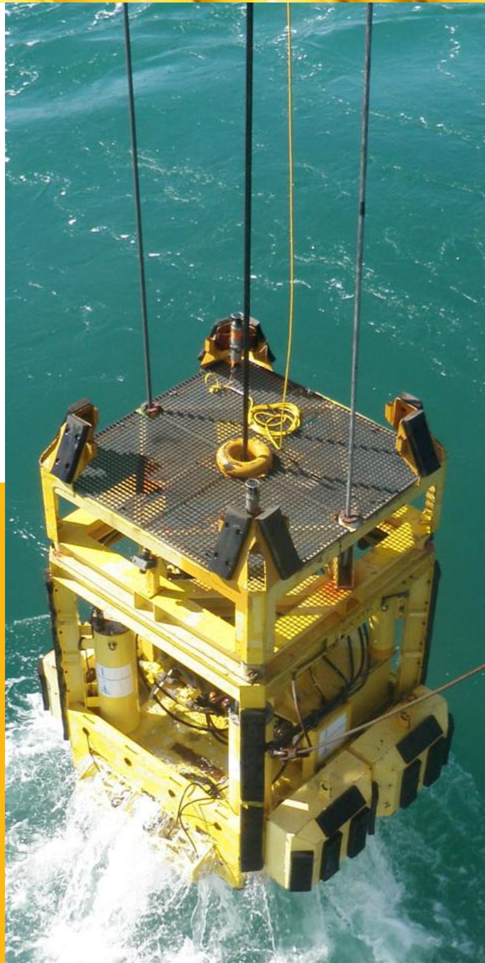
Geomil equipment



Introduction

About the Speaker

William Bond

- Master of Geology (MGeol)
- Project Engineer for UK CPT specialist – SCPT
- Moved to Hong Kong 2015: Project management in CPT, HDD, HDC
- Joined Geomil as Technical Manager in 2017

Introduction

Geomil equipment

Schedule

- Introduction to the CPT
- Advantages and limitations
- Applications
- State of CPT in Hong Kong
- Challenges of CPT in Hong Kong – and some in general
- The future of CPT in Hong Kong
  - Advanced technology
  - Control of CPT in Hong Kong
- Q&A

Introduction

Geomil equipment

The CPT

- Ground investigation technique used in soils
- Instrumented cone advanced into ground
- Measures:
  - Cone Resistance (q_c)
  - Sleeve Friction (f_s)
  - Pore Water Pressure (u_2)
  - Inclination
- Connected to the Data Acquisition System (DAQ) via cable and provides data to the operator in real time
- Provides soil strength and behaviour characteristics
- Advanced into the ground using hydraulic rams and reaction force

The CPT
Deployment

Geomil equipment

Dead weight

Ground anchors

The CPT
Deployment

Geomil equipment

Ground anchors

The CPT
Deployment

Ground anchors + dead weight

The CPT

Deployment

Ground anchors + dead weight

The CPT

Deployment

Geomil equipment

Structure

The CPT
Deployment

Geomil equipment

Full sized trucks – Geomil Grizzly

The CPT
Deployment

Geomil equipment

Crawlers

The CPT
Deployment

Geomil equipment

The CPT
Deployment

Geomil equipment

Seabed units (full sized cone):

ROSON

MANTA

The CPT Deployment

MANTA

The CPT
Deployment

Source: Datem

Seabed units

(miniature cone
and coiled tubing):

NEPTUNE

SIDEWINDER

Source: Sage Engineering

For shallow investigations (pipeline and cable routing)

Advantages of CPT

Compared to Conventional GI

Geomil equipment

- Effective and efficient alternative for conventional Site Investigation methods such as drilling or SPT
- In-situ test
- Real-time data
- Established and recognized method
- Repeatable, accurate and reliable
- Very fast (1 meter = 1 minute)
- High resolution data (1 point per cm)
- High sensitivity data (Just a few kPa)

Limitations of CPT

Compared to Conventional GI

Geomil equipment

- Soil conditions may limit the use of CPT, for example due to gravel, boulders or rock
- Workarounds: drill out, run casing or use a larger (15 cm^2) cone
- Depth might be limited due to reaching maximum thrust
- It might be impossible to obtain sufficient reaction force
- Relatively high investment (compared to SPT)
- Requires trained operators
- Site accessibility

This is not limited to CPT!

