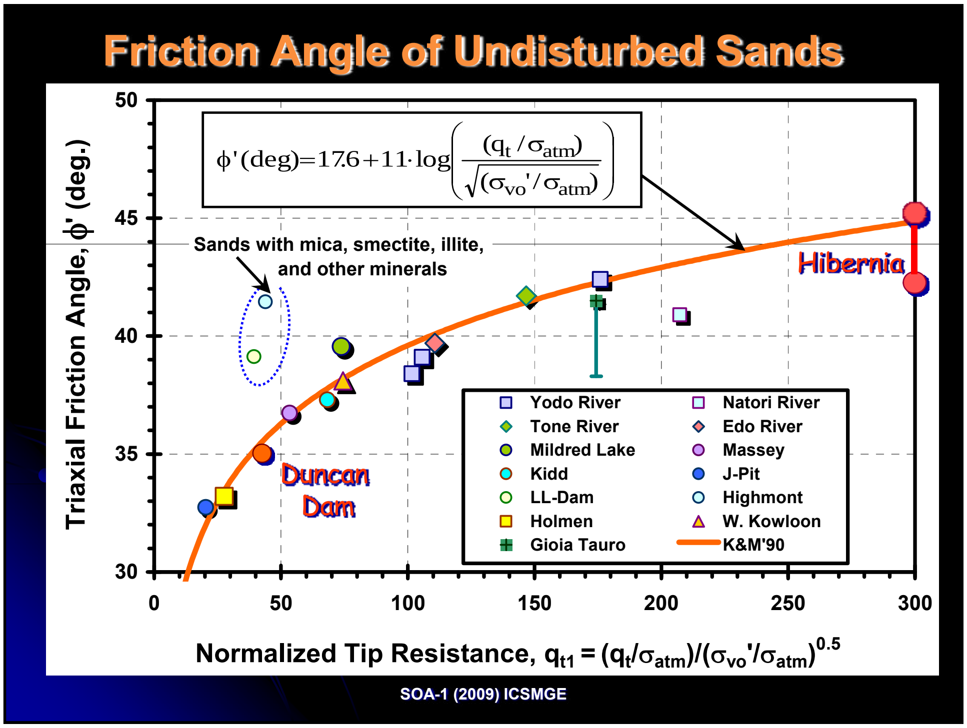
SOA-1: 17th ICSMGE 2009 - Alexandria

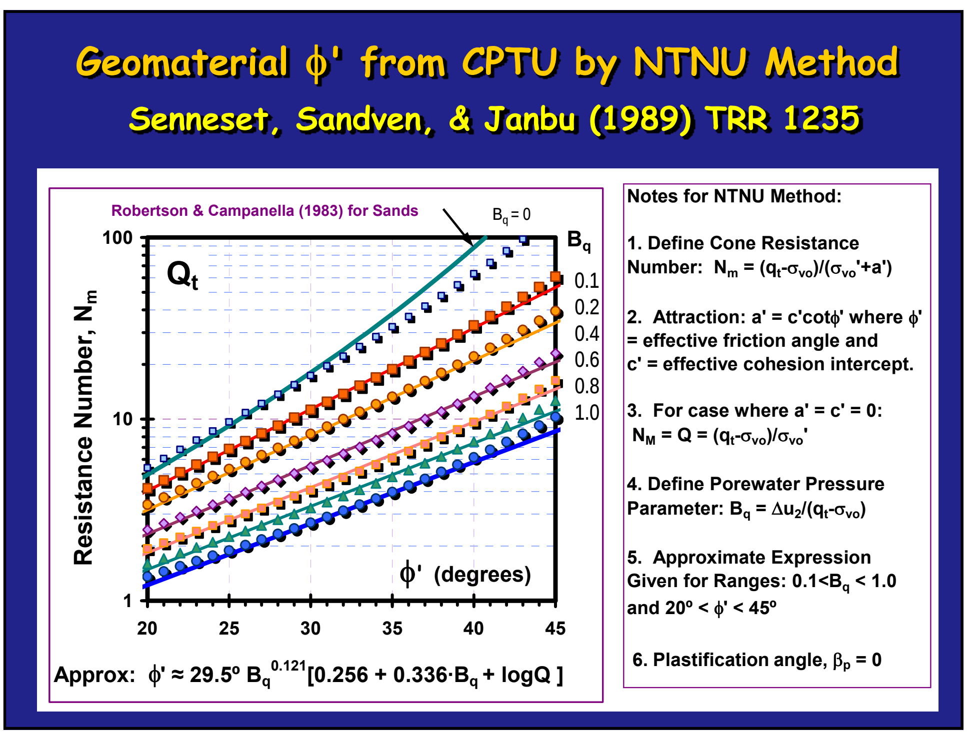
Undisturbed vs Reconstituted Sand

Drained Triaxial Compression Tests (Mimura 2003)

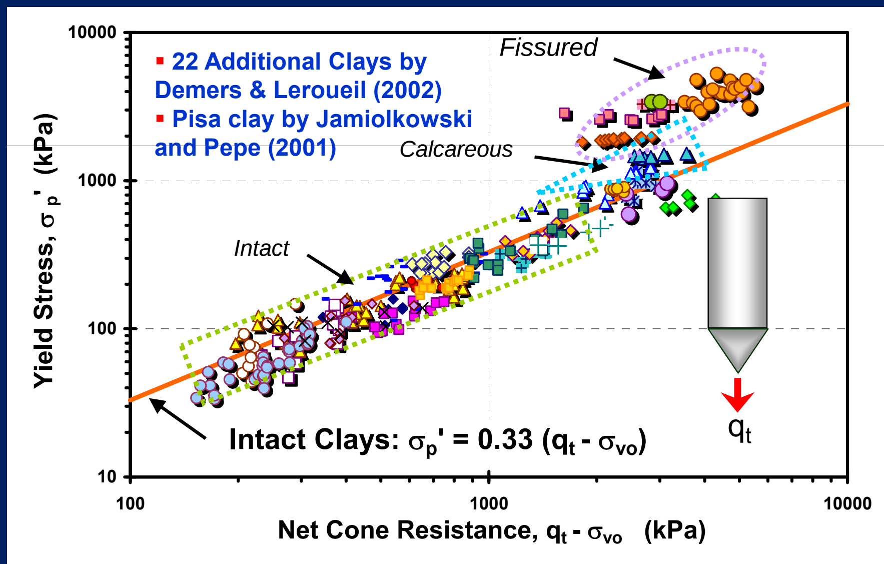


SOA-1: 17th ICSMGE 2009 - Alexandria


Friction Angle of Undisturbed Sands
φ'(deg)=17.6+11·log((q_t/σ_atm)/√(σ_vo'/σ_atm))
Sands with mica, smectite, illite, and other minerals
Hibernia
Duncan Dam
Yodo River
Natori River
Tone River
Edo River
Mildred Lake
Massey
Kidd
J-Pit
LL-Dam
Highmont
Holmen
W. Kowloon
Gioia Tauro
K&M'90
Triaxial Friction Angle, φ' (deg.)
Normalized Tip Resistance, q_t1 = (q_t/σ_atm)/(σ_vo'/σ_atm)^0.5
SOA-1 (2009) ICSMGE


Geomaterial φ' from CPTU by NTNU Method
Senneset, Sandven, & Janbu (1989) TRR 1235
Robertson & Campanella (1983) for Sands
B_q = 0
Q_t
B_q
Resistance Number, N_m
φ' (degrees)
Approx: φ' ≈ 29.5° B_q^0.121 [0.256 + 0.336·B_q + logQ]
Notes for NTNU Method:
1. Define Cone Resistance Number: N_m = (q_t-σ_vo)/(σ_vo'+a')
2. Attraction: a' = c'cotφ' where φ' = effective friction angle and c' = effective cohesion intercept.
3. For case where a' = c' = 0: N_M = Q = (q_t-σ_vo)/σ_vo'
4. Define Porewater Pressure Parameter: B_q = Δu_2/(q_t-σ_vo)
5. Approximate Expression Given for Ranges: 0.1<B_q < 1.0 and 20° < φ' < 45°
6. Plastification angle, β_p = 0

