Geotechnical Site Characterization: Cohesive Offshore Sediments

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Abstract:

The presentation gives recommendations for conducting site characterization programs to determine the geotechnical engineering properties of cohesive offshore sediments. The engineering behavior of cohesive sediments is complex and characterization of their in situ properties is magnified by additional challenges presented by offshore environments. Accurate analyses of past submarine landslides and prediction of the risk of future events require reliable soil properties, especially for that of the undrained shear strength. Traditional site investigations often rely on measurement of the undrained shear strength via strength index tests conducted on gravity core samples. Such samples are often of poor quality (in terms of mechanical properties) and strength index tests do not consider soil anisotropy, rate effects and sample disturbance. As a result, such data sets often produce scattered and unreliable undrained shear strength data for analysis of submarine landslides. Site investigation programs in cohesive soils are best conducted using well calibrated in situ tests and laboratory testing of good quality undisturbed samples. Results from these test programs should be coupled with geophysical data and collectively evaluated in the context of a regional geological framework. The presentation reviews clay behavior and lists key cohesive soil parameters required for analysis of submarine landslides. Best practice recommendations founded on these fundamentals are presented including drilling methods, in situ testing and instrumentation, soil sampling, and laboratory testing. The piezocone penetration test (CPTU) is an excellent in situ tool for soil profiling and can also provide data for estimating undrained shear strength via empirical correlations. Samplers that utilize appropriate tube geometry for cohesive sediments and a piston that is fixed relative to the seabed can provide good quality samples for laboratory testing. Continuing development of offshore test equipment has resulted in the availability of seabed frames that can push CPTU tooling and samplers in excess of 20 meters below seabed.

Geotechnical site characterization - cohesive offshore sediments

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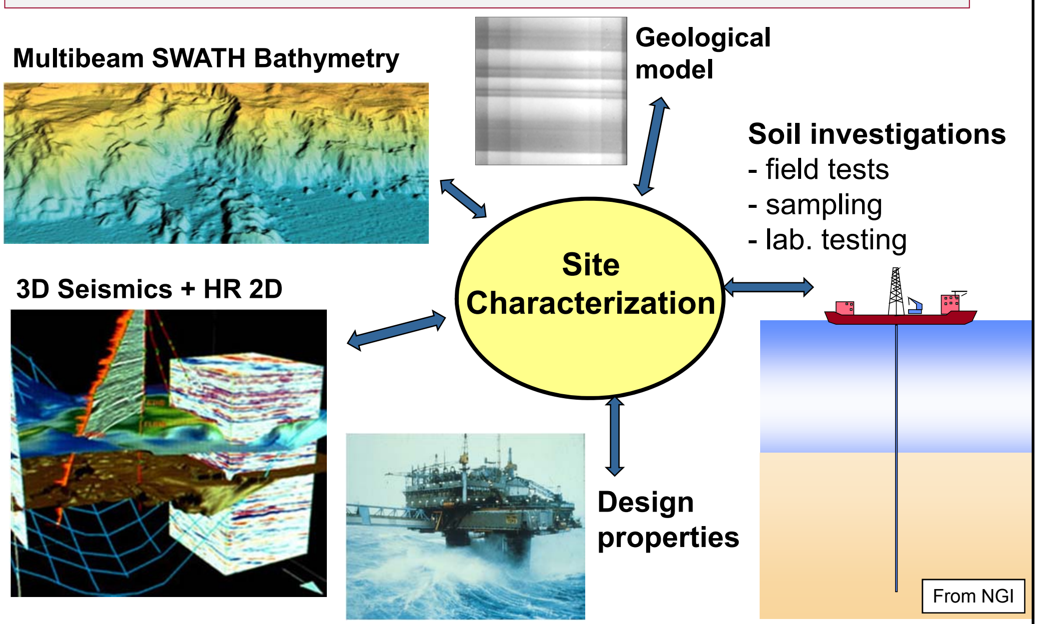
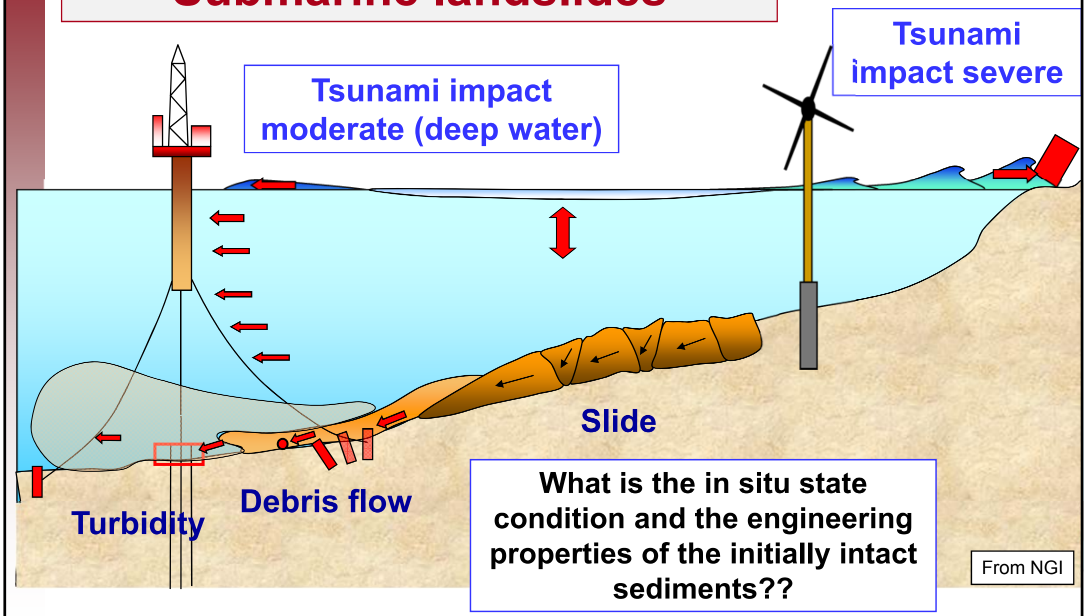
Presentation is based on the paper by Don J. DeGroot (UMass Amherst), Tom Lunne (Norwegian Geotechnical Institute) and Tor Inge Tjelta (Forewind-Statoil): "Recommended best practice for geotechnical site charaterisation of offshore cohesive sediments." Invited Keynote Paper. *Proceedings of the 2nd International Symposium on Frontiers in Offshore Geotechnics*. Perth, Western Australia, Nov. 2010.

