

**Keynote lecture, Session 1: Equipment and procedures**

# **Influence of test equipment and procedures on obtained accuracy in CPTU**

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# Accuracy in CPTU

## Preparation, performance and control

### Content

- **Introduction**
  - ✓ From CPT'95 to CPT'10
- **New international standard on CPT/CPTU**
  - ✓ EN-ISO standard 22476-1
  - ✓ Important requirements on test accuracy
- **Factors influencing test accuracy**
  - ✓ Preparations before testing
  - ✓ In situ test procedures
- **Quality control of test data**
  - ✓ Evaluation of test profile
  - ✓ Evaluation of accuracy
- **Closing remarks**





# Introduction

## From CPT'95 to CPT'10

# Accuracy in CPTU

## Preparation, performance and control



## CPT'95 Linköping, Sweden

### Trends and development in 1995

- Improved technology and accuracy of CPTU probes
- Implementation of new sensors to broaden CPTU measurements
- Better understanding of factors with influence on test accuracy
- Increased use of CPTU in many countries
- Extension of local databases
- National standardization of CPTU

# Accuracy in CPTU

## Preparation, performance and control



## CPT'10 Huntington Beach, USA

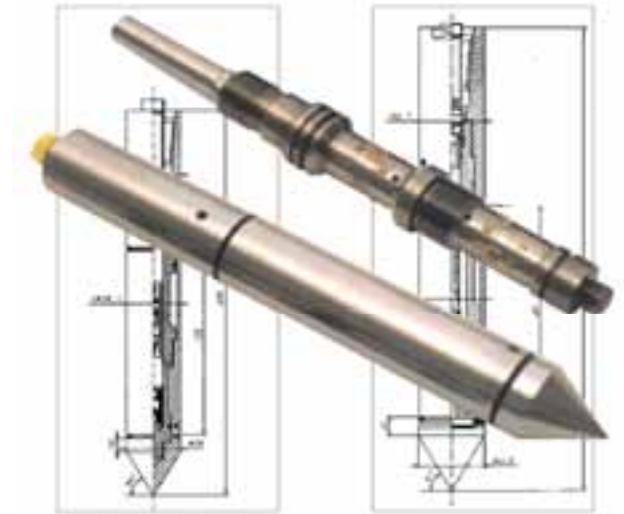
### Trends and development in 2010

- Further improvement of test equipment
- Specialized probes, including full-flow penetrometers, are used increasingly
- Increased competence among engineers and field operators
- Testing in challenging soils is becoming more common
- A new international standard is forthcoming
- CPTU has become a preferred test in many countries, but...
- Is the method still under-used compared to its potential?

# Accuracy in CPTU

## Preparation, performance and control

### Conventional CPTU probes



# Accuracy in CPTU

## Preparation, performance and control

### Special CPTU probes

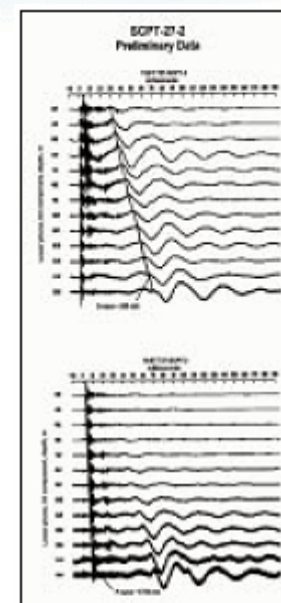
Resistivity probes



Miniature penetrometers



Seismic cones



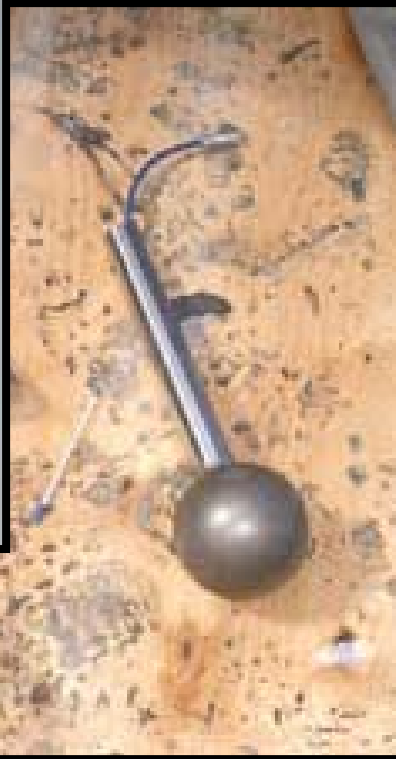
# Accuracy in CPTU

## Preparation, performance and control

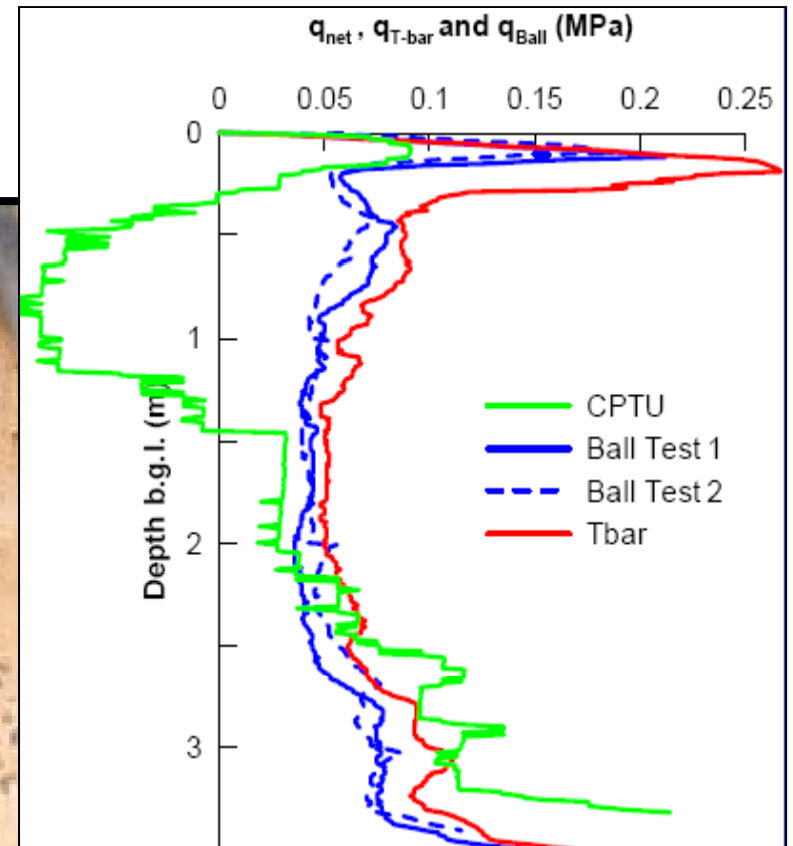
### Full-flow penetrometers



T-bar



Piezo-ball



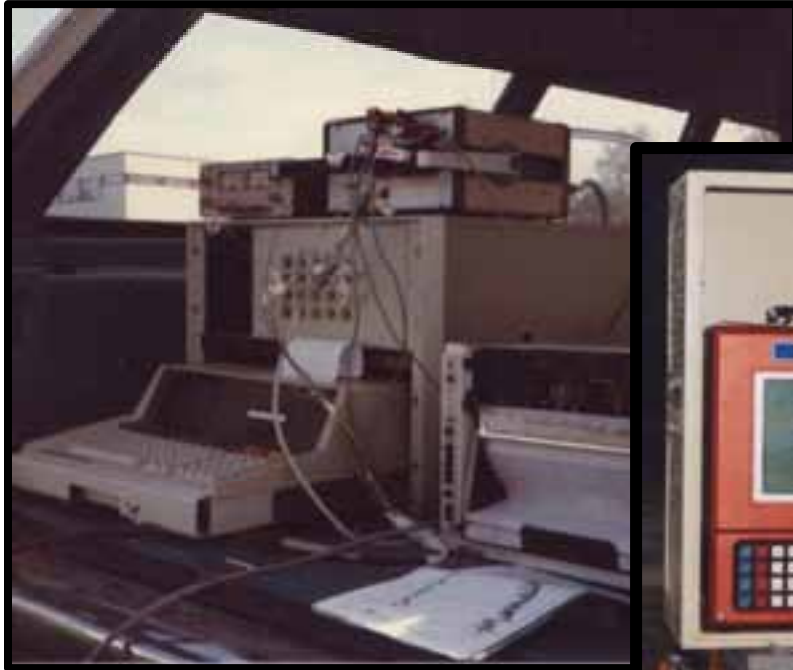
Comparison of  $q$  in peat (Boylan (2008))