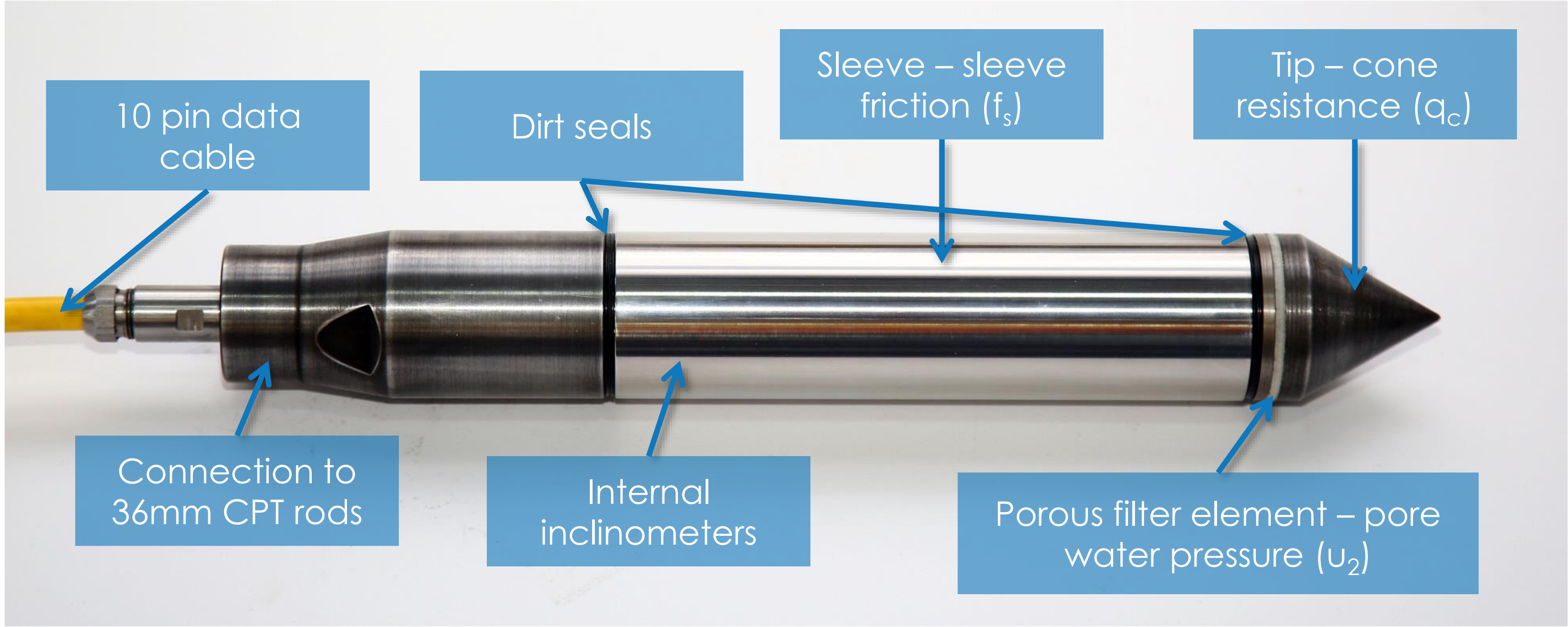
Advancement of the CPT

A Brief History

Geomil equipment

- First mechanical cone produced by Geomil's predecessor GMF :1934
- First manually operated 10 tonne test: 1935
- Conically shaped part added to prevent soil ingress: 1948
- Friction sleeve added: 1953
- First commercially developed electric cone introduced by Fugro: 1965
- Pore pressure probes first deployed alongside CPT: 1974
- Introduction of the piezocone (CPTu): 1980
- Several rapid developments since:
  - Magnetometer cones
  - Environmental cones
  - Video cones
  - Seismic cones