UMASS AMHERST

Integrated approach via multidisciplinary geo-teams

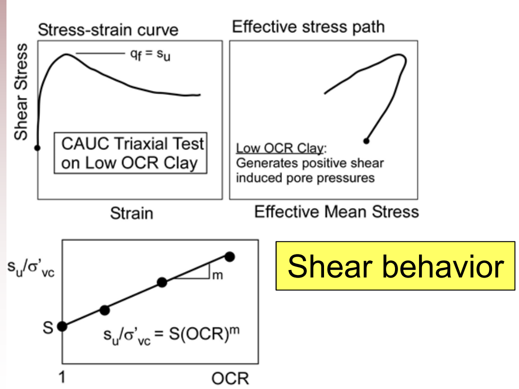


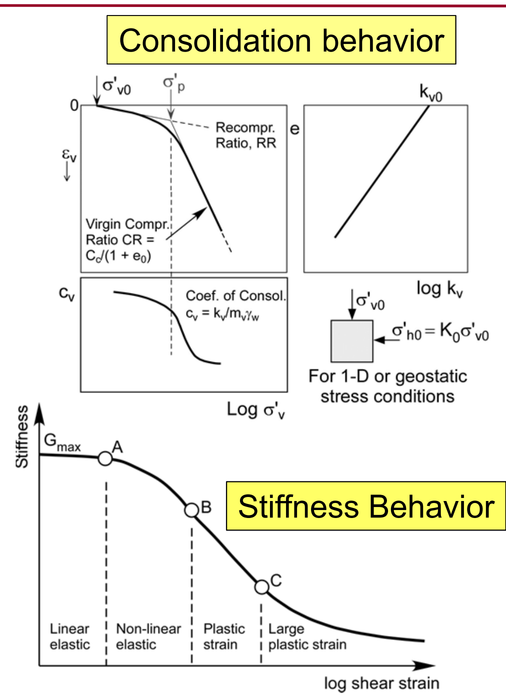
Submarine landslides



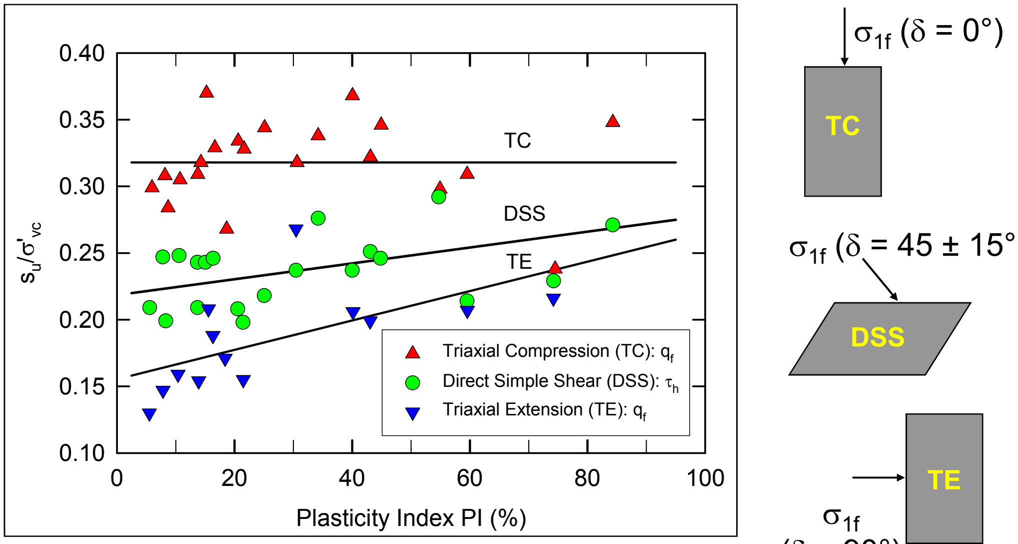
Clay soil behavior

- stress (geologic) history
- anisotropy
- rate effects, temp effects
- stiffness degradation



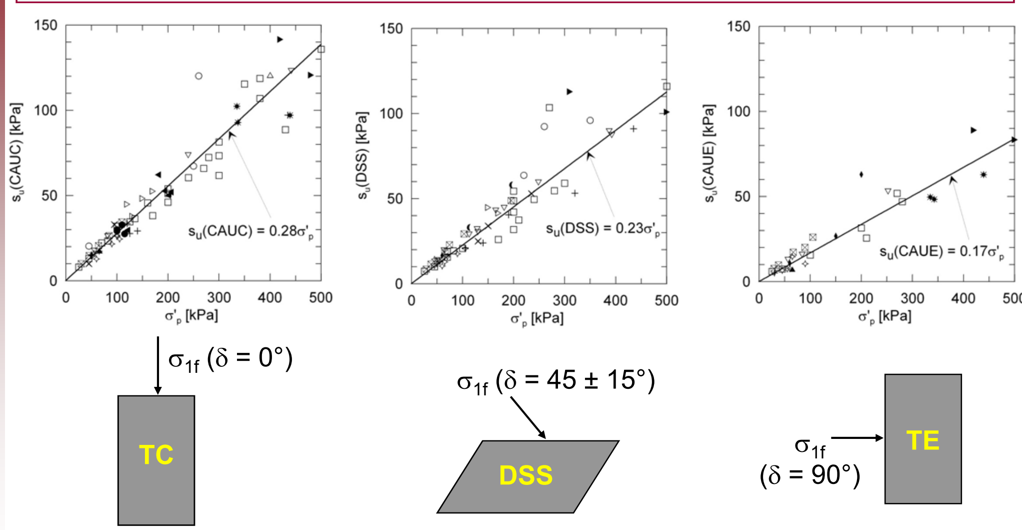


Undrained Shear Strength (s_u) Anisotropy



[Ladd 1991, Ladd and DeGroot 2003]

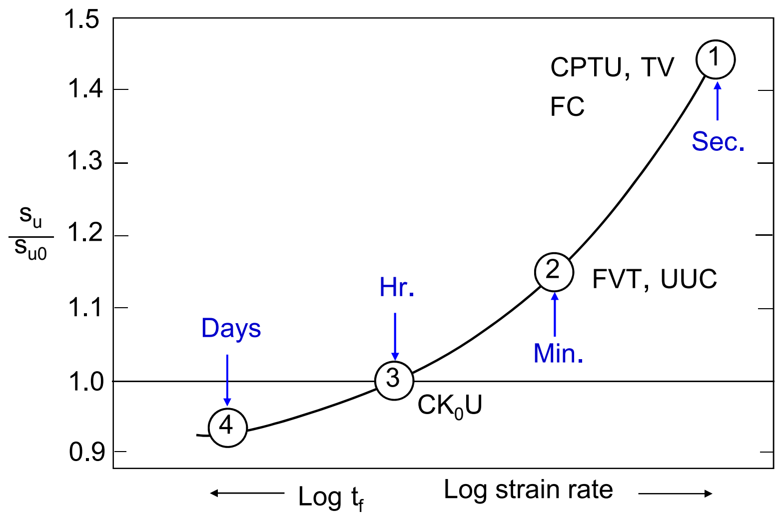
Offshore clays worldwide – s_u anisotropy