# Accuracy in CPTU

## Preparation, performance and control

### Data acquisition systems

1985



1995



2010



# Accuracy in CPTU

## Preparation, performance and control



### CPTU in practical engineering

- Production of data for design applications
- Mixed bedded profiles with soft and stiff layers usual
- Rough testing environment may happen
- Use of versatile all-round probes
- Many operators with varying competence in performance
- Many engineers with varying competence in interpretation and evaluation
- High tempo – "time is money"
- Limited amount of available data
  - ✓ Data from previous investigations
  - ✓ Laboratory reference parameters



**New international standard on CPT/CPTU**  
**EN-ISO standard 22476-1**  
**Important requirements on test accuracy**

# Accuracy in CPTU

## Preparation, performance and control

### Background

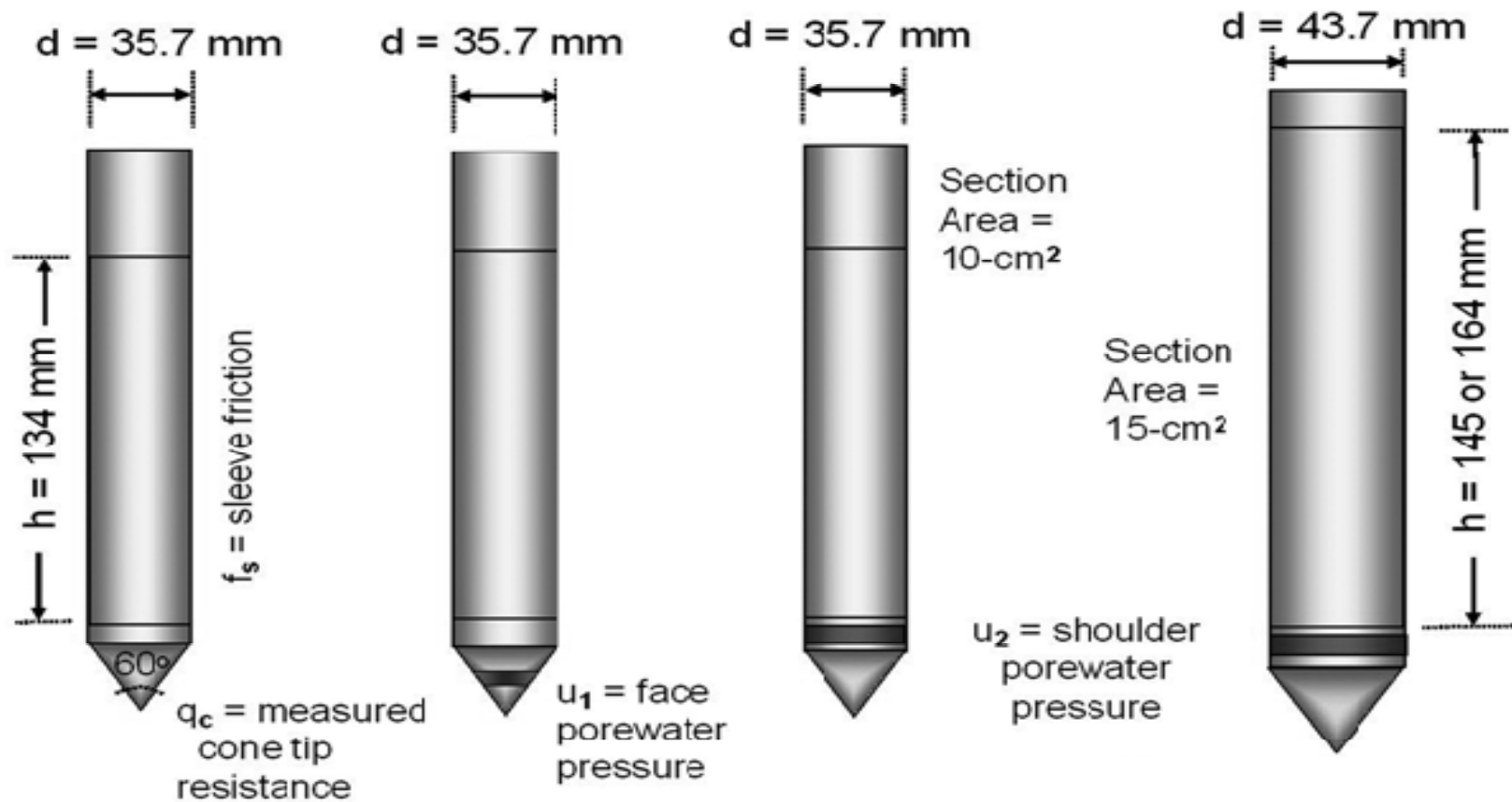
#### Available standards and guidelines for CPTU

- American Standard for Testing and Materials (ASTM D 5778 2000)
- International Reference Test procedure (IRTP) (ISSGME 1999)
- National guidelines e.g.:
  - ✓ Dutch guidelines
  - ✓ Swedish guidelines
  - ✓ Norwegian guidelines
- ✓ Previous guidelines and standards on CPT



# Accuracy in CPTU

## Preparation, performance and control



Type 1	Type 2		Type 2
Friction cone	Piezocone	Reference piezocone	Optional size

# Accuracy in CPTU

## Preparation, performance and control

### EN-ISO 22476-1

Electrical cone  
penetration testing

### Application classes

Give guidance on selecting  
type of CPT and required  
accuracy

Choice of Application class  
shall reflect the occurring  
ground conditions and  
potential use of results.

Class	Test type	Recommended ground conditions
1	TE2: $q_c, f_s, u$ Inclinometer	<b>Soft to very soft soil deposits.</b> Normally not apt for mixed bedded profiles with soft to dense layers ( $q_c < 3$ MPa).
2	TE2: $q_c, f_s, u$ TE1: $q_c, f_s$ Inclinometer	<b>Mixed bedded profiles with soft to dense soils.</b> Profiling and material identification, indicative interpretation in soft layers.
3	TE2: $q_c, f_s, u$ TE1: $q_c, f_s$ Inclinometer	<b>Mixed bedded profiles with soft to dense soils.</b> Profiling and material identification, interpretation in stiff to very stiff soils.
4	TE1: $q_c, f_s$	<b>Mixed bedded profiles with soft (loose) to very stiff (dense) layers.</b> Indicative profiling and material identification. No interpretation of engineering parameters.

# Accuracy in CPTU

## Preparation, performance and control

### Application classes

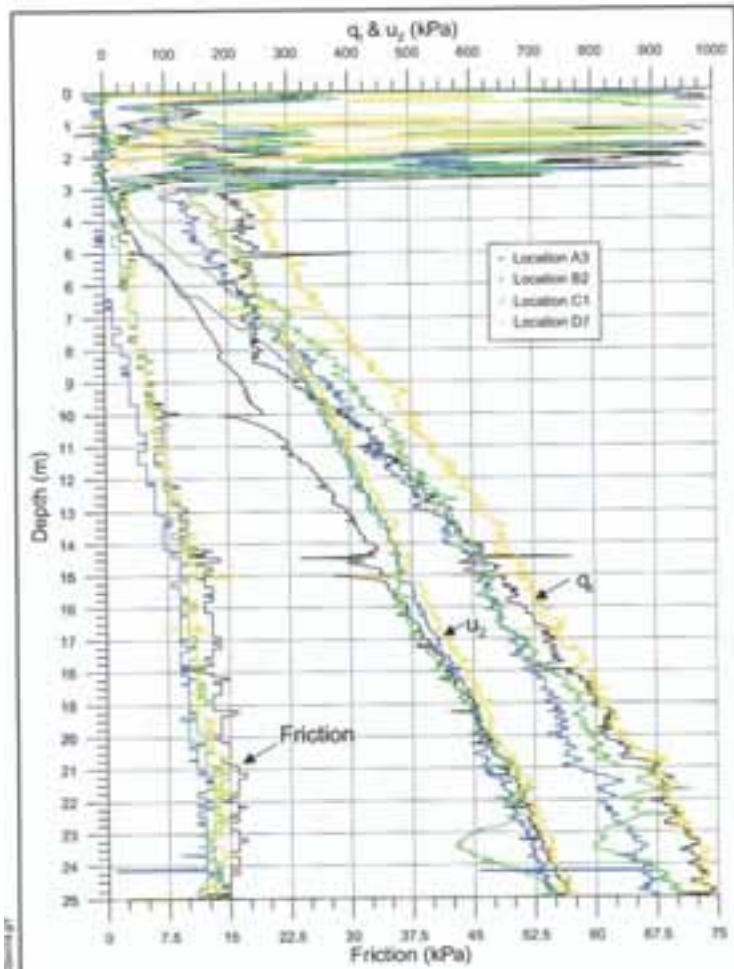
#### Required accuracy

- Include all contributions to the total accuracy of measurements
- The relative accuracies refer to the measured value, not the measuring range
- **Evaluation of test accuracy:**  
**Shall include evaluation of internal friction, errors in data acquisition, eccentric loading, temperature effects and dimensional errors.**