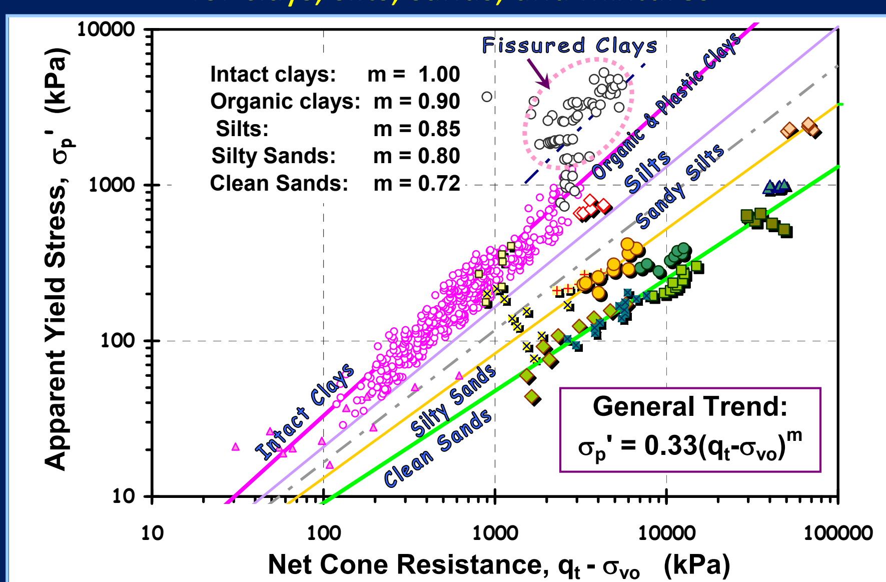
Profiling P_c' in Clays by Cone Penetrometer

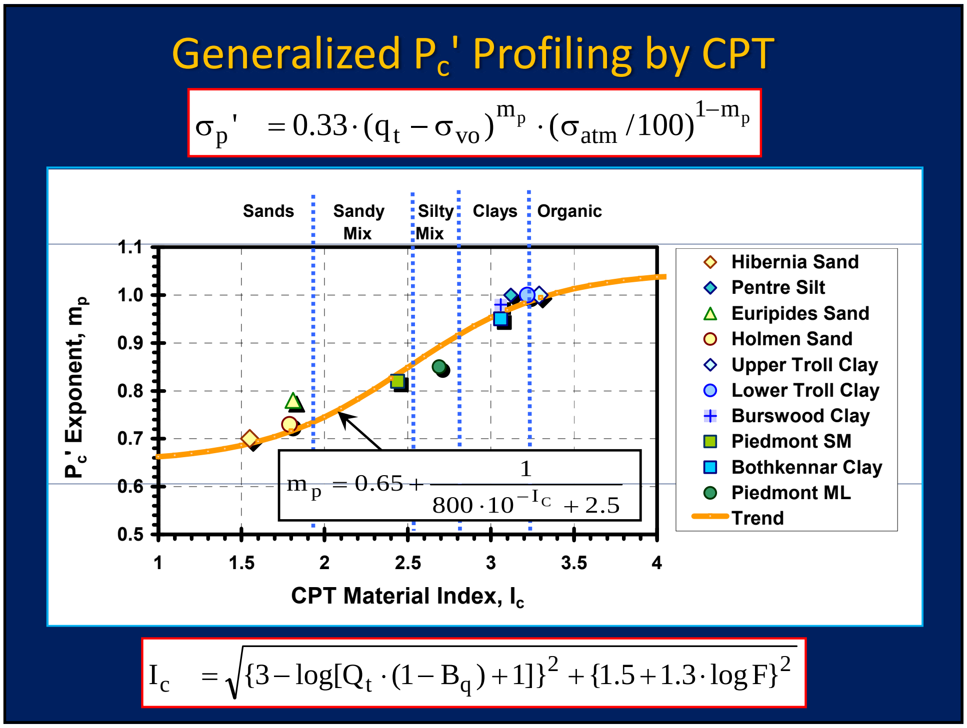


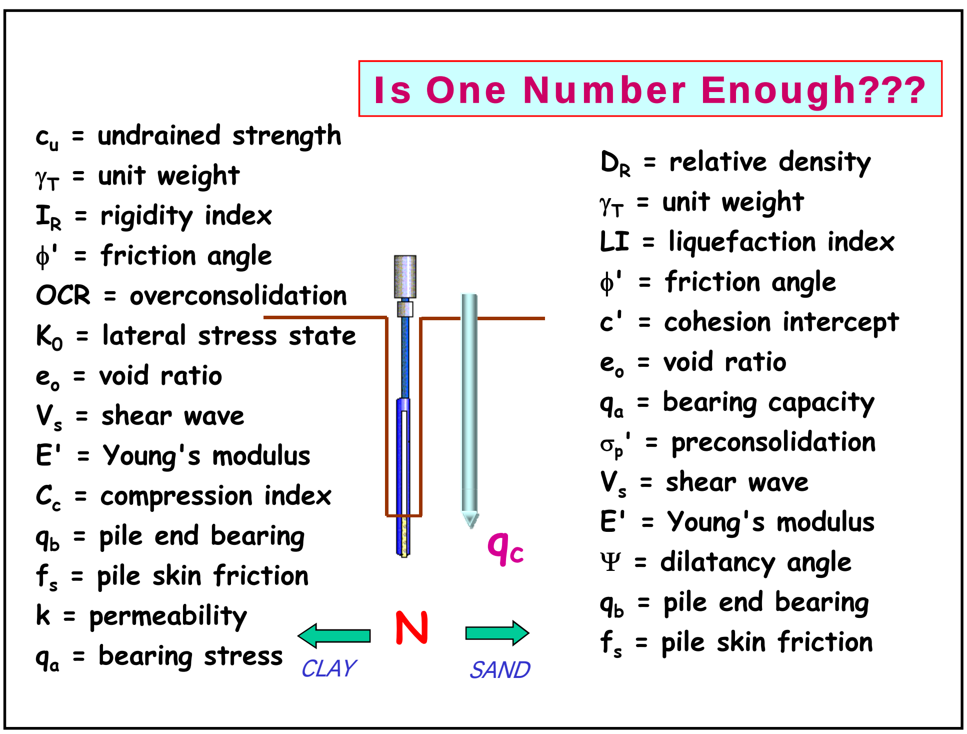
SOA-1: 17th ICSMGE 2009 - Alexandria

Generalized P_c' Profiling by CPT

for clays, silts, sands, and mixtures




Generalized P_c' Profiling by CPT
$\sigma_p' = 0.33 \cdot (q_t - \sigma_{vo})^{m_p} \cdot (\sigma_{atm}/100)^{1-m_p}$
Sands
Sandy Mix
Silty Mix
Clays
Organic
P_c' Exponent, m_p
CPT Material Index, I_c
$m_p = 0.65 + \frac{1}{800 \cdot 10^{-I_c} + 2.5}$
Hibernia Sand
Pentre Silt
Euripides Sand
Holmen Sand
Upper Troll Clay
Lower Troll Clay
Burswood Clay
Piedmont SM
Bothkennar Clay
Piedmont ML
Trend
$I_c = \sqrt{\{3 - \log[Q_t \cdot (1 - B_q) + 1]\}^2 + \{1.5 + 1.3 \cdot \log F\}^2}$


Is One Number Enough???
c_u = undrained strength
γ_T = unit weight
I_R = rigidity index
ϕ' = friction angle
OCR = overconsolidation
K_0 = lateral stress state
e_o = void ratio
V_s = shear wave
E' = Young's modulus
C_c = compression index
q_b = pile end bearing
f_s = pile skin friction
k = permeability
q_a = bearing stress
q_c
N
CLAY
SAND
D_R = relative density
γ_T = unit weight
LI = liquefaction index
ϕ' = friction angle
c' = cohesion intercept
e_o = void ratio
q_a = bearing capacity
σ_p' = preconsolidation
V_s = shear wave
E' = Young's modulus
Ψ = dilatancy angle
q_b = pile end bearing
f_s = pile skin friction

Geotechnical Site Characterization

What is Our Image to the Public ?