$s_u(CAUC) = 0.28\sigma'_p$ $s_u(DSS) = 0.23\sigma'_p$ $s_u(CAUE) = 0.17\sigma'_p$

DeGroot et al. (2010)

Clay soil behavior – rate effects

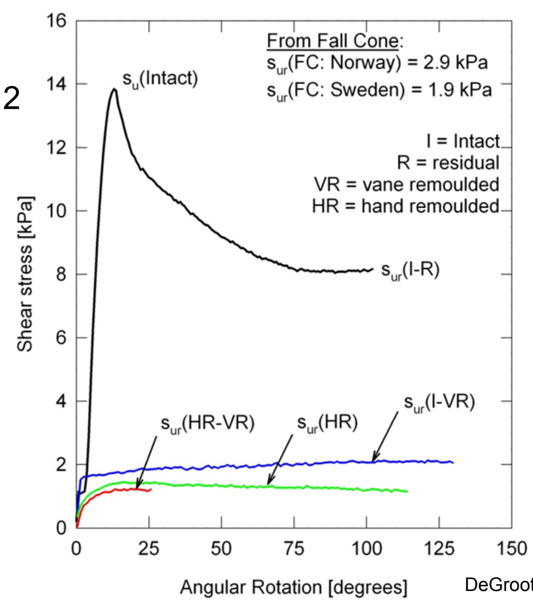


Ladd and DeGroot (2003)

Clay soil behavior – remolded shear strength

Troll clay – North Sea

Sensitivity = s_u/s_{ur} = 2 to 12



DeGroot et al. (2010)

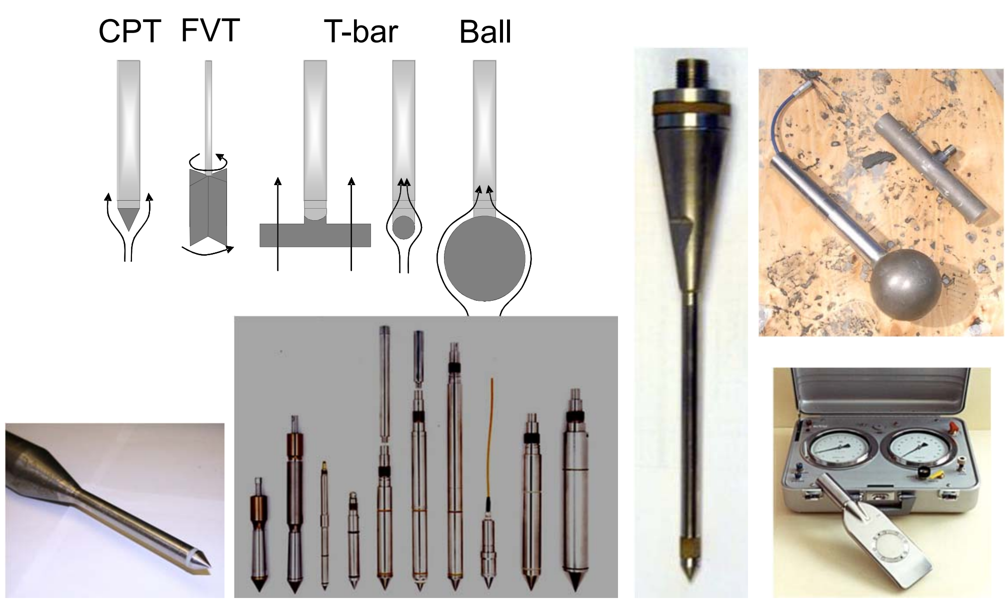
Design/analysis parameters - clays

1. State condition (σ'_{v0}, σ'_{h0}) – u_0 is the challenge
2. Stress (geologic) history = yield stress ($\sigma'_{vy} = \sigma'_p$)
3. Undrained shear strength (s_u) anisotropy
4. Strain softening to remolded s_{ur}
5. Cyclic and dynamic properties
6. Stiffness (e.g., G_{max}, $G(\gamma)$, M)

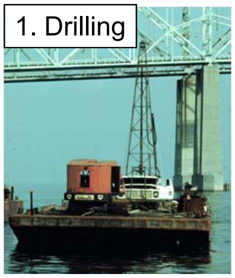
Most critical:
σ'_{v0}, σ'_p, s_u, $\rightarrow s_{ur}$

How to best determine (accurately) these soil properties??