Class	Parameter	Accepted accuracy (largest value of the two)
1	Cone resistance Sleeve friction Pore pressure Inclination	35 kPa or 5 % 5 kPa or 10 % 10 kPa or 2 % 2°
2	Cone resistance Sleeve friction Pore pressure Inclination	100 kPa or 5 % 15 kPa or 15 % 25 kPa or 3 % 2°
3	Cone resistance Sleeve friction Pore pressure Inclination	200 kPa or 5 % 25 kPa or 15 % 50 kPa or 5 % 5°
4	Cone resistance Sleeve friction	500 kPa or 5 % 50 kPa or 20 %

# Accuracy in CPTU

## Preparation, performance and control



### Quality of CPTU data

#### ➤ Some recent studies

Tiggelmann & Beukema (2006) Bothkennar

Powell and Lunne (2005) Bothkennar

Lunne et al (2005) Onsøy

#### ➤ Major conclusions

- ✓ Measured friction ( $f_s$ ) shows the largest scatter
- ✓ The scatter in the corrected cone resistance ( $q_t$ ) is larger than for the recorded pore pressure ( $u_2$ )
- ✓ The ranges of measured  $q_t$  and  $u_2$  are exceeding the required accuracy in Application class 1

#### ➤ Further development of test equipment



# Factors influencing test accuracy

## Preparations before testing

Choice of test equipment

Calibration status

Inspection, maintenance and mounting of test equipment

## In situ test procedures

Saturation of pore pressure system

Reading of zero load values

Control of inclination

# Accuracy in CPTU

## Preparation, performance and control

### Inaccuracies in CPTU measurements

- **Errors and inaccuracies in transducers and data acquisition system**
  - ✓ Resolution, non-linearity and hysteresis in transducers
  - ✓ Internal friction and "cross-talk" between transducers
  - ✓ Loss of resolution in data transfer (e.g. acoustically through the CPT rods)
- **Calibration errors**
  - ✓ Deviations from traceable reference values
  - ✓ Errors due to overloading or damages
- **Temperature effects**
  - ✓ Effects of ambient temperature
  - ✓ Temperature gradients in the probe (e.g. from air to ground)
  - ✓ Transient effects during penetration (e.g. through dense layers)
- **Shift in zero load values before and after testing**
- **Deficient saturation of the pore pressure system**
- **Irregular use or lack of maintenance**
  - ✓ Transfer of loads due to poor cleaning and maintenance of gaps and seals
  - ✓ Errors in mounting of the probe
  - ✓ Wear of cone tip and friction sleeve

# Accuracy in CPTU

## Preparation, performance and control

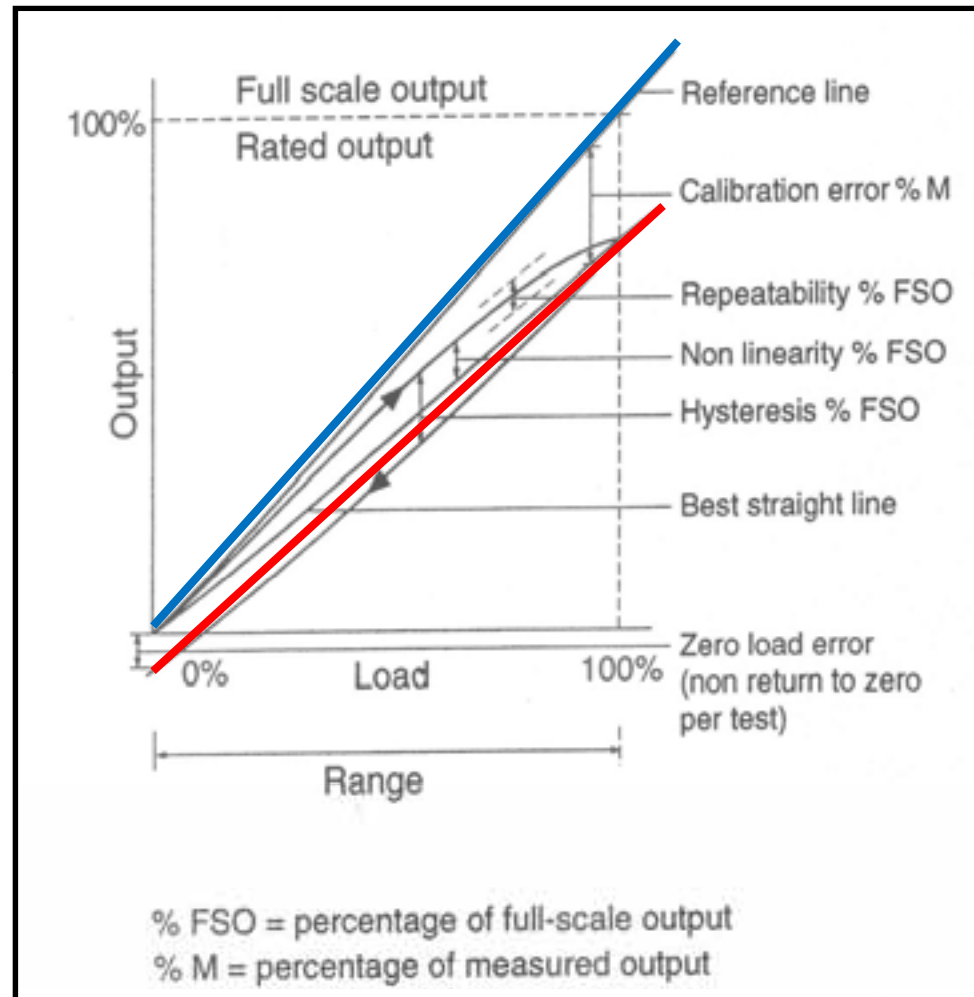
### Transducer accuracy

Defined by:

- Resolution
- Non-linearity
- Repeatability
- Hysteresis
- Zero load error
- Calibration error

Lunne et al (1997):

"The transducer should be both precise and accurate"



Lunne et al (1997)

# Accuracy in CPTU

## Preparation, performance and control

### Before testing

#### Choice of test lay-out

- **Application class (1-4) in EN-ISO 22476-1**
  - ✓ Evaluation of ground conditions at the site
  - ✓ Required use of test data
- **Test equipment**
  - ✓ Probe type
  - ✓ Measuring range of transducers
  - ✓ Thrust equipment and penetration range
    - Need for anchoring
    - Reduction of rod friction
- **Special features**
  - ✓ Need for pilot sounding with possible pre-drilling
  - ✓ Procedure for penetration of possible hard layers
  - ✓ Stop for temperature balancing and/or re-saturation after dense layers



# Accuracy in CPTU

## Preparation, performance and control

### Before testing

#### Control of test equipment

- Calibration and previous performance of the probe should be checked.
- If available, control of track record with zero load readings
- Control of data acquisition system
- The cone and the friction sleeve should be inspected for wear and damages
- The sounding rods should be straight and linear
- Seals should be clean, elastic and intact
- Porous filters should be saturated in-house before transport to the test site