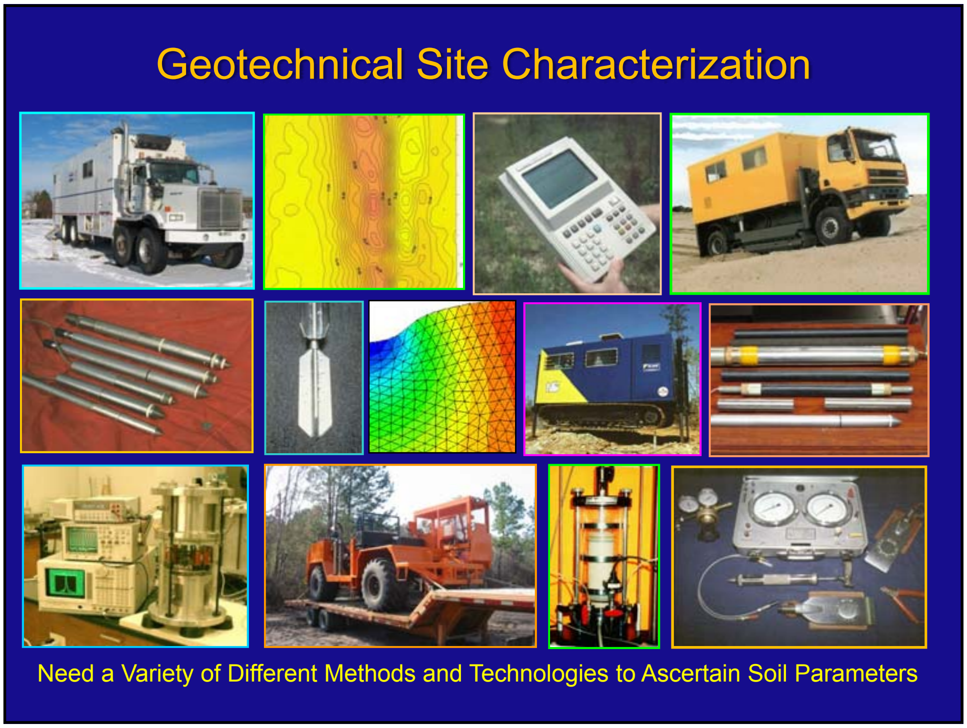
Every Soil Parameter from SPT N-value ?

European Foundations - Most Recent 2009 Issue

What the Public Sees and Our Image to Structural Engineers & Architects

View of Geotech Site Investigation

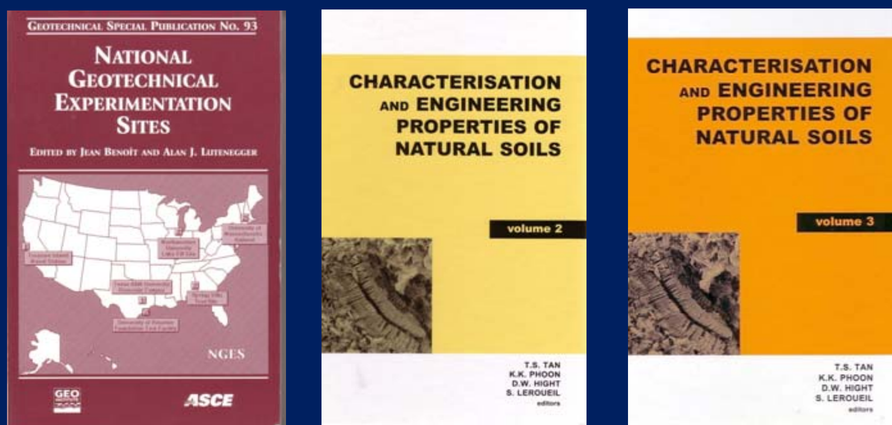
View of Construction Operations


Geotechnical Site Characterization
Need a Variety of Different Methods and Technologies to Ascertain Soil Parameters


Holmen Island in Drammen River (Lunne, et al. 2003)
NGI testing: 1956 to 2009
= 53 years

Geotechnical Experimentation Sites

Todate: 65 International Test Sites



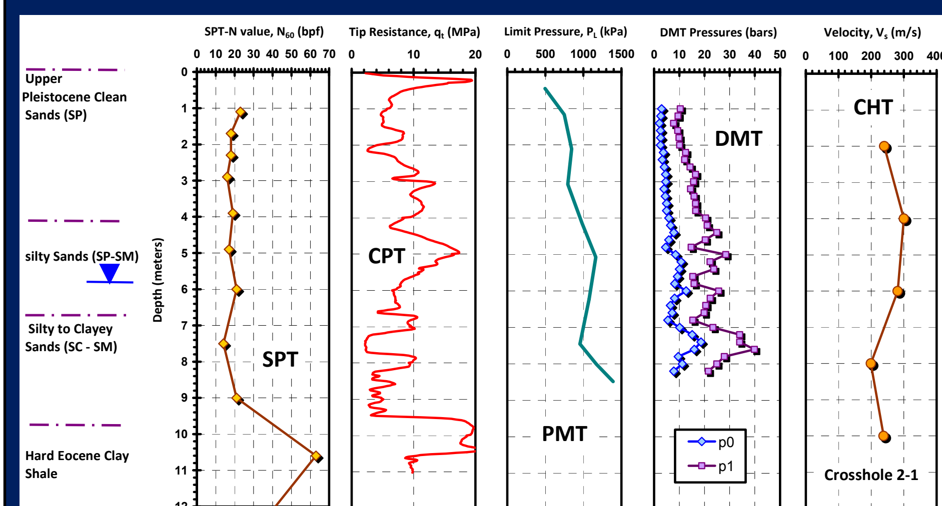
(2000) (2002) (2006)

SOA-1: 17th ICSMGE 2009 - Alexandria

Texas A&M Sand Site

US National Geotechnical Test Site

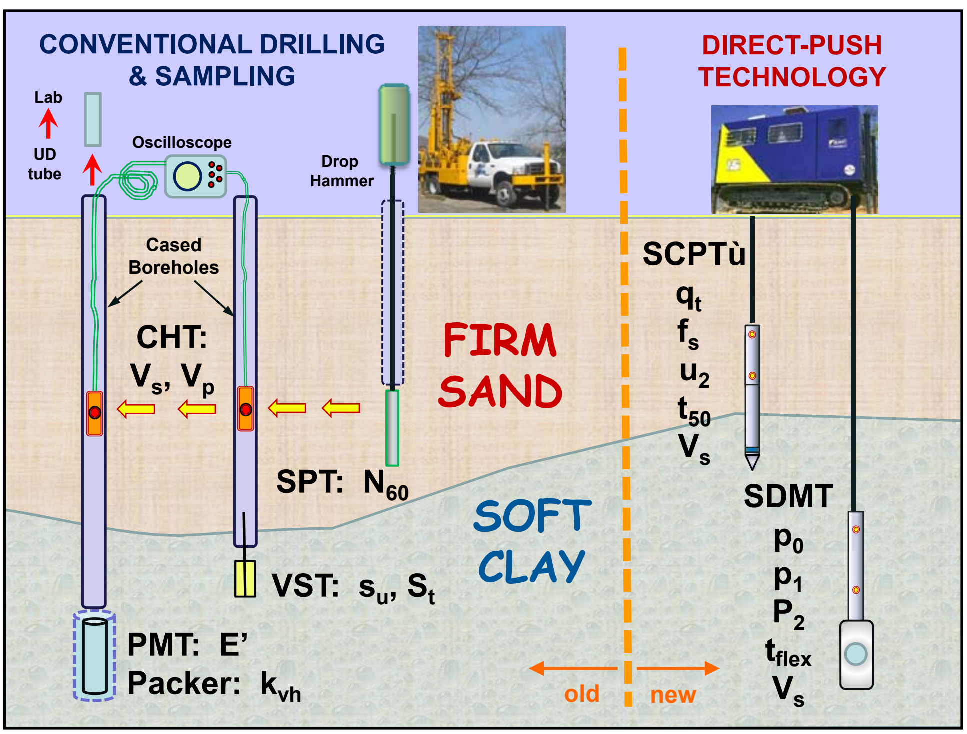
(Briaud & Gibbens, 1999; Briaud, 2007, ASCE JGGE)