In Situ Testing Enterprise

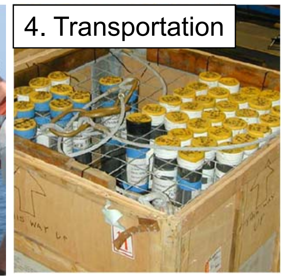


The Soil Sampling Enterprise


1. Drilling


2. Sampler

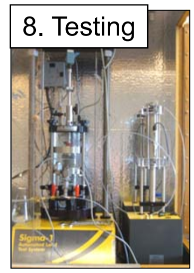

3. Processing


4. Transportation

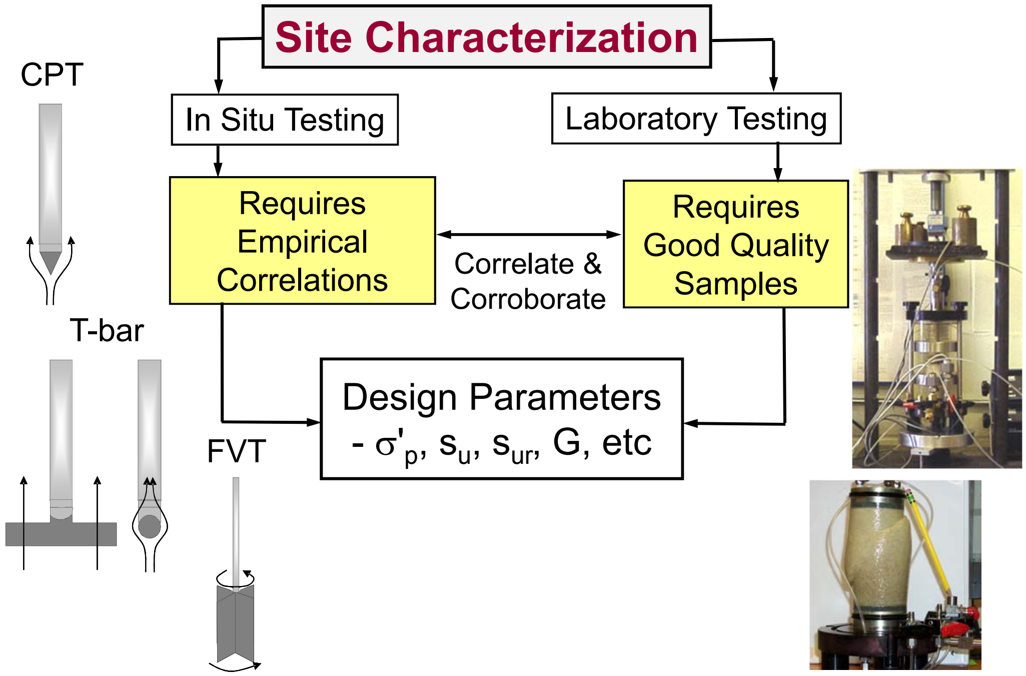

5. Storage


6. Extraction


7. Specimen Prep.


8. Testing

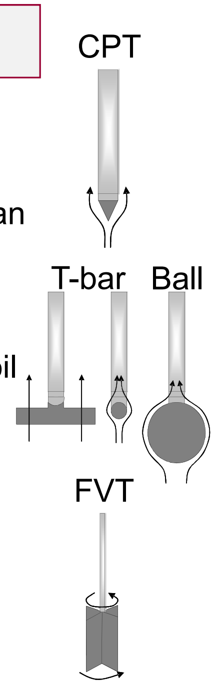
Site Characterization



In situ testing - recommendations

Tools

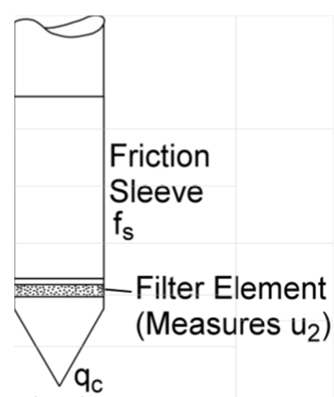
1. **CPTU** - main recommended tool. Best tool for soil profiling, soil behavior type, estimating σ'_p and s_u, can measure V_{vh} (G_{vh}), u(t).
2. **Full-flow penetrometers = T-bar and Ball** - especially for very soft sediments, best option for soil shear degradation, can do variable rate testing
3. **FVT** - remains a good tool for estimating s_u and s_{ur} but CPTU and full-flow more cost effective and give continuous profiles



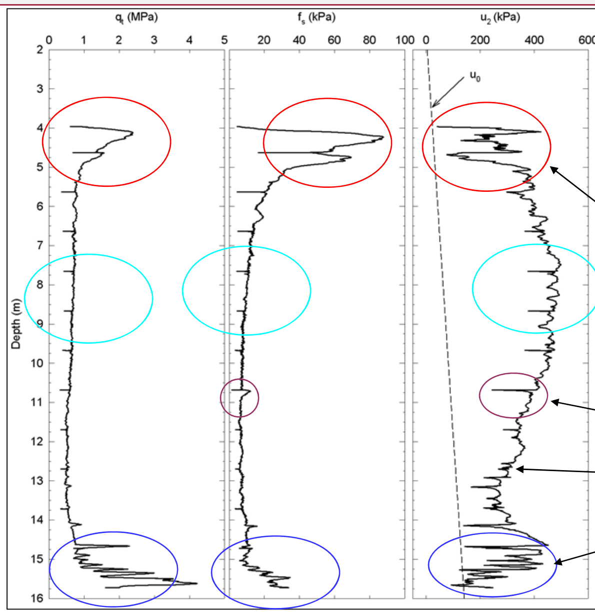
CPT/CPTU Field Measurements

Typical Field Measurements:

1. Cone geometry – tip area A_t (usually 5, 10 or 15 cm^2), sleeve area A_s (usually 150 cm^2)
2. Tip force – F_t
3. Sleeve friction force – F_s
4. Pore pressure - u_2
5. Inclination – vertical and horizontal



Example CPTU in NE Massachusetts



Boston Blue Clay - Newbury, MA

Significant variations in q_t, f_s and u_2 with depth

Stiff, high OCR CLAY Crust

Sensitive, soft CLAY

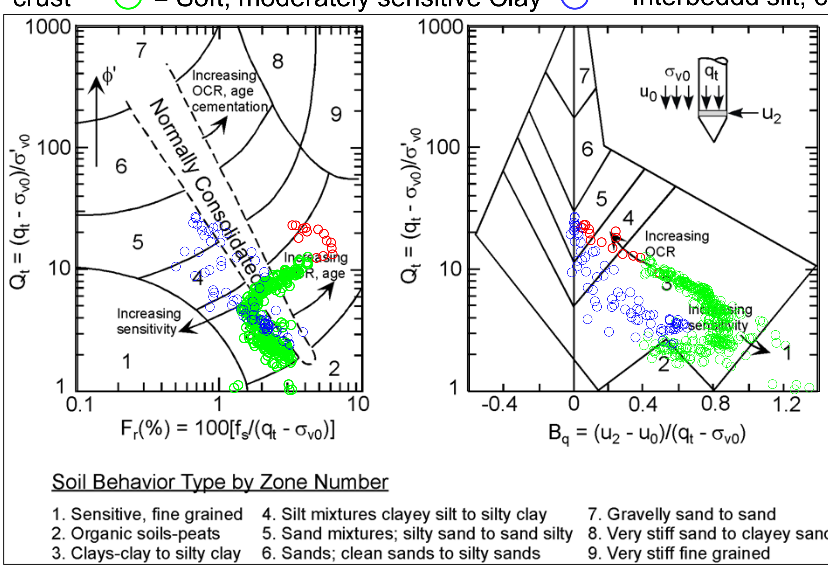
Dissipation Test

Increasing silt content

Interbedded Layers, Silt, Clay, Sand

Newbury BBC classification chart

○ = "crust" ○ = Soft, moderately sensitive Clay ○ = "Interbeddd silt, clay, sand



Undrained Shear Strength from CPTU Data

s_u is <u>not unique</u>, CPTU data are influenced by fundamental soil behavior but <u>cannot directly measure</u> s_u and hence CPTU interpretation relies on empirical correlations