Introduction
The Cone

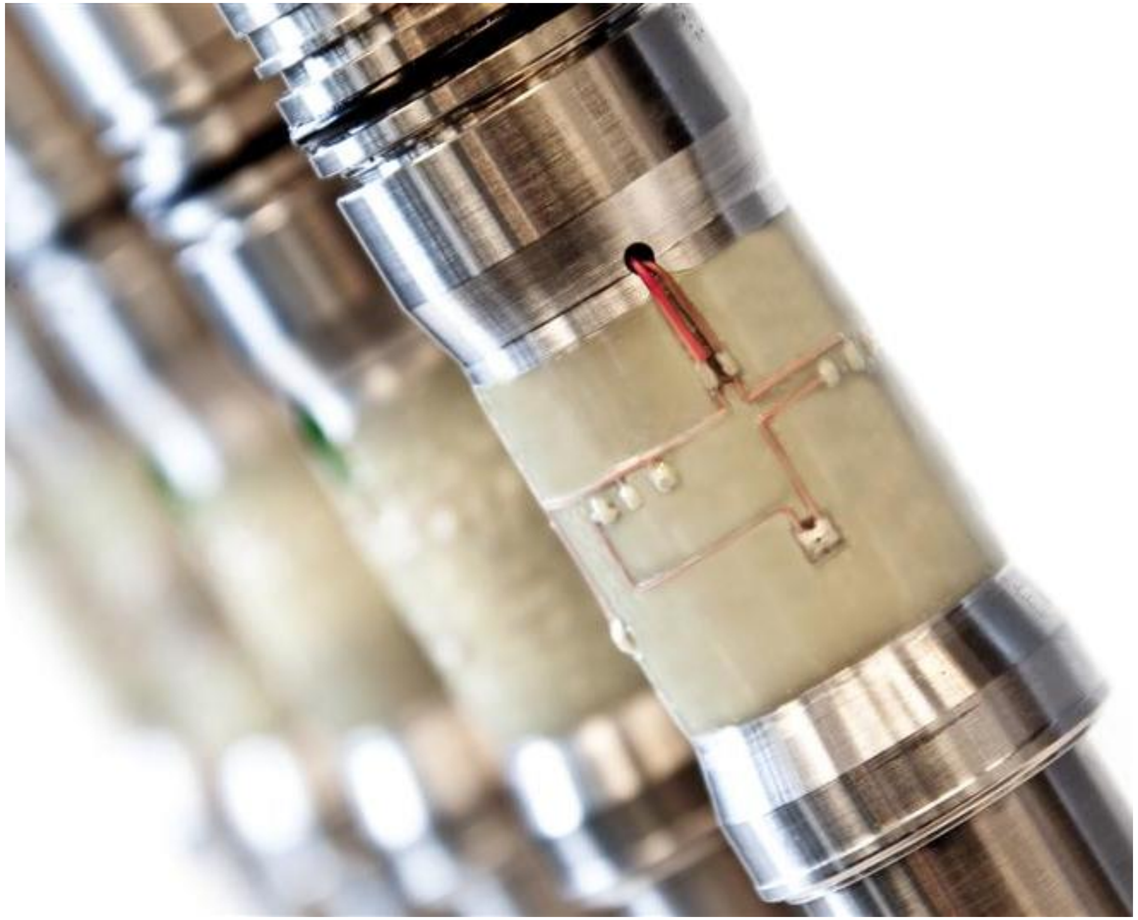


Compression vs Subtraction

Introduction

Geomil equipment

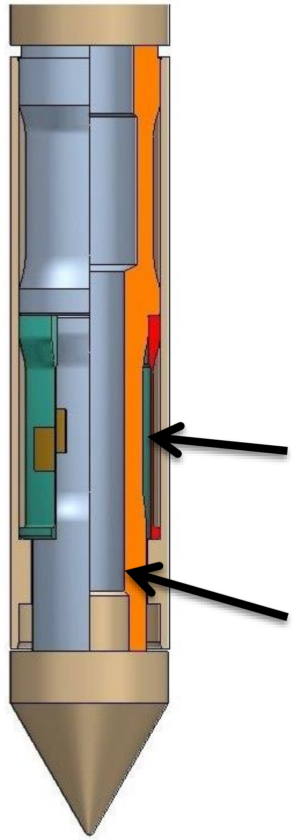
- Cone designs:
  - Compression cone
    - Accurate
    - Sensitive
  - Subtraction cone
    - Solid
  - Tension cone (hardly used)