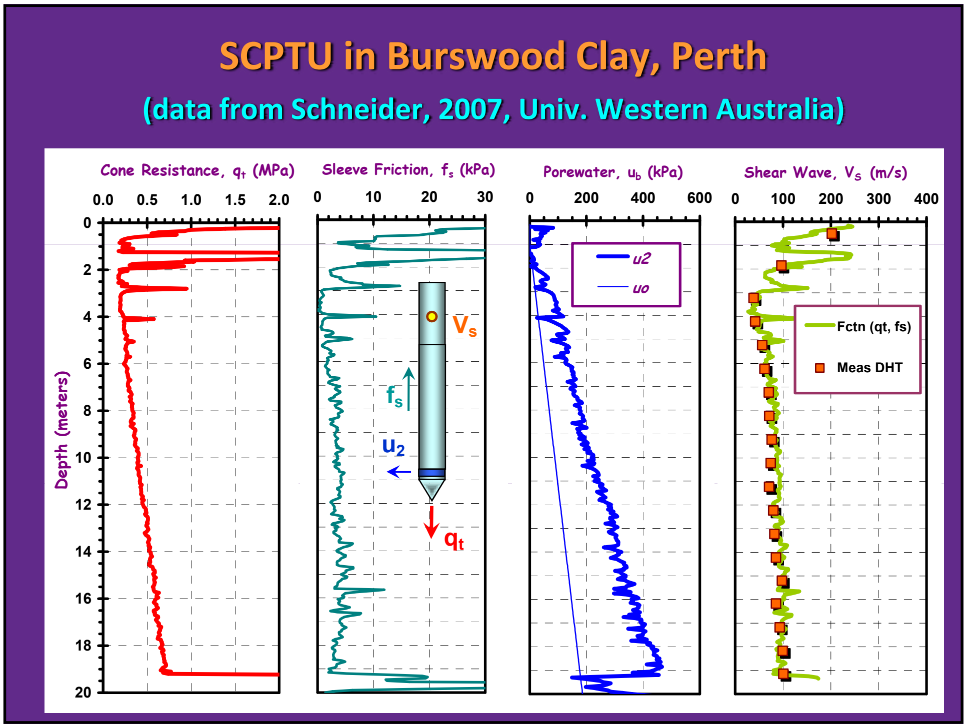


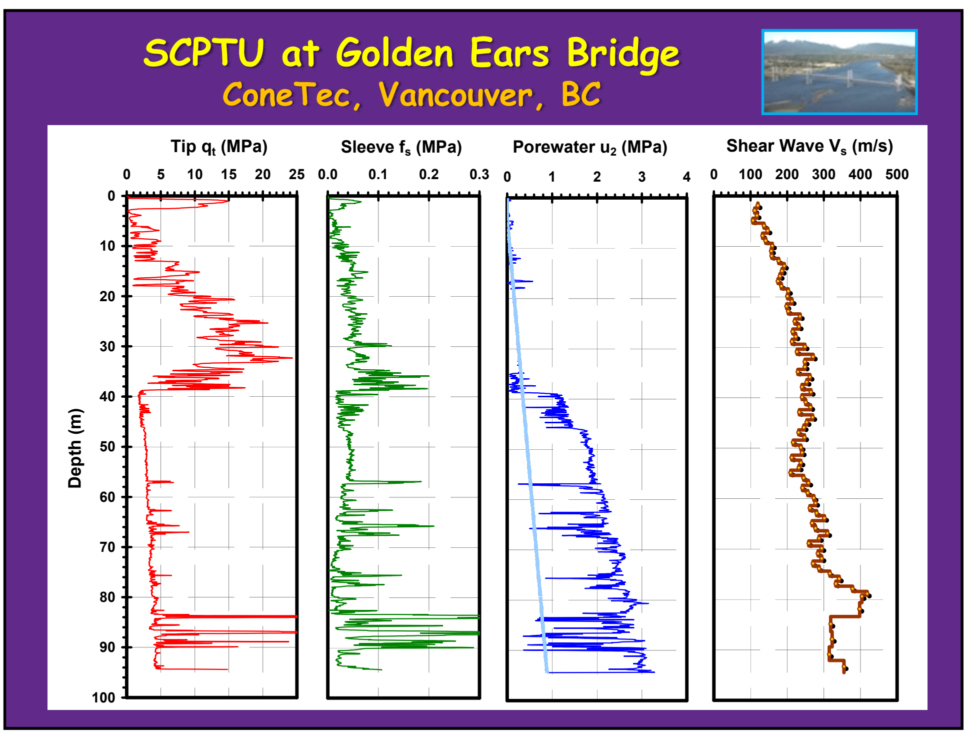
International Geotechnical Test Sites

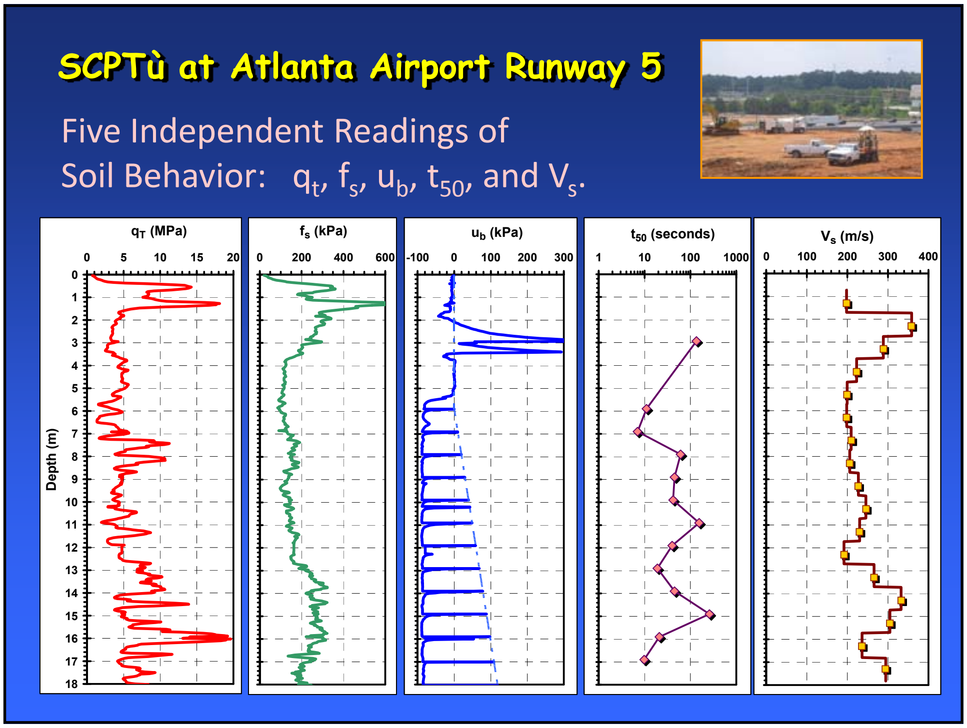
- Each site required decades of study
- Years worth of laboratory tests
- Many types of field testing
- Considerable amount of funds needed
- Backfigured soil engineering parameters from full-scale load tests
- Not have enough time !
- Conclusion: Need multiple measurements