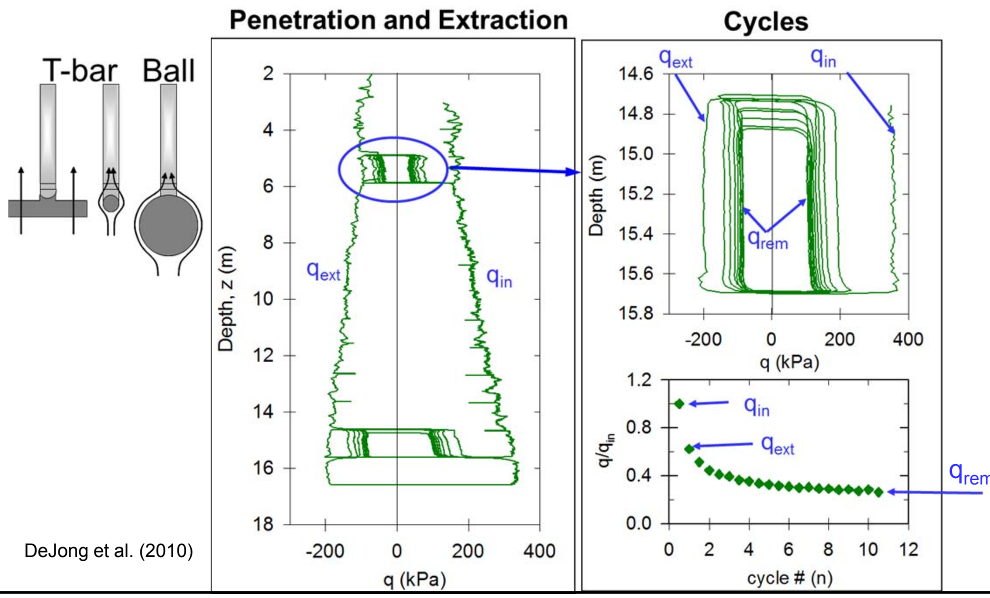
Most Common

$$s_u = q_{net}/N_{kt} = (q_t - \sigma_{v0})/N_{kt}$$

- need empirical correlation factor N_{kt} correlated to a specific measure of s_u e.g., s_u(CAUC) or s_u(ave)

- Ideally want site specific correlation linked with lab data

s_u degradation from full flow penetrometers

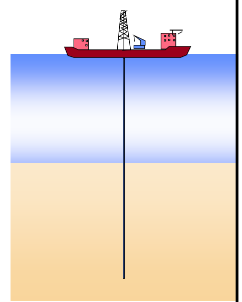


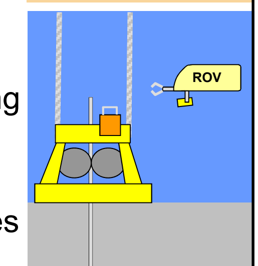
DeJong et al. (2010)

Deployment modes - recommendations

Drilling mode: borehole advanced using rotary drilling from vessel (= vessel based drilling) or seabed system (= seabed based drilling)

Non-drilling mode: advance of tools from seabed (i.e., no borehole drilling)



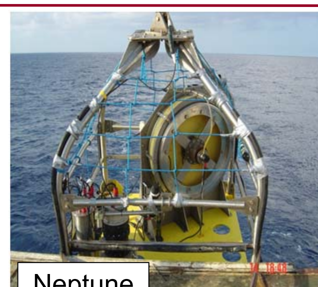


Strout & Tjelta (2007)

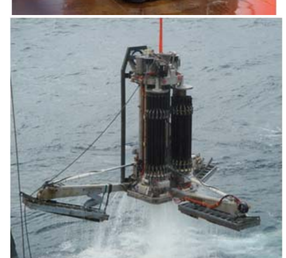
Critical issues:

1. **Dynamic positioning**
2. **Depth accuracy** for in situ testing and soil sampling is critical
3. **Set down conditions** – for seabed systems, minimize disturbance and imposed seabed stresses

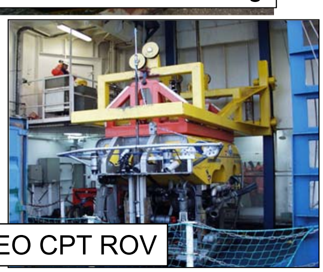
Roson – A.P. van den Berg



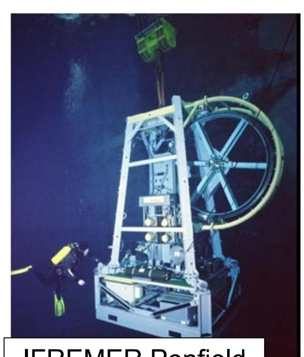
Neptune



Benthic GeoTech PROD



GEO CPT ROV



IFREMER Penfield

Deepwater In Situ Testing – Seabed Frames

- Vessel mounted power pack
- Water depths up to 1,500 to 4,000 m
- Penetrations to 20 - 50m

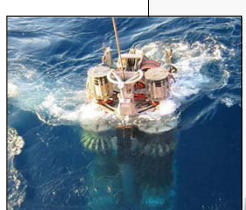
- Subsea hydraulic power pack
- Coiled rod, 1 umbilical
- Water depths up to 3000m
- Penetrations to 20m

a.p. van den Berg

Datem, Neptune

<u>Benthic GeoTech</u>:
Portable Remotely
Operated Drill (PROD)

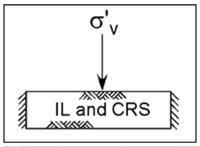
- 260 meters of drill tools

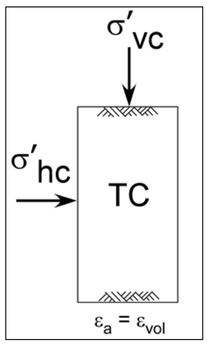


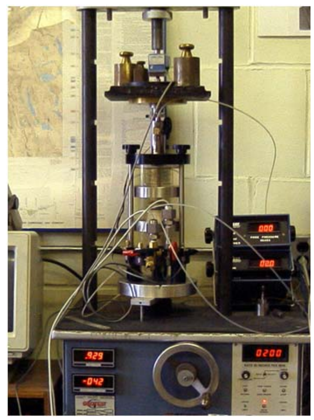
From Benthic GeoTech

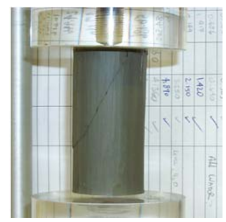
Laboratory testing

1. Classification and index testing
2. Index strength tests (e.g., FC, UUC, TV, etc.)
3. "Advanced" laboratory tests (e.g., CRS, Triaxial, DSS, etc.)