Compression vs Subtraction

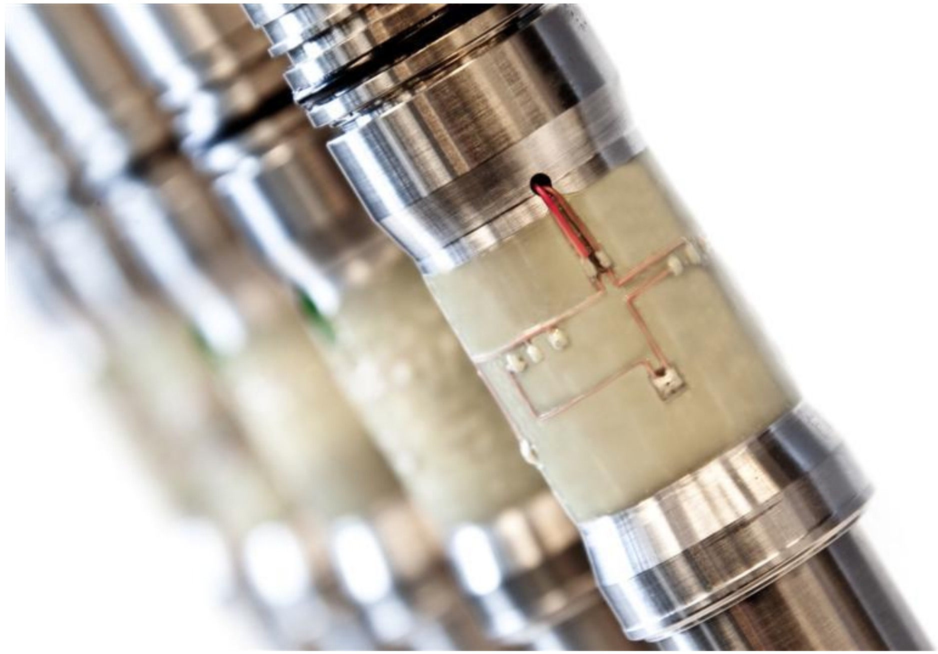
Compression Design

Geomil equipment



Principle:

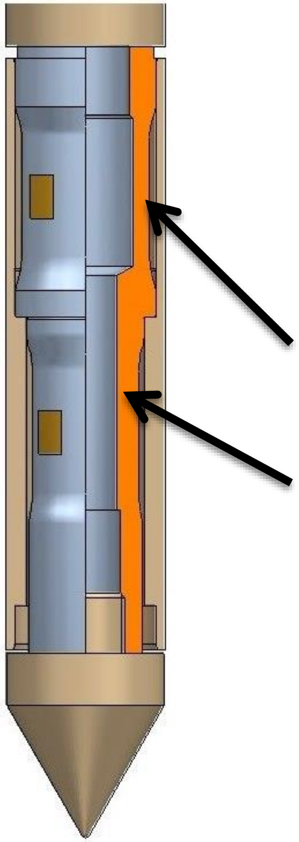
- Independent measurement of cone resistance (qc) and local sleeve friction (fs)
- Two separate load cells
- Outer strain gauge bridge measures sleeve friction (fs)
- Inner strain gauge bridge measures cone resistance (qc)
- No further processing required



Compression vs Subtraction

Subtraction Design

Geomil equipment



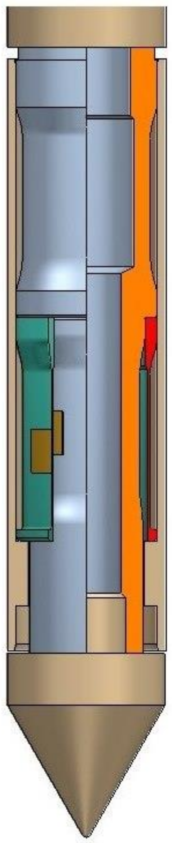
Principle:

- Combined measurement of cone resistance (q_c) and local sleeve friction (f_s)
- One combined load cell
- Upper strain gauge bridge measures cone resistance (q_c) + sleeve friction (f_s)
- Lower strain gauge bridge measures cone resistance (q_c) only
- Further processing required

(f_s = output upper bridge -/- output lower bridge)

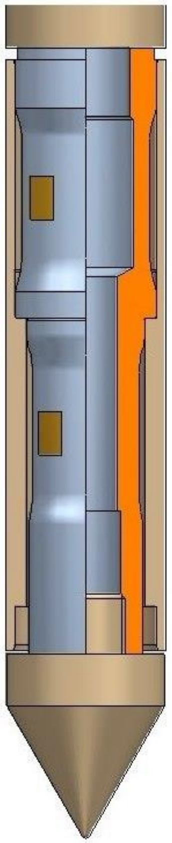
Compression vs Subtraction

Which to use?