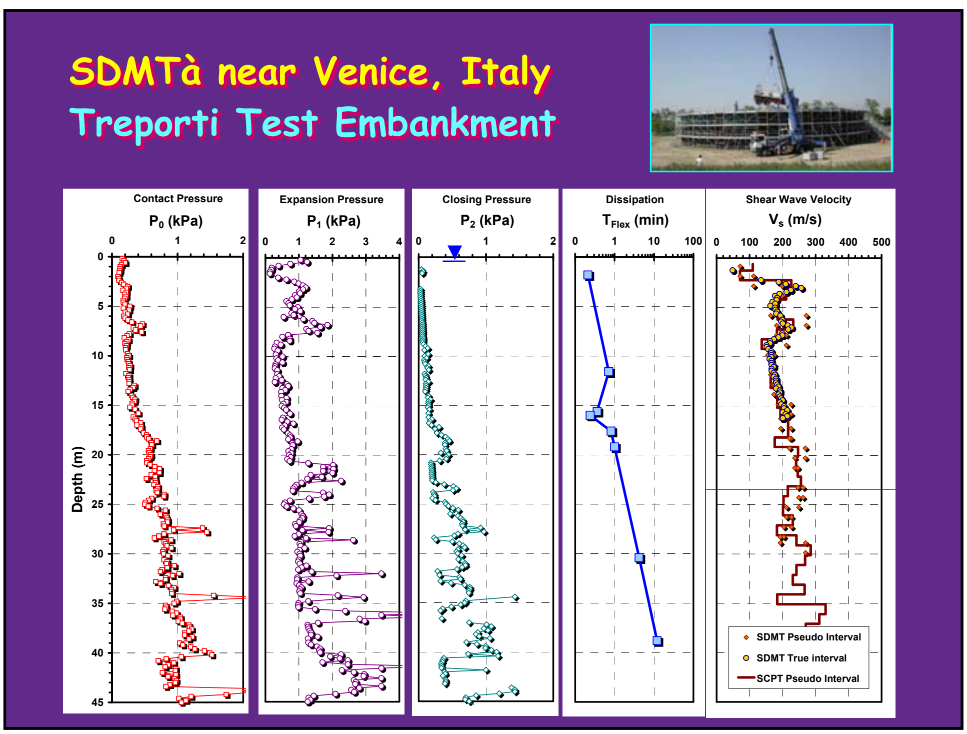
SOA-1: 17th ICSMGE 2009 - Alexandria

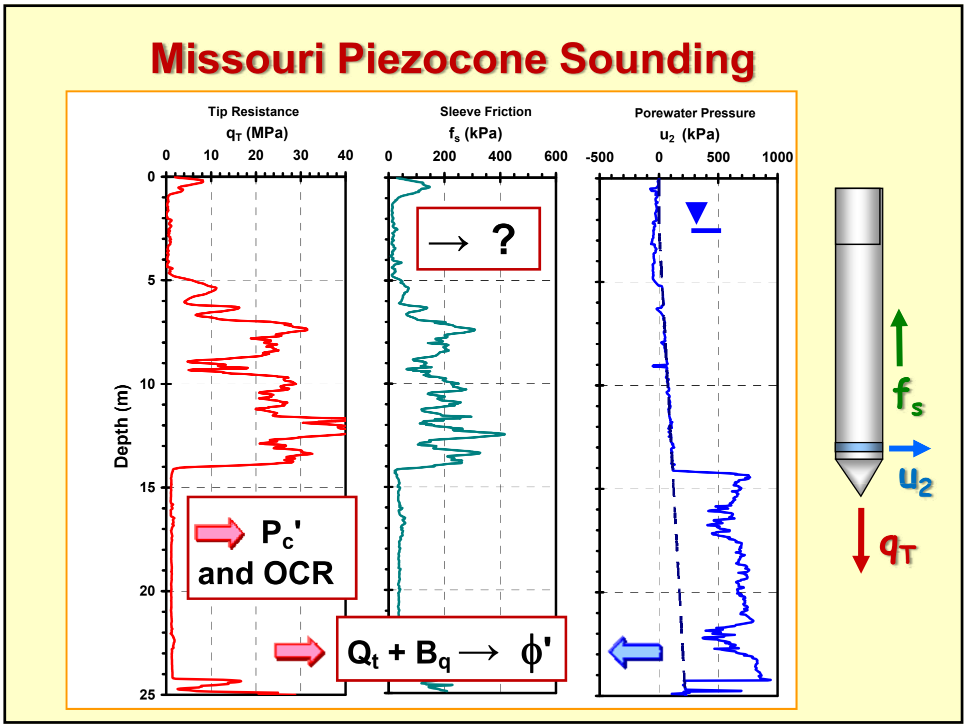


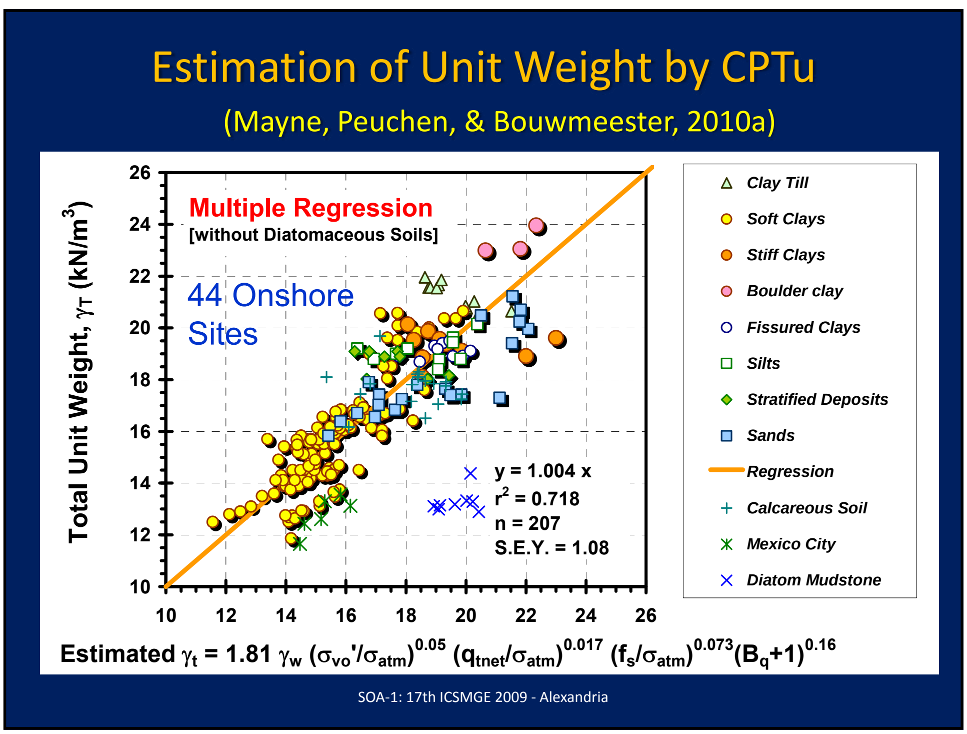

SCPTU in Burswood Clay, Perth
(data from Schneider, 2007, Univ. Western Australia)
Cone Resistance, qt (MPa)
Sleeve Friction, fs (kPa)
Porewater, ub (kPa)
Shear Wave, Vs (m/s)
Depth (meters)
u2
uo
Fctn (qt, fs)
Meas DHT
Vs
fs
u2
qt


SCPTU at Golden Ears Bridge
ConeTec, Vancouver, BC
Tip qt (MPa)
Sleeve fs (MPa)
Porewater u2 (MPa)
Shear Wave Vs (m/s)
Depth (m)


SCPTù at Atlanta Airport Runway 5
Five Independent Readings of
Soil Behavior: q_t, f_s, u_b, t_{50}, and V_s.
q_T (MPa)
f_s (kPa)
u_b (kPa)
t_{50} (seconds)
V_s (m/s)
Depth (m)

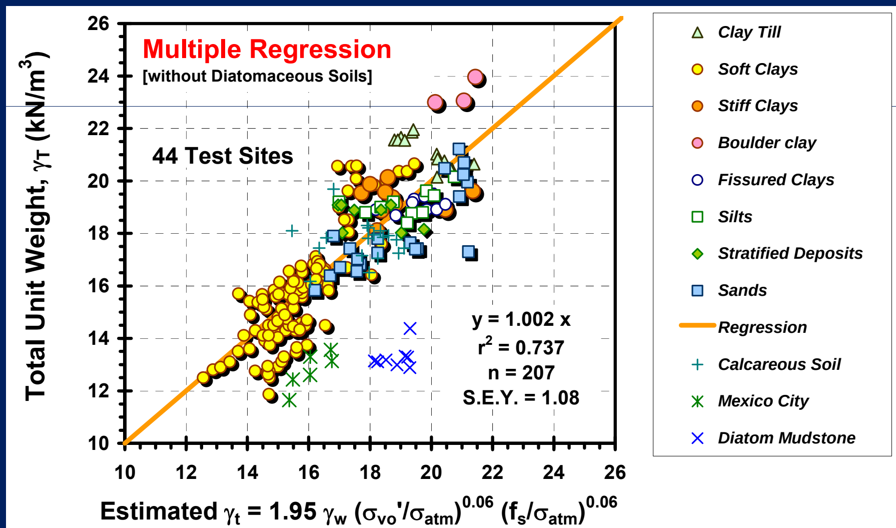

SDMTà near Venice, Italy
Treporti Test Embankment
Contact Pressure
P_0 (kPa)
Expansion Pressure
P_1 (kPa)
Closing Pressure
P_2 (kPa)
Dissipation
T_{Flex} (min)
Shear Wave Velocity
V_s (m/s)
Depth (m)
SDMT Pseudo Interval
SDMT True interval
SCPT Pseudo Interval