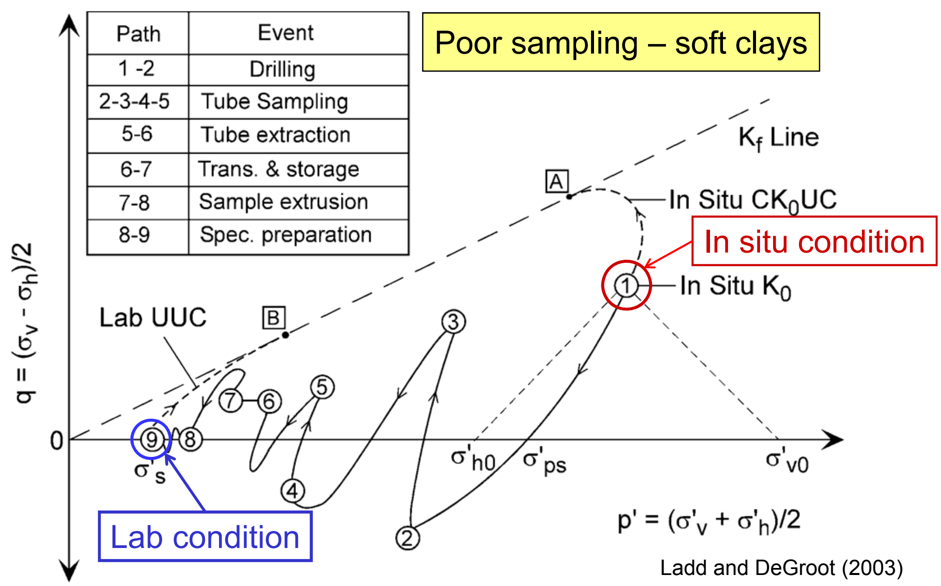




Sampling and sample quality

Poor sampling – soft clays

Path	Event
1 -2	Drilling
2-3-4-5	Tube Sampling
5-6	Tube extraction
6-7	Trans. & storage
7-8	Sample extrusion
8-9	Spec. preparation



Ladd and DeGroot (2003)

Laboratory testing - recommendations

1. *Reliable* determination of *design* parameters:

- 1-D CRS test for stress history, compressibility & flow behavior
- Consolidated-undrained (CU) tests (e.g. CAUC, DSS, CAUE) for measurement of stress-strain-strength behavior and anisotropy

2. Essential to evaluate sample quality (e.g., $\Delta e/e_0$ at σ'_{v0})

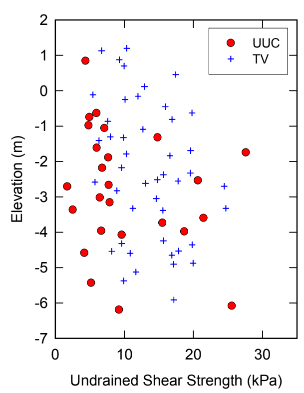
3. Always evaluate s_u profiles in context of stress history data

4. Remediation of sample disturbance

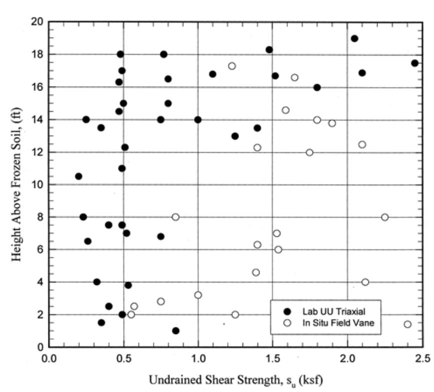
Problems with Index strength testing (FC, TV, PP, UUC, etc.)

- unknown effective stress state
- significant influence of sample disturbance
- highly variable (and often fast) shear rates
- how account for anisotropy

Net result = highly scattered, often unreliable, data



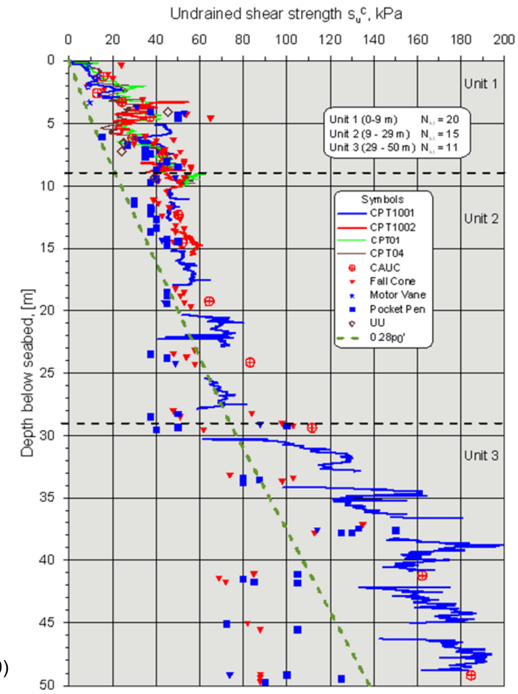
CH Clay Nigerian Swamp



Harrison Bay, Alaska

Index strength test data are especially unreliable with increasing depth

Undrained shear strength data for low OCR soft clay site, Haltenbanken area of the Norwegian Sea.

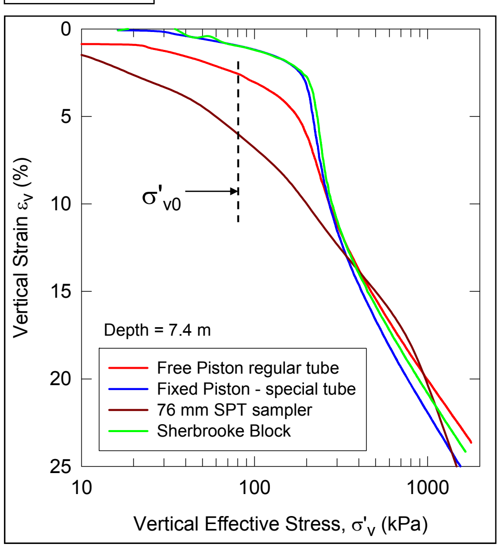


DeGroot et al. (2010)

Consequences of poor quality sampling

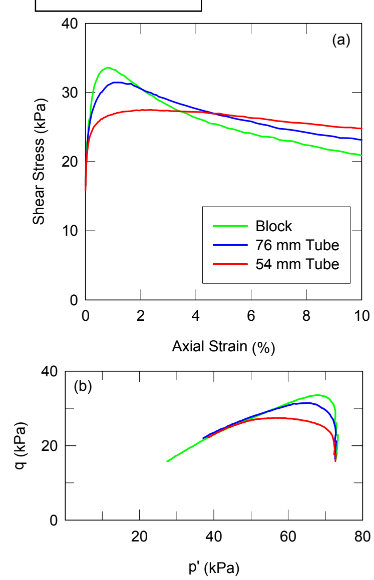
2 marine clays

CRS Tests



DeGroot et al. (2007)