Compression

- Smaller strain gauge bridge for sleeve friction
- Based on Hooke's law same force will result in larger deformation
- More sensitive to small strains
- More delicate



Subtraction

- One large strain gauge bridge for both sleeve friction and cone resistance
- Based on Hooke's law same force will result in smaller deformation
- Less sensitive to small strains
- Less delicate

Compression vs Subtraction

Which to use?

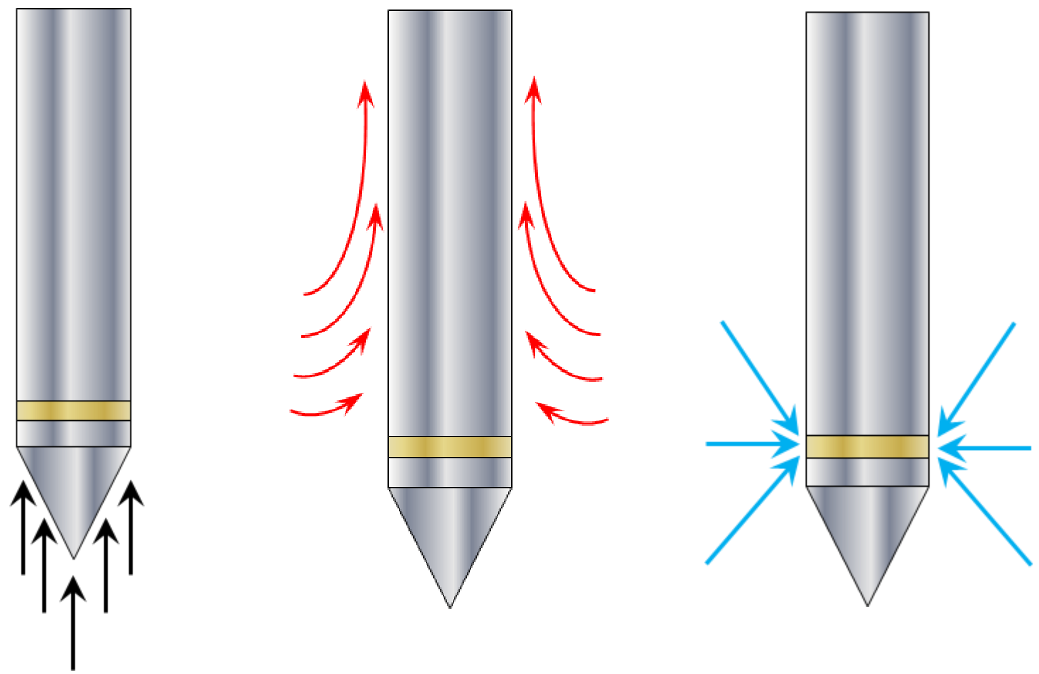
- *What is the purpose of the investigation?*
- *What kind of soils are we testing?*
  - Range of load cell(s) and transducers
  - Cone type and size
  - Application of standards
  - Area factor (a)