Missouri Piezocone Sounding
Tip Resistance
q_T (MPa)
Sleeve Friction
f_s (kPa)
Porewater Pressure
u_2 (kPa)
Depth (m)
→ ?
P_c'
and OCR
$Q_t + B_q \rightarrow \phi'$
f_s
u_2
q_T


Estimation of Unit Weight by CPTu
(Mayne, Peuchen, & Bouwmeester, 2010a)
Multiple Regression
[without Diatomaceous Soils]
44 Onshore
Sites
y = 1.004 x
r^2 = 0.718
n = 207
S.E.Y. = 1.08
Total Unit Weight, γ_T (kN/m³)
Clay Till
Soft Clays
Stiff Clays
Boulder clay
Fissured Clays
Silts
Stratified Deposits
Sands
Regression
Calcareous Soil
Mexico City
Diatom Mudstone
Estimated $\gamma_t = 1.81\ \gamma_w\ (\sigma_{vo}'/\sigma_{atm})^{0.05}\ (q_{tnet}/\sigma_{atm})^{0.017}\ (f_s/\sigma_{atm})^{0.073} (B_q+1)^{0.16}$
SOA-1: 17th ICSMGE 2009 - Alexandria

Estimation of Unit Weight by CPTu

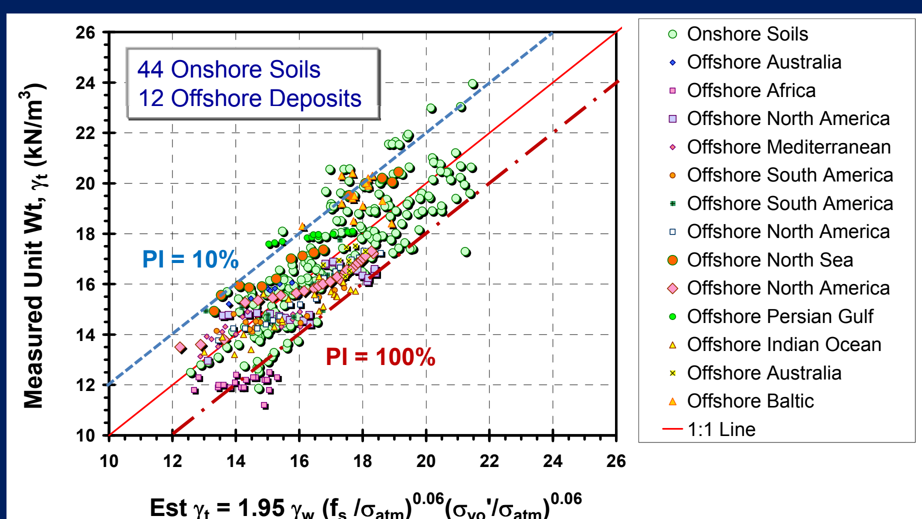
(Mayne, Peuchen, & Bouwmeester, 2010a)



SOA-1: 17th ICSMGE 2009 - Alexandria

Estimation of Unit Weight by CPTu

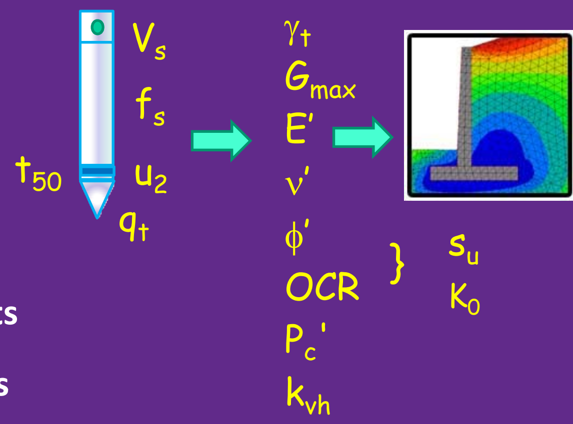
(Mayne, Peuchen, & Bouwmeester, 2010a)



SOA-1: 17th ICSMGE 2009 - Alexandria

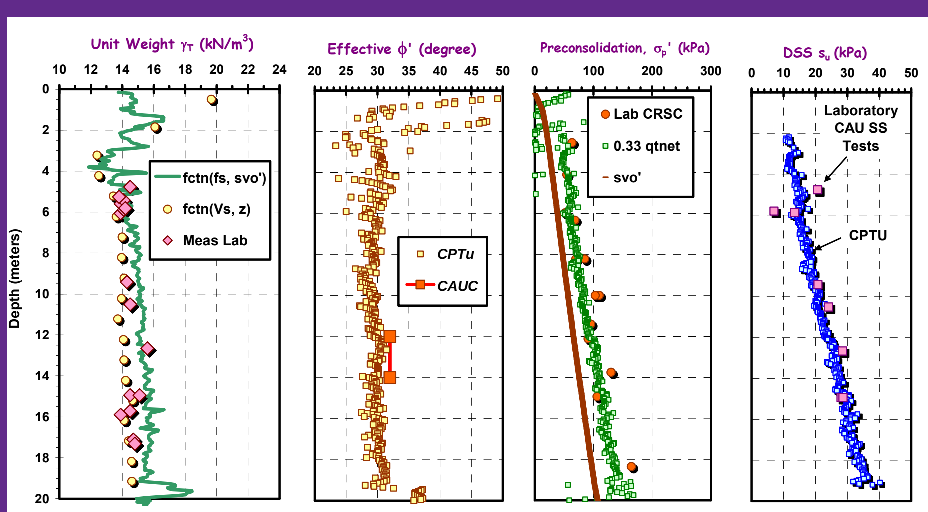
Seismic Piezocone Tests (SCPTu)

- Fast
- Economical
- Continuous
- Immediate results
- Multiple readings
- Digital data logged to computer
- Post-process information in real-time



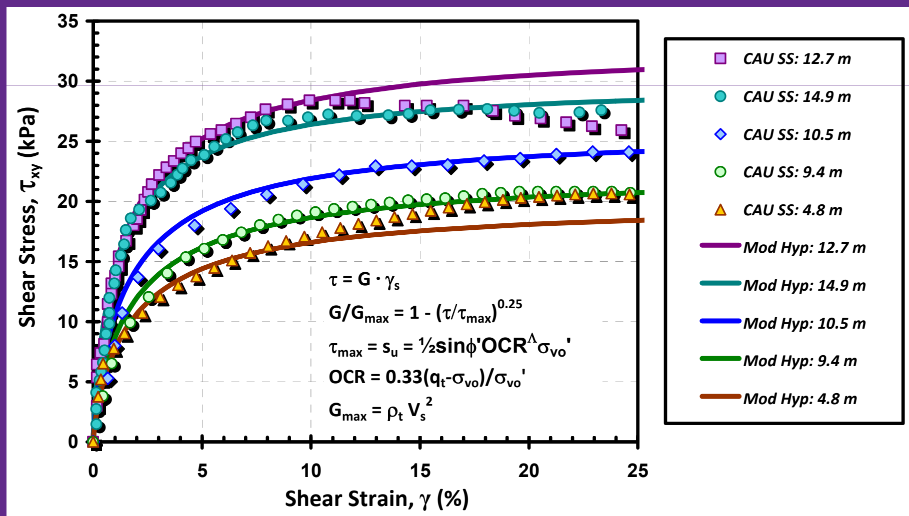
SCPTU in Burswood Clay, Perth

(Chung, 2005; Schneider, 2007, Univ. Western Australia)