CAUC Tests

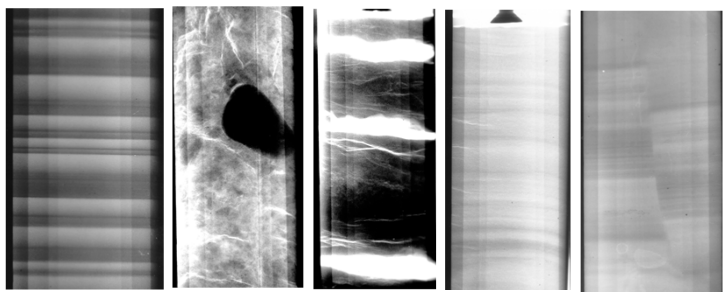


Assessment of sample quality - recommendations

1. No definitive method to determine quality relative to the "perfect sample".

2. Ideally want an *a priori* non-destructive method for quantification of sample quality (x-raying is non-destructive but not quantitative)

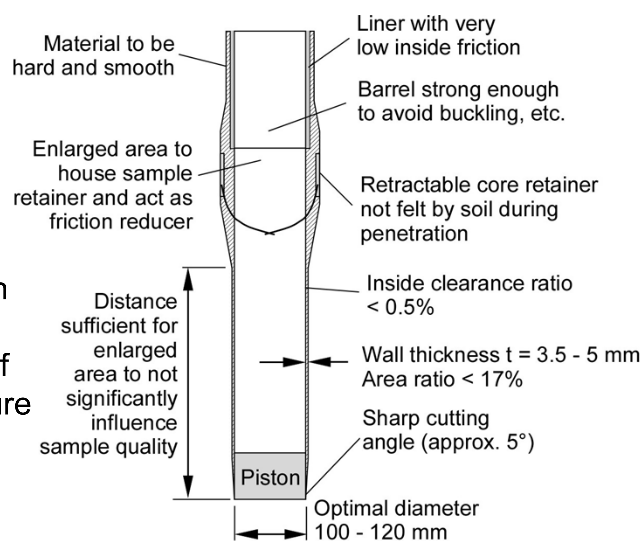
76 mm tubes



3. The current "gold" standard for rating of sample quality = volumetric strain (ε_v or $\Delta e/e_0$) during laboratory 1-D reconsolidation to estimated in situ stress state [σ'_{v0}, σ'_{h0}] (i.e., NGI method; Lunne et al. 2006)

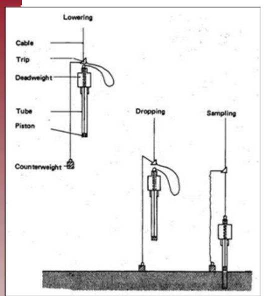
Sampler design - recommendations

- appropriate sampler geometry
- truly stationary piston relative to seabed
- steady rate of penetration
- real time measurement of penetration & underpressure below piston



After Lunne and Long (2006), Lunne et al. (2008)

Kullenberg Type Samplers

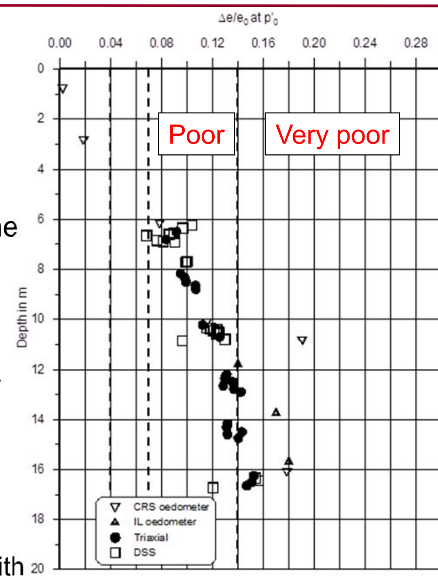


Piston fixed to cable.

Various degrees of control, but always some movement which normally leads to low core recovery.

Problem: Relatively low recovery (0.7 – 0.9), uncertain which part of core is lost.

Exception is STACOR with piston stationary relative to seabed, w/ general high recovery ratio



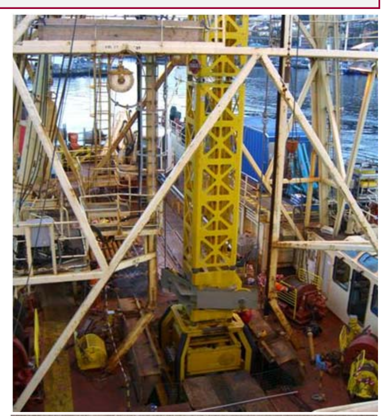
Example offshore Africa - recovery about 70 %.

After Lunne et al. (2008)

Sampler design - recommendations

Drilling mode (vessel or seabed):
- thin walled piston sampling with favorable geometery

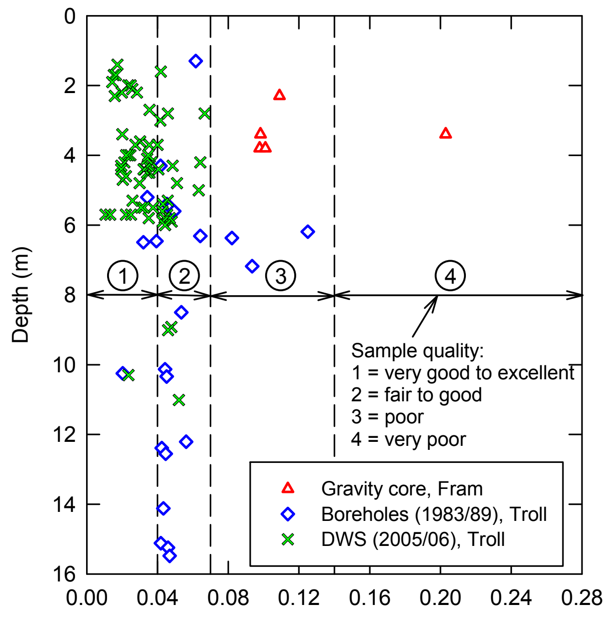
Non-drilling mode (seabed based)
- samplers such as DWS
- gravity sampler with piston fixed relative to seabed, e.g., STACOR
- gravity sampler but piston fixed relative to vessel e.g., Kullenberg
- gravity sampler without fixed piston



Deep water sampler (DWS)

Troll Field (North Sea)