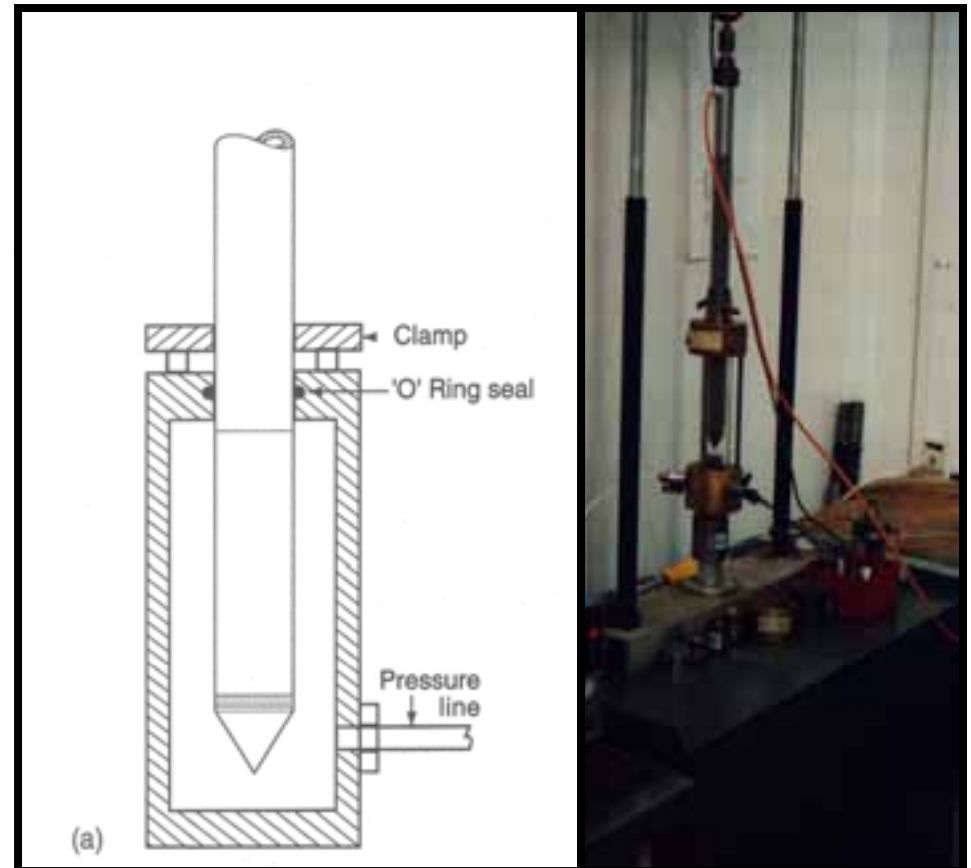
# Accuracy in CPTU

## Preparation, performance and control

### Before testing

#### Calibration requirements

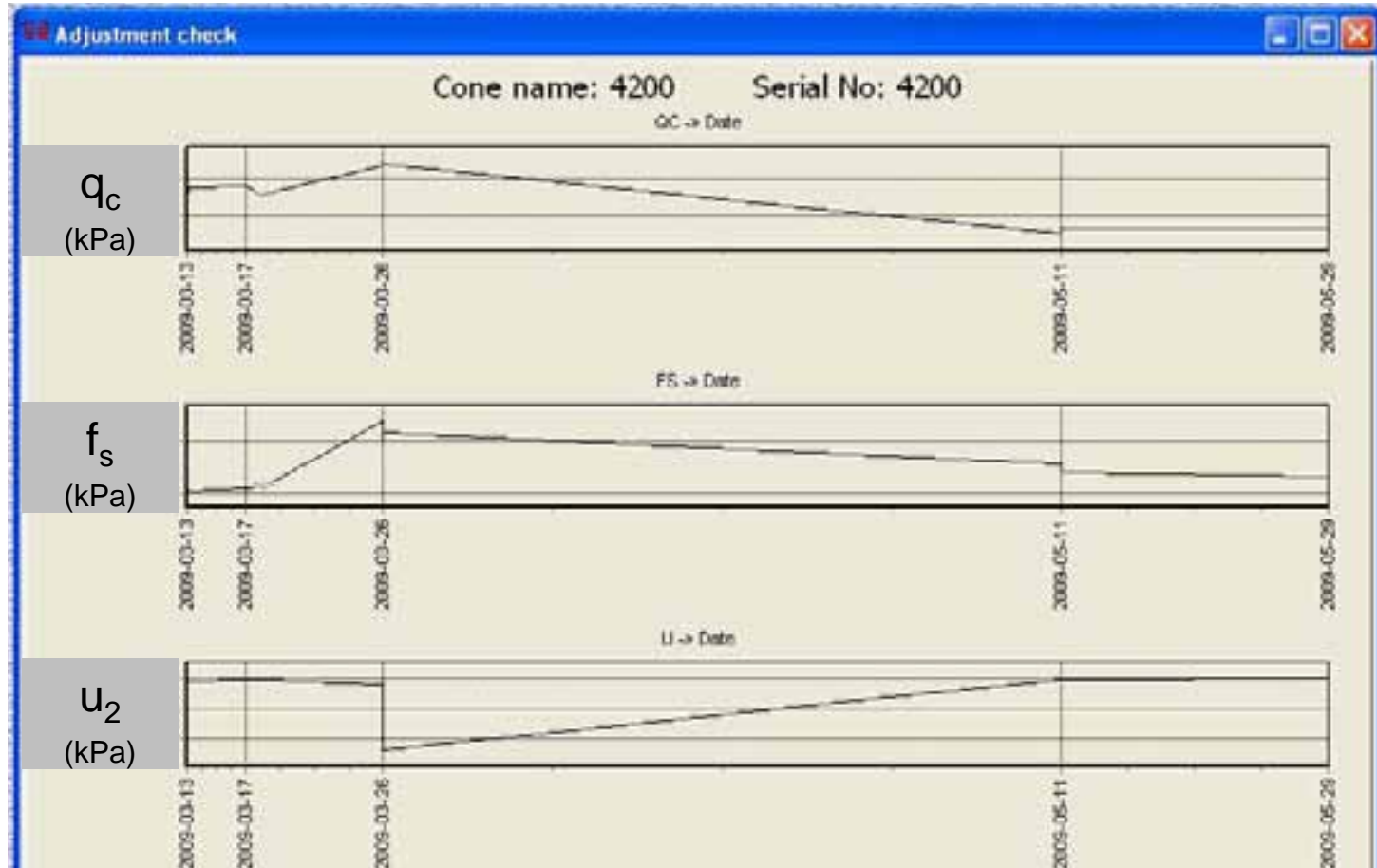
- **The probe shall be calibrated regularly:**
  - ✓ At least every 6<sup>th</sup> month if the probe is in continuous use
  - ✓ Optional: After ~3000 drilling meters
  - ✓ After sounding in difficult conditions with risk of loading over or near the maximum capacity
  - ✓ **Probe performance:**
    - The new standard allows the calibration intervals to be evaluated according to the track record of zero load values**



# Accuracy in CPTU

## Preparation, performance and control

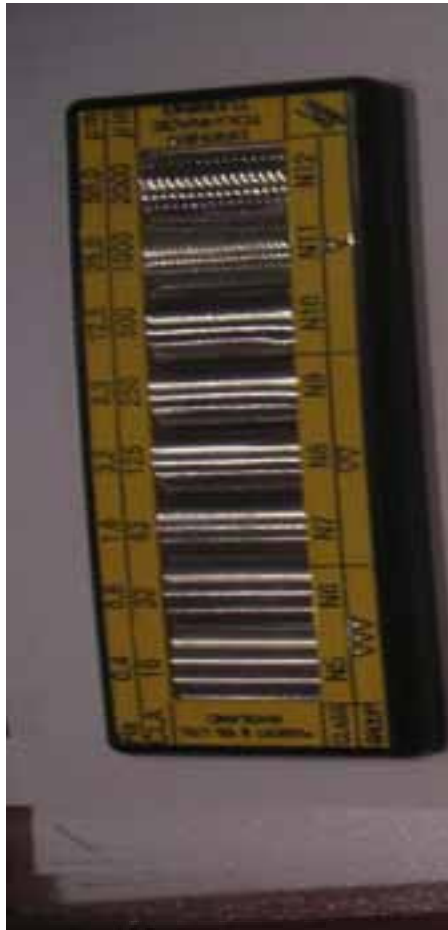
### Track record - control of zero load readings



# Accuracy in CPTU

Preparation, performance and control

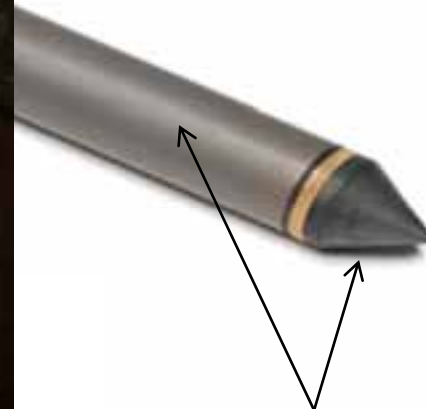
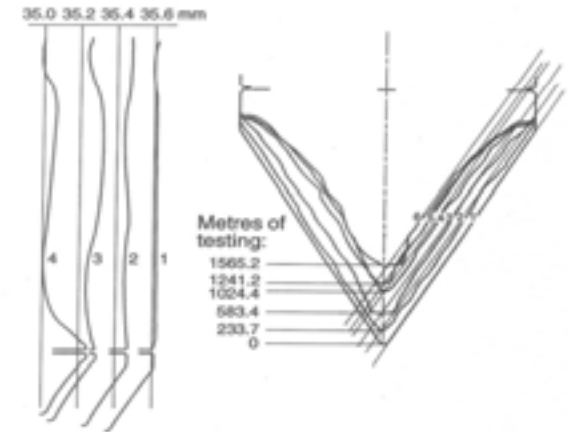
## Inspection of wear and damages



Roughness pattern



Geometry pattern



Inspection of wear



# Accuracy in CPTU

## Preparation, performance and control

Cleaning of gaps and seals



Mounting of seals (X-ring)



Mounting of cone tip....