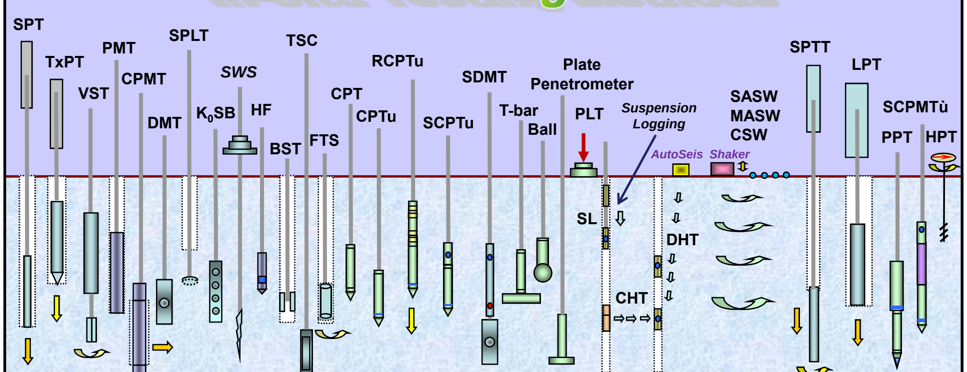


SCPTU in Burswood Clay, Perth

(Chung, 2005 UWA; Langdon, 2007 UMass-Amherst)



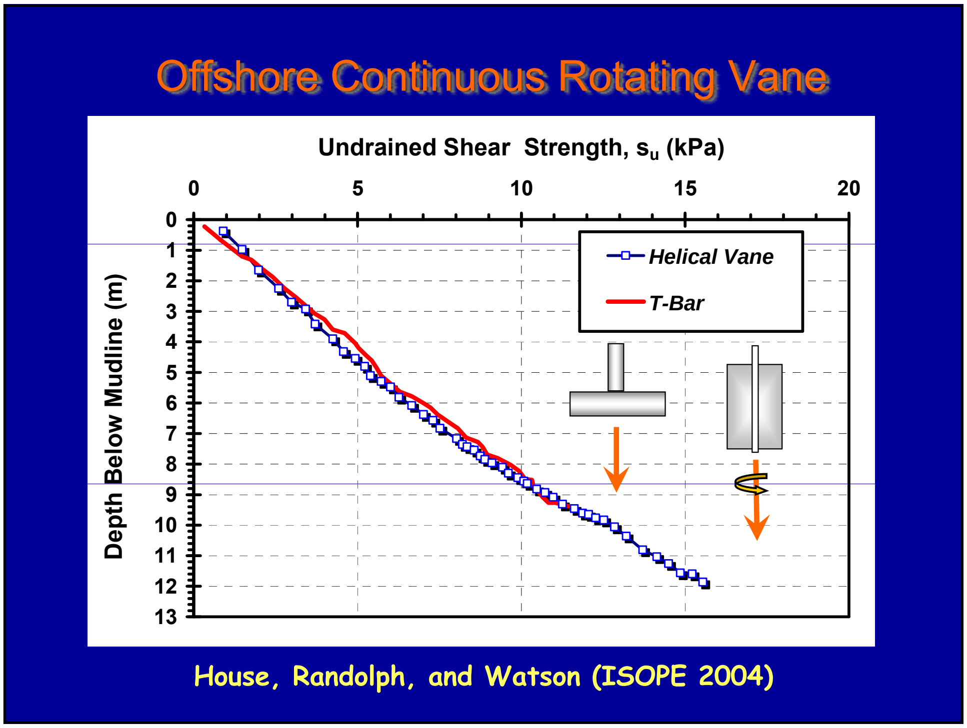
In-Situ Testing Methods

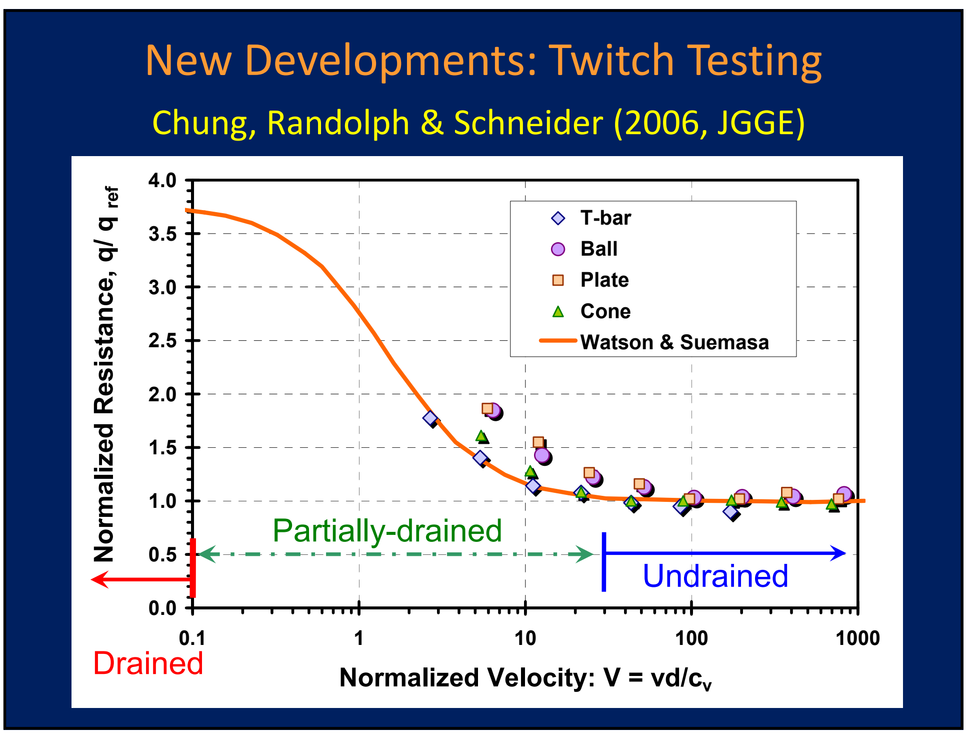


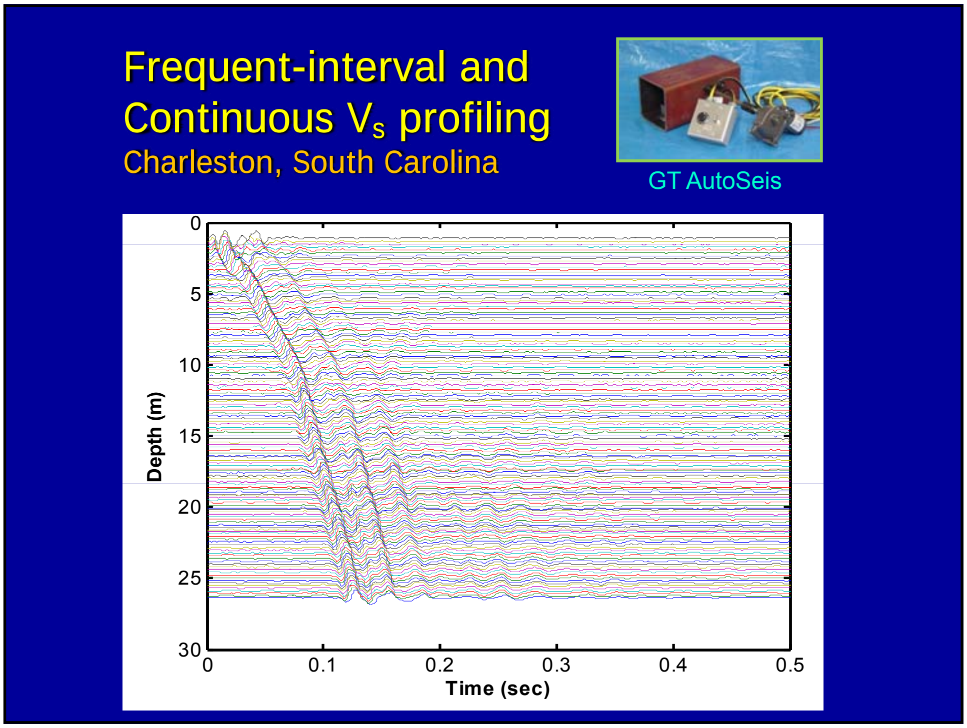
Standard Penetration Test
Texas Penetration Test
Vane Shear Test
Pressuremeter Test
Cone Pressuremeter
Dilatometer Test
Screw Plate Test
K_0 Stepped Blade
Swedish Weight Sounding
Hydraulic Fracture
Borehole Shear Test