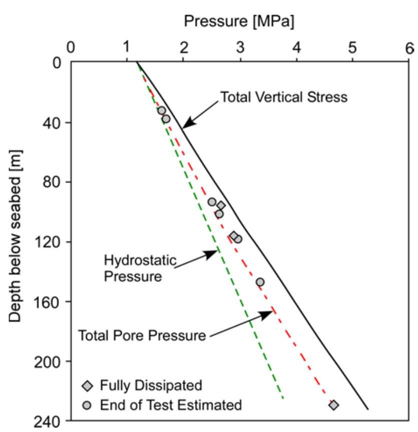
- borehole drilling with tube sampling
- deep water sampler
- gravity core sampler



DeGroot et al. (2010)

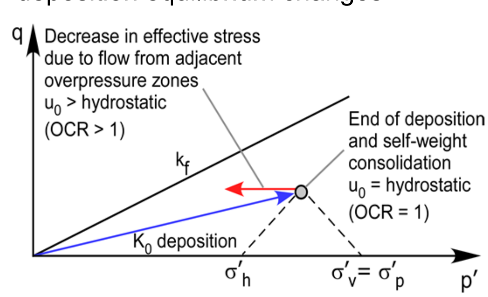
In situ pore pressure

- critical to conduct of reliable site charaterisation program → σ'_{v0}
- very difficult challenge → but exciting developments continue



West Azeri field (Allen et al. 2005)

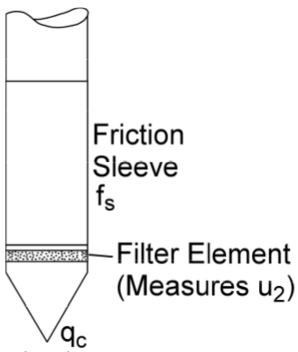
Genesis: "under-consolidated" vs post deposition equilibrium changes

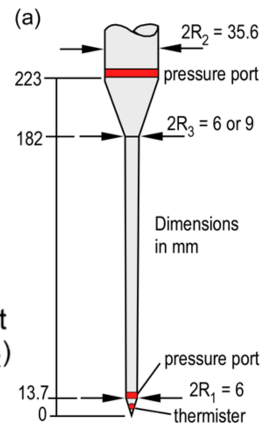


Workshop Report: Sheahan & DeGroot. (2009). *Seabed sediment pore pressure: genesis, measurement and implications for Design/Analysis*

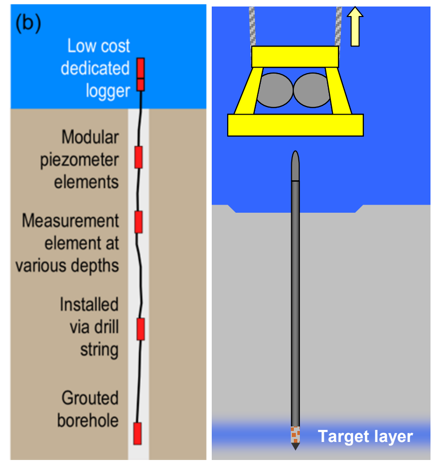
In situ pore pressure - direct measurement options

1. CPTU & Piezoprobes – dissipation testing
2. Piezometers – predrilled borehole or push-in piezometer



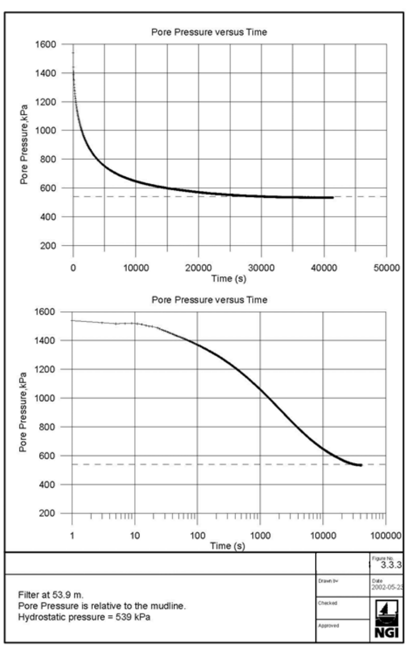


Flemings et al. (2008)

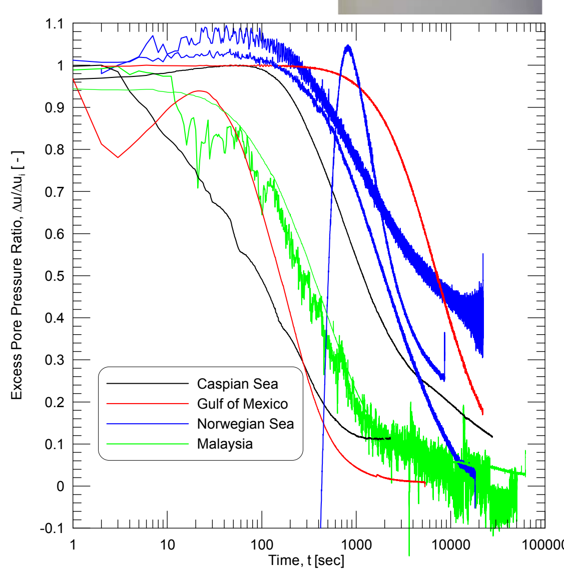


Strout & Tjelta (2007)

Regular CPTU dissipation



Piezoprobe measurements

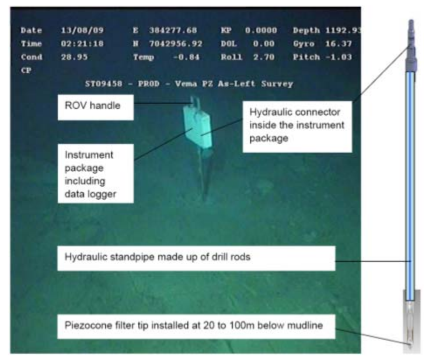


In situ pore pressure - recommendations

Piezometers via long term monitoring is the only reliable method to obtain direct measurement of equilibrium in situ pore pressure

Cost is not trivial and installation has often been challenging but new solutions keep being developed, e.g.,

Luva Investigation (Tjelta & Strout 2010)
- 1300 m water depth
- used PROD system
- very accurate depth control
- 20 to 100 meters bml
- Δt ~ 4 to 5 hrs for 20 m,
- 100% success rate



Summary:

<u>CPTU</u>: excellent for soil profiling, empirically correlate to s_u, excellent for spatial variability

<u>Sampling</u>: good quality samples for lab testing is critical, direct measurement s_u anisotropy, s_{ur}

<u>Deployment systems:</u> – seabed based drilling system, non-drilling mode (from seabed)

ISO draft (2011) standard on
Marine Soil Investigations
will provide a valuable reference

International Organization for Standardization