...by light screwing!



# Accuracy in CPTU

## Preparation, performance and control

### In situ test procedures

#### Important features

- **Saturation of the pore pressure system**
  - ✓ Choice of saturation method
  - ✓ Choice of saturation medium
- **Reading of zero load values**
  - ✓ Temperature stabilization
  - ✓ Mounting and withdrawal effects
  - ✓ Cleaning of gaps
- **Control of penetration conditions**
  - ✓ Rate of penetration
  - ✓ Rod inclination
  - ✓ Recording of test incidents



# Accuracy in CPTU

## Preparation, performance and control



Saturation with syringe

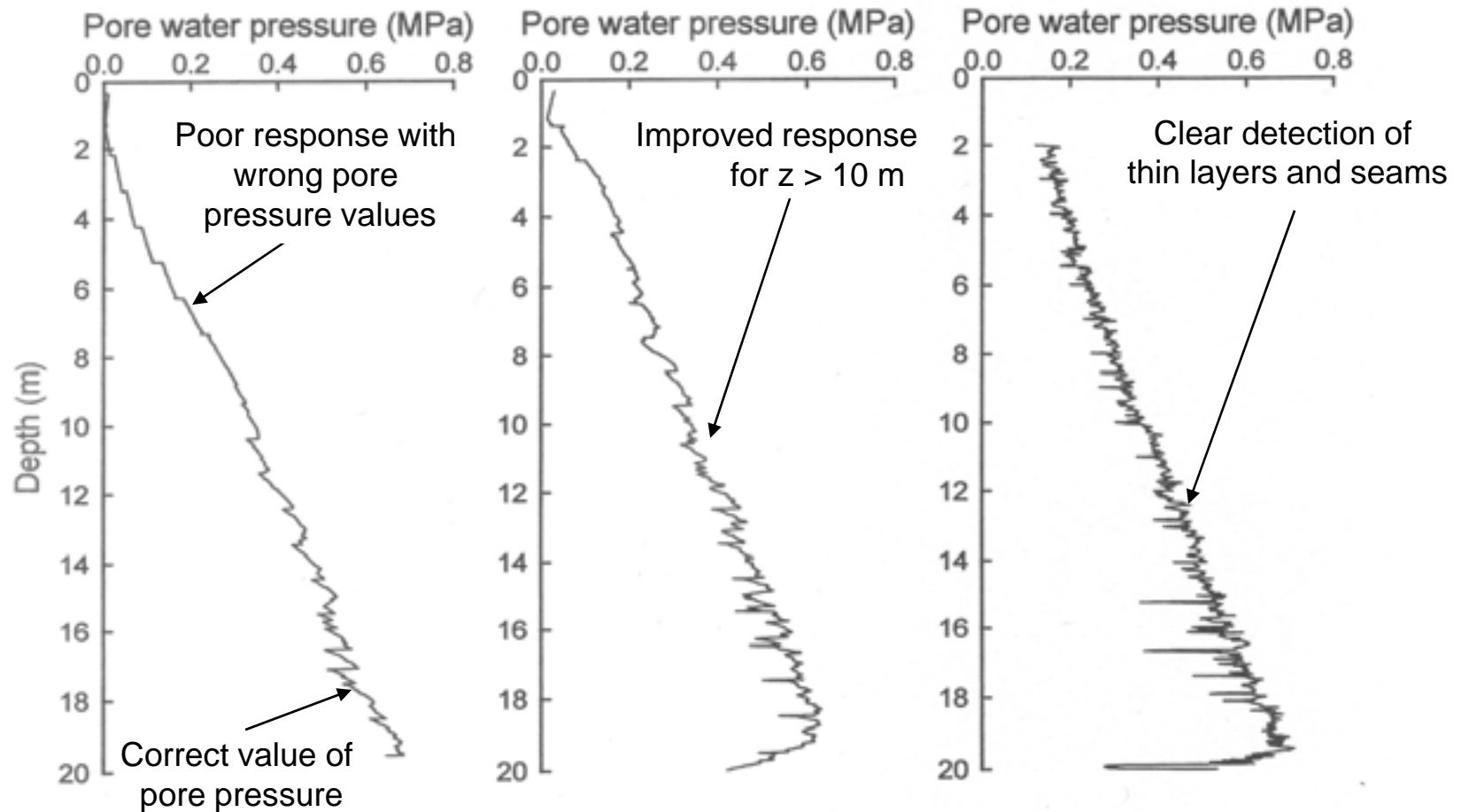
### Importance of the pore pressure

- **Necessary for optimal profiling of the soil**
  - ✓ Stratification and soil structure
  - ✓ Identification of soil type
- **Necessary for correction of measured values**
  - ✓ Cone resistance
  - ✓ Sleeve friction (optional)
- **Important for interpretation of engineering parameters**
  - ✓ Undrained shear strength
  - ✓ Effective friction angle
  - ✓ Preconsolidation stress and stress history
  - ✓ Consolidation and drainage parameters from dissipation tests

# Accuracy in CPTU

## Preparation, performance and control

### Influence of poor saturation on test results



Lunne et al (1997)