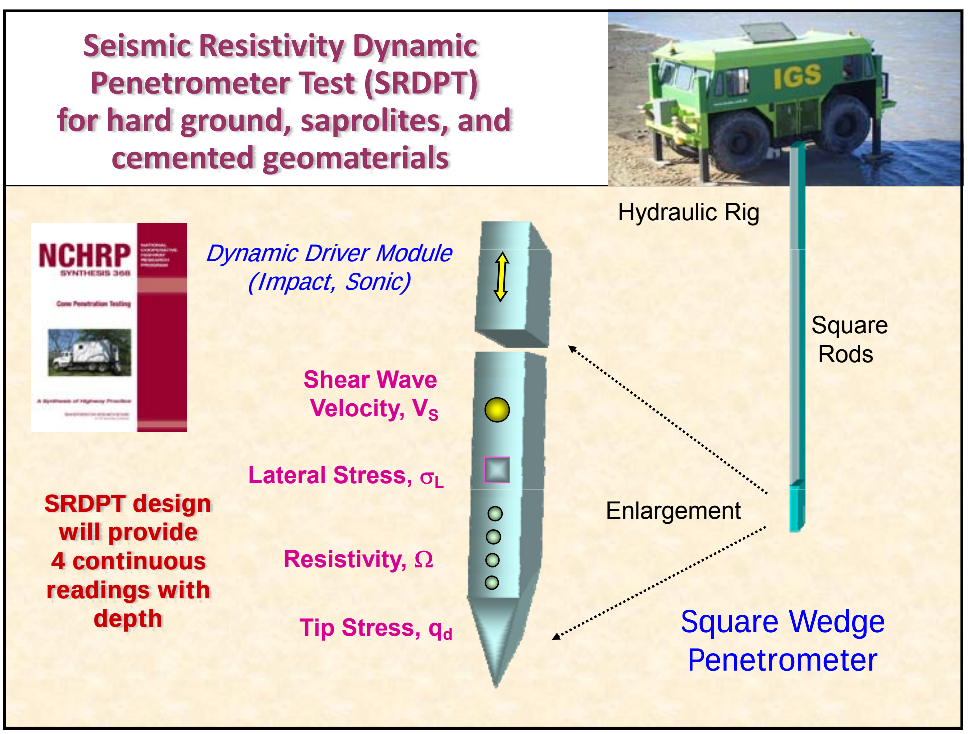
Total Stress Cell
Freestand Torsional Shear
Cone Penetration Test
Piezocone Penetration
Resistivity Piezocone
Seismic Cone
Seismic Flat Dilatometer
T-Bar Penetrometer
Ball Penetrometer
Plate Penetrometer
Plate Load Test

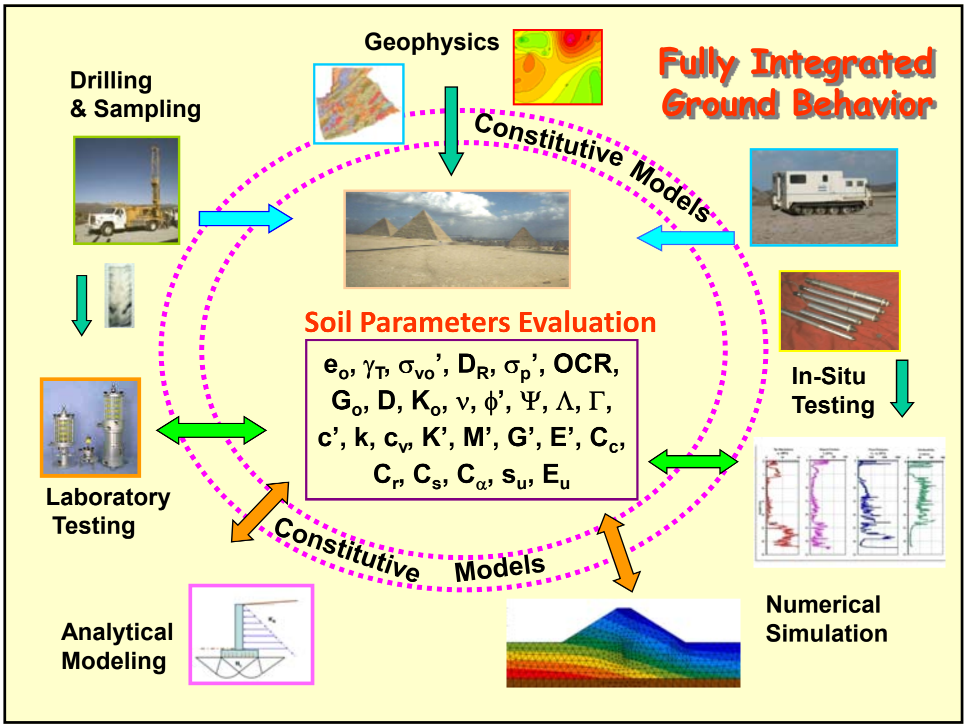
Suspension Logger
Crosshole Geophysical Test
Downhole Test
Spectral Analysis of Surface Waves
Modal Analysis (Rayleigh Waves)
Continuous Surface Waves
Standard Penetration Test with Torque
Large Penetration Test
PiezoProbe Test
Seismic Piezocone Pressuremeter
Helix Probe Test


Offshore Continuous Rotating Vane
Undrained Shear Strength, su (kPa)
0
5
10
15
20
Depth Below Mudline (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Helical Vane
T-Bar
House, Randolph, and Watson (ISOPE 2004)


New Developments: Twitch Testing
Chung, Randolph & Schneider (2006, JGGE)
Normalized Resistance, q/ q ref
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
T-bar
Ball
Plate
Cone
Watson & Suemasa
Partially-drained
Undrained
Drained
0.1
1
10
100
1000
Normalized Velocity: V = vd/cv


Frequent-interval and
Continuous V_s profiling
Charleston, South Carolina
GT AutoSeis
Depth (m)
Time (sec)
0
5
10
15
20
25
30
0
0.1
0.2
0.3
0.4
0.5


Seismic Resistivity Dynamic
Penetrometer Test (SRDPT)
for hard ground, saprolites, and
cemented geomaterials
IGS
Hydraulic Rig
NCHRP
SYNTHESIS 368
Cone Penetration Testing
Dynamic Driver Module
(Impact, Sonic)
Square
Rods
Shear Wave
Velocity, V_S
Lateral Stress, σ_L
Enlargement
SRDPT design
will provide
4 continuous
readings with
depth
Resistivity, Ω
Tip Stress, q_d
Square Wedge
Penetrometer



Summary: SOA-1 - Geomaterial Behaviour

- Geomaterial characterization is challenging
- Need *multiple measurements* - One number is insufficient for evaluation of soil parameters
- Let us teach *critical-state soil mechanics* in our colleges and use it in practice.
- Adopt *seismic piezocone* as the minimum level of effort for routine site investigation
- Continue to develop *international geotechnical experimentation sites* for calibration & reference

SOA-1: 17th ICSMGE 2009 - Alexandria

2nd International Symposium on Cone Penetration Testing

Huntington Beach, California

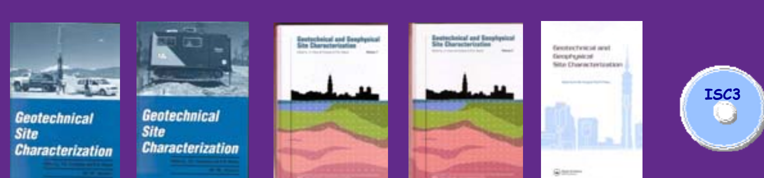
Host: Peter K. Robertson

HUNTINGTON BEACH, CA
CPT '10
May

CPT 2010: www.cpt10.org

4th International Conference on Site Characterization - 2012
Recife, Brazil (ISC-4)

- Professor Roberto Quental Coutinho
- Federal University of Pernambuco
- Brazilian Soc. Soil Mechanics & Geotechnical Engrg.



www.geoforum.com/tc16