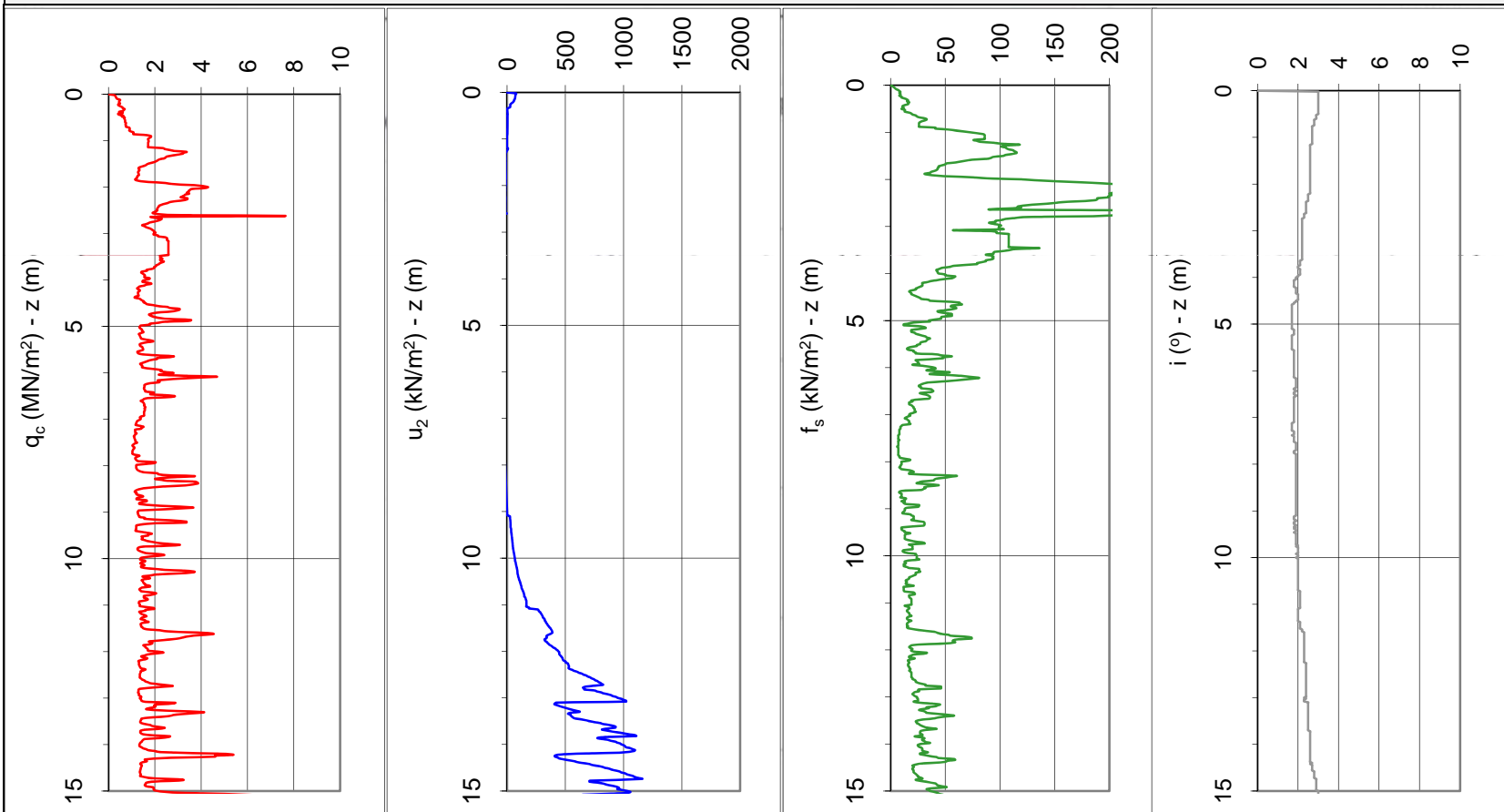
Poor saturation

Good saturation

# Accuracy in CPTU

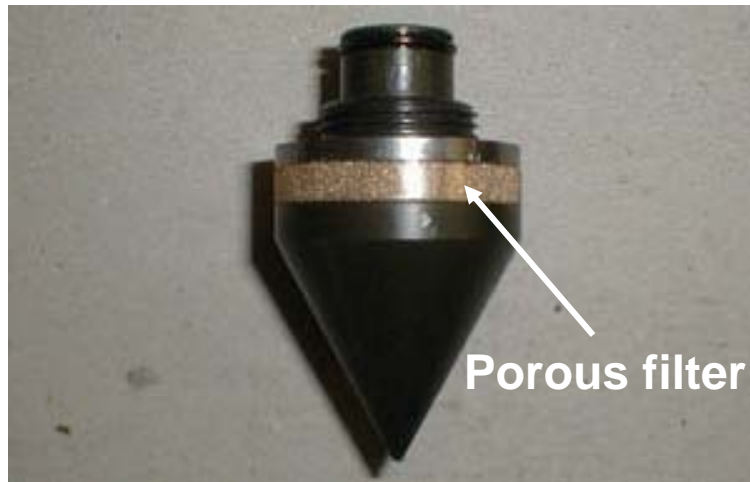
## Preparation, performance and control

### Insufficient pore pressure response due to poorly saturated system



# Accuracy in CPTU

## Preparation, performance and control



### Saturation of pore pressure system

#### Porous filters

- **Popular methods**
  - ✓ Vacuum treatment of filter and probe
  - ✓ Submerged mounting in funnel
- **Pre-saturation of filters before use**
  - ✓ Treatment in vacuum chamber
  - ✓ Saturated filter submerged in saturation medium
- **Saturation media**
  - De-aired water
  - Antifreeze
  - Glycerine or similar liquids
- **Special problems**
  - Maintenance of saturation above GWT
  - Loss of saturation in dilative layers
  - Clogging and smearing of filter

# Accuracy in CPTU

## Preparation, performance and control

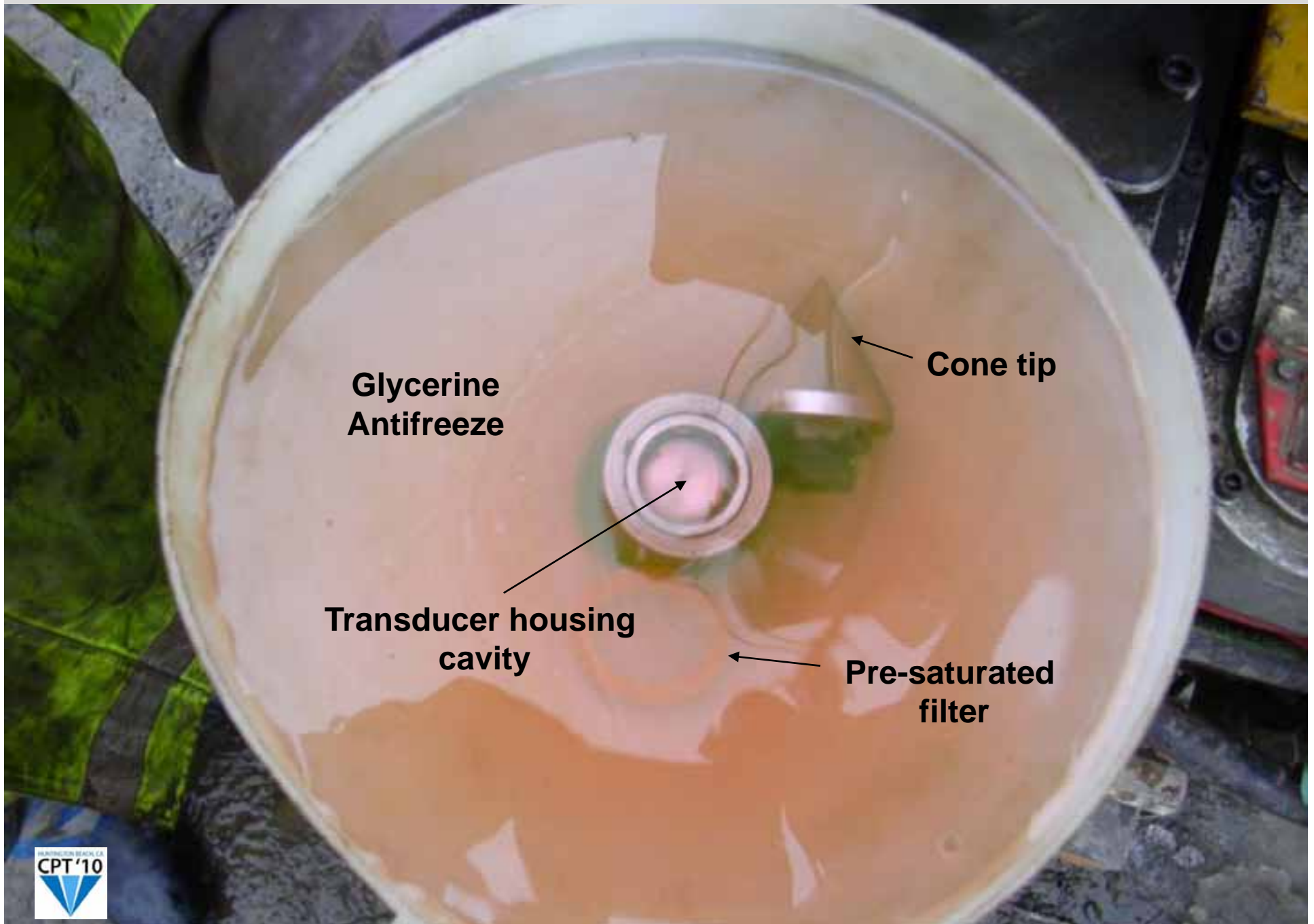


### Saturation methods

#### Vacuum treatment

- The mounted probe is saturated in a vacuum chamber at the site
- The vacuum treatment continues until no air bubbles are expelled from the probe
- Pre-saturation of porous filter in vacuum chamber
- Transport of filters in sealed containers
- Submerged mounting in saturation liquid
- Very good saturation is usually obtained.

## Submerged mounting in a sealed funnel



# Accuracy in CPTU

## Preparation, performance and control

### Saturation methods

#### Pre-saturated filters

- Commercially available
- Sintered bronze filters saturated by a mixture of glycerine and gel

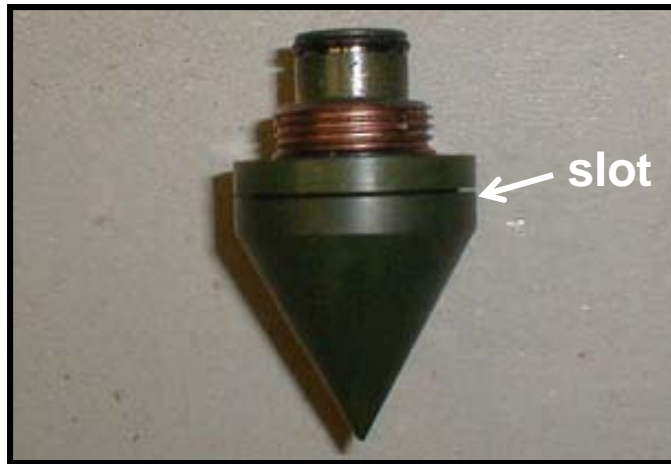
#### Some practical experiences

- Maintains saturation well during penetration of dense, dilative layers
- Cleaning and re-saturation possible after use
- May be used down to temperatures around  $-15^{\circ}\text{C}$



# Accuracy in CPTU

## Preparation, performance and control

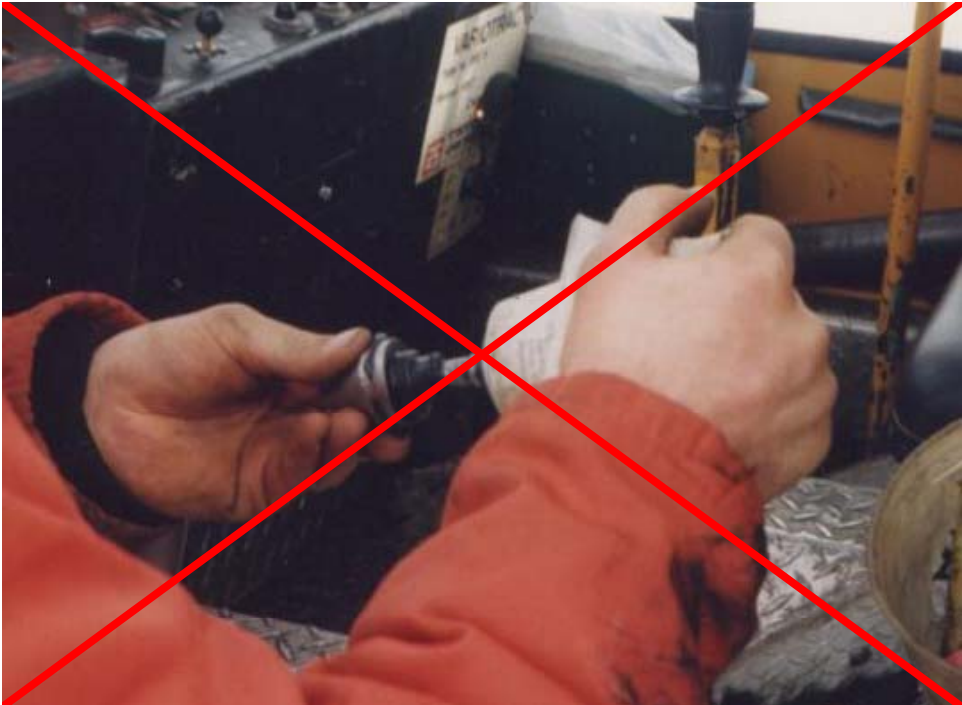


Injection of grease

## Saturation methods

### Slot filter

- Small 0,3 mm slot communicating with the transducer housing cavity through channels
- The slot and channels are saturated with silicone grease, gelatin or similar
- The transducer housing cavity is saturated with oil, antifreeze or de-aired water
- Saturation is simpler and quicker than for probes with porous filters
- Easier to maintain saturation when sounding through dilative soils (e.g.dense sand, dry crust)



**Saturation with silicon grease**

**Saturation with gelatin**

# Accuracy in CPTU

## Preparation, performance and control



### Deviation in zero load readings

#### Equipment features

- Mechanical damages caused by overloading or obstructions in the ground.
- Damages of the electronic system during testing.
- Inherent errors like hysteresis and zero load shift in transducers after repeated loading-unloading cycles in the test.
- Zero readings may be influenced by worn or damaged seals (X-ring).

# Accuracy in CPTU

## Preparation, performance and control



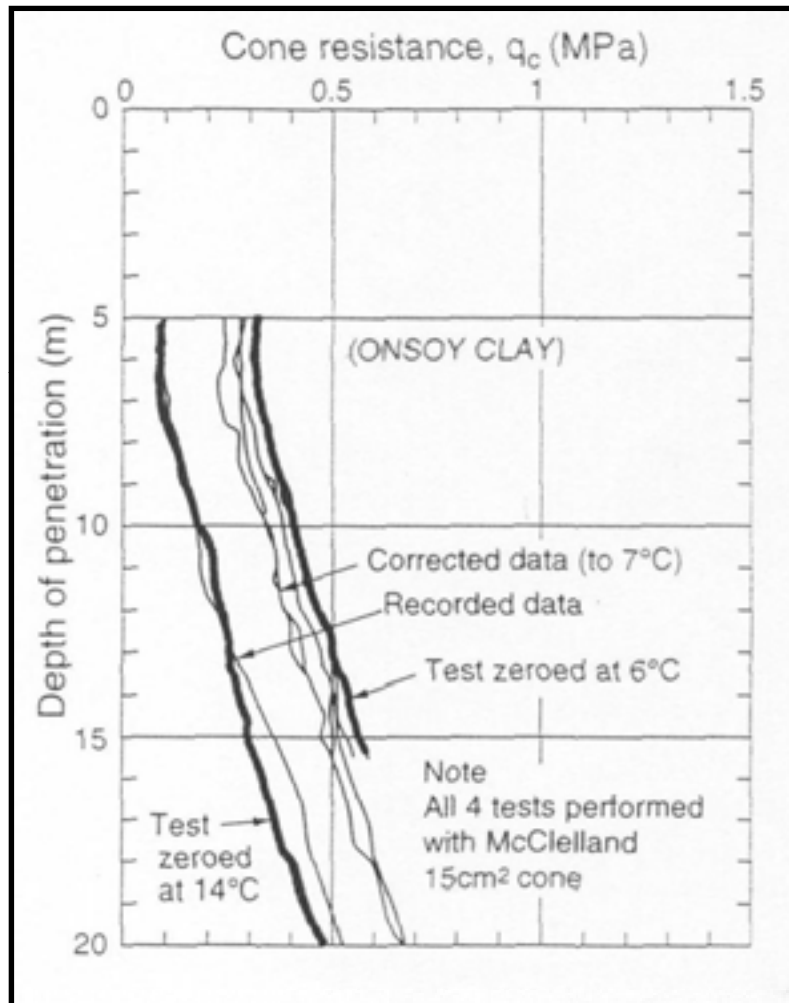
### Deviation in zero load readings

#### Effects from in situ test procedure:

- Temperature gradients in the probe due to insufficient stabilization to the ground temperature.
- Mounting of cone tip and porous filter may set up forces on the friction sleeve.
- Mounting of the cone tip may cause temporary pore pressure build-up in the transducer housing cavity.
- Residual pore pressure (suction) may occur after withdrawal of the probe.
- Load transfer to the friction sleeve after withdrawal due to insufficient cleaning.

# Accuracy in CPTU

## Preparation, performance and control



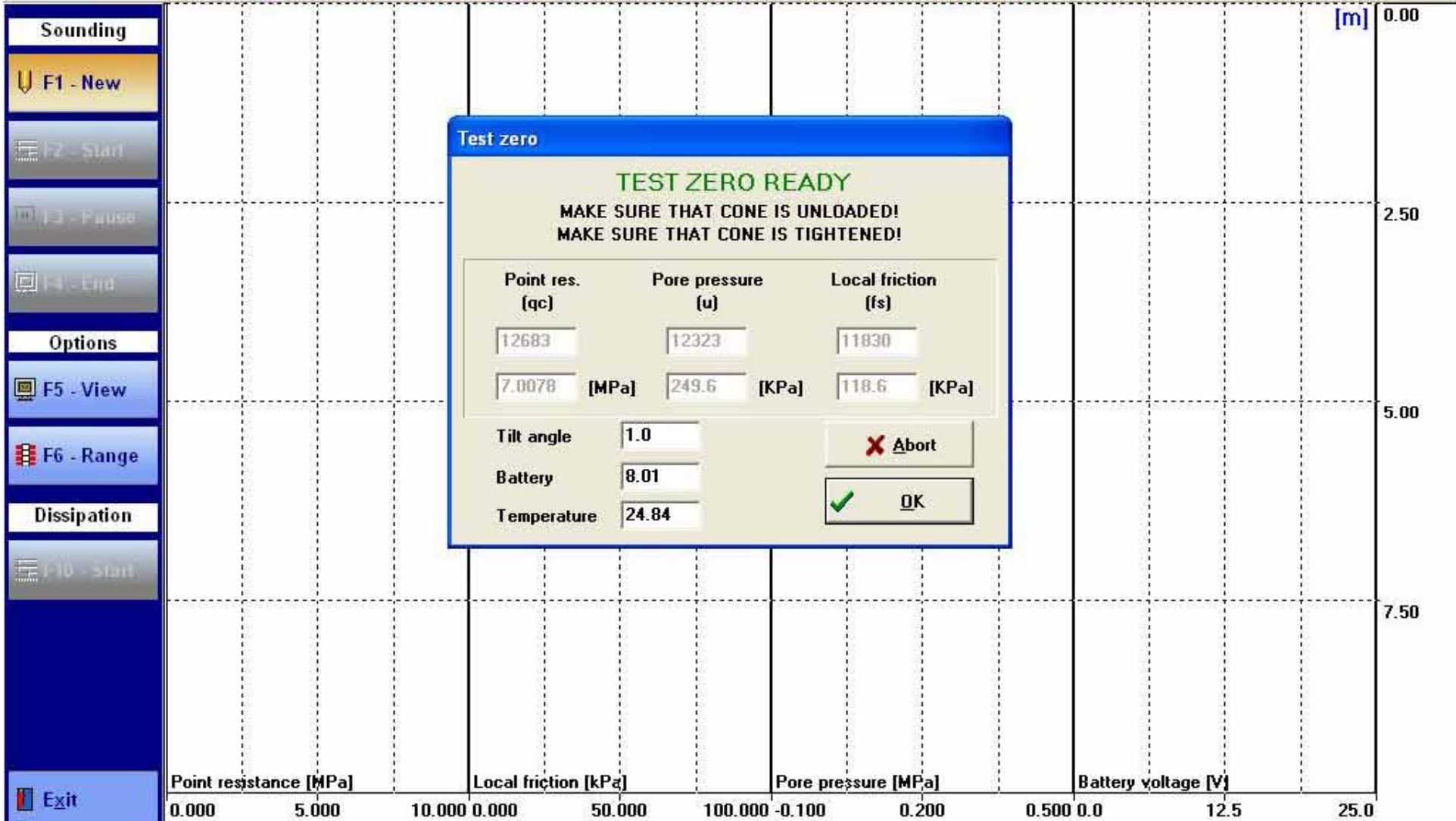
Lunne et al (1997)

## Reading of zero load values

### Important procedures

- The temperature of the probe should be kept close to the ground temperature before testing (e.g. ~ 5-7 °C).
- Zero load readings should be taken for a temperature stable, unloaded probe, preferably in a pre-drilled borehole.
- Temperature stabilization after penetrating hard, dense layers also an issue.
- Stability of zero load readings can be monitored real-time on new data systems
- Waiting time after mounting and withdrawal recommended (dissipation of pore pressure/suction.)
- Gaps in both ends of the friction sleeve should be cleaned after withdrawal to avoid additional loading of the friction sleeve.

Tilt angle	<b>0.0</b>	Speed	<b>0.0</b>	Battery		temp.	<b>0.0</b>
Depth	<b>0.000</b>	qc	<b>0.0</b>	fs	<b>0.0</b>	u	<b>0.0</b>
CPT Status		<b>CPT-SOUNDING</b>		VER. #M232	<b>Signal OK</b>		



**Test zero**

**TEST ZERO READY**  
 MAKE SURE THAT CONE IS UNLOADED!  
 MAKE SURE THAT CONE IS TIGHTENED!

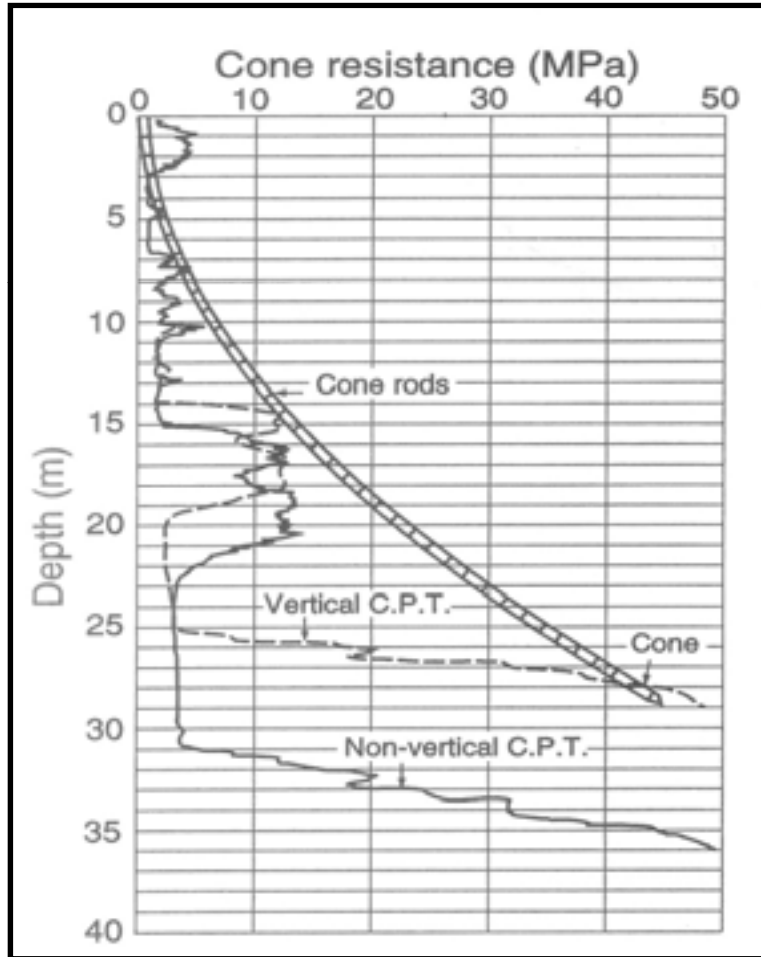
Point res. (qc)	Pore pressure (u)	Local friction (fs)
12683	12323	11830
7.0078 [MPa]	249.6 [KPa]	118.6 [KPa]

Tilt angle: 1.0  
 Battery: 8.01  
 Temperature: 24.84

# Accuracy in CPTU

## Preparation, performance and control

### Inclination of rod system





**Quality control of test data**  
**Evaluation of test profile**  
**Evaluation of test accuracy**

# Accuracy in CPTU

## Preparation, performance and control

### Control of obtained CPTU data

#### ➤ Inspection of test probe

- ✓ Cone tip and friction sleeve for wear or damages
- ✓ Filter for smearing or clogging

#### ➤ Control of zero load values before and after testing

#### ➤ Control of sounding profile

- ✓ Overall profile: Cross-comparing profiles of cone resistance, friction and pore pressure
- ✓ Measured values: Obtained versus expected values in penetrated soil types
- ✓ Saturation: Response of pore pressure to variations in layering and soil structure
- ✓ Test performance: Total inclination and shape of inclination profile

# Accuracy in CPTU

## Preparation, performance and control

### Documentation of test accuracy

#### ➤ Probe characteristics

- ✓ Capacity and measuring range of transducers
- ✓ Transducer specifications (resolution, hysteresis, zero load value, internal friction)

#### ➤ Calibration certificate in agreement with recommended intervals

#### ➤ Documentation of test procedures

- ✓ Method for saturation of pore pressure system
- ✓ Procedures for reading of zero load values before and after testing

#### ➤ Resolution of measurements after data transfer

#### ➤ Zero load readings before and after testing and possible correction

#### ➤ Other test parameters

- ✓ Maximum inclination and required depth correction
- ✓ Control of penetration rate

#### ➤ Evaluation of obtained profile



**Closing remarks**  
**Session 1: Test equipment and procedures**

# Accuracy in CPTU

## Preparation, performance and control

### Closing remarks – 1

- CPTU has become a frequently used and popular method in many countries.
- An international standard on CPTU will be available soon.
- Division of test quality in Application classes may result in further improvement of equipment and test procedures.
- Independent control and quality audits require better documentation of CPTU in practical engineering.
- Certification of field operators may become necessary as a result of stricter quality requirements.



# Accuracy in CPTU

## Preparation, performance and control

### Closing remarks - 2

- Modern technology and production techniques have resulted in more accurate and precise probes.
- New data acquisition systems with field lap-tops enable improved control of the test .
- The relative complexity of equipment and procedures opens for some operator variation:
  - Operator experience may be limited.
  - Proper education programmes for field operators and engineers are necessary.
  - Good communication between engineers and field operators is important in all phases of the test.



A blessing ritual before a CPTU is not (longer) required!



Thank you for your attention!