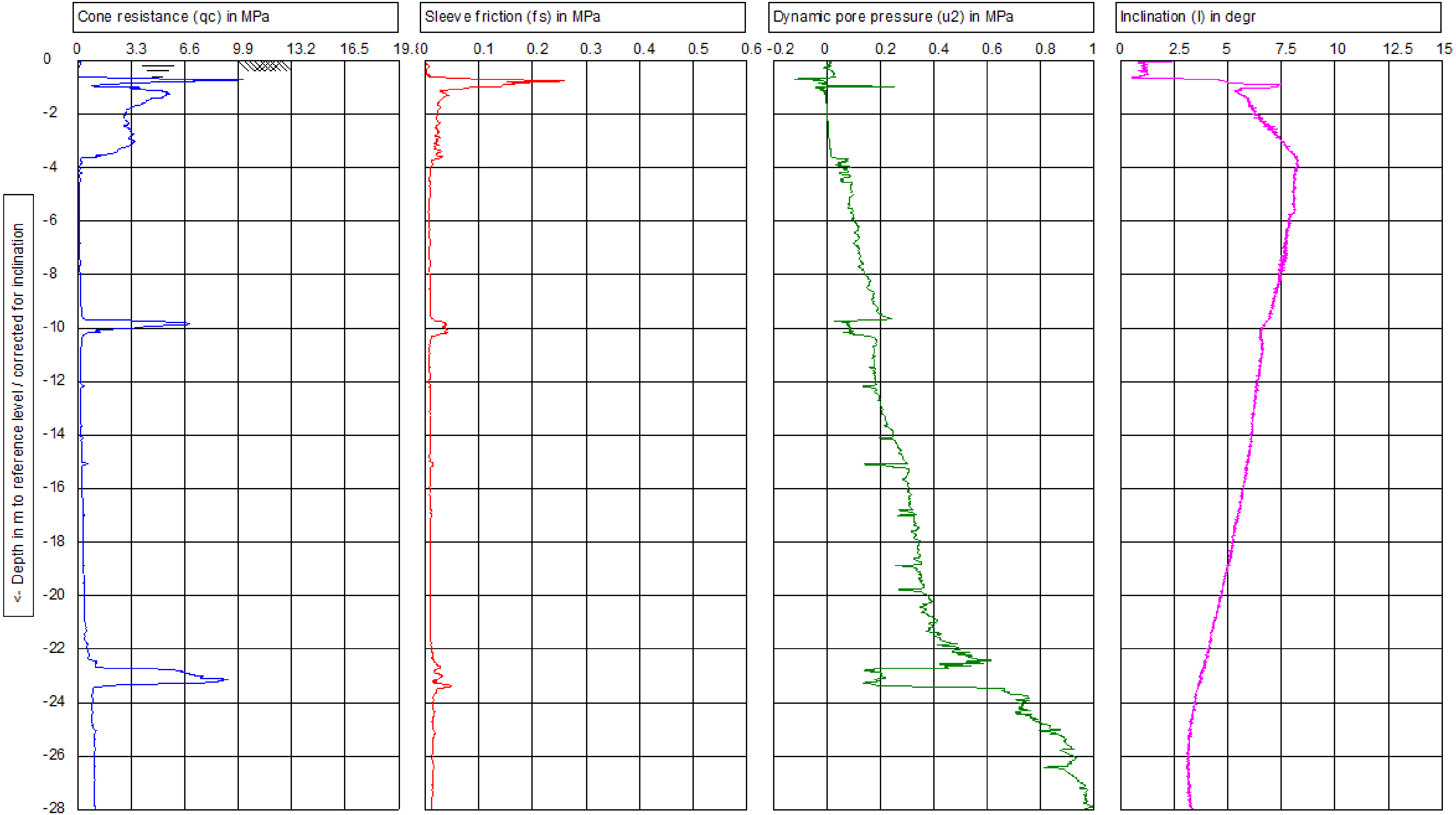
	Compression	Equally good	Subtraction
Predominantly soft soils	**X**		
Mixed soils		**X**	
Predominantly hard soils			**X**
Accurate f_s data required	**X**		
High production required			**X**

Applications of CPT Data

Parameters Obtained

- Directly Measured Parameters
  - Cone Resistance (q_C)
  - Sleeve Friction (f_s)
  - Pore Pressure (u_1, $_2$ or $_3$)
- Directly Derived Parameters
  - Friction Ratio (Rf=(fs/qt) · 100%)
  - Equilibrium pore pressure (u_0)
  - Excess pore pressure (Δu=u2 - u0)
  - Corrected cone resistance (qt=qc + (1 - a) · u2
  - Effective cone resistance ($q_e = q_c - u_2$)





Cone resistance (qc) in MPa
0
3.3
6.6
9.9
13.2
16.5
19.8
Sleeve friction (fs) in MPa
0
0.1
0.2
0.3
0.4
0.5
0.6
Dynamic pore pressure (u2) in MPa
-0.2
0
0.2
0.4
0.6
0.8
1
Inclination (I) in degr
0
2.5
5
7.5
10
12.5
15
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
<- Depth in m to reference level / corrected for inclination

Applications of CPT Data

Parameters Obtained

- Directly Measured Parameters
  - Cone Resistance (q_C)
  - Sleeve Friction (f_s)
  - Pore Pressure (u_1, $_2$ or $_3$)
- Directly Derived Parameters
  - Friction Ratio (Rf=(fs/qt) · 100%)
  - Equilibrium pore pressure (u_0)
  - Excess pore pressure (Δu=u2 - u0)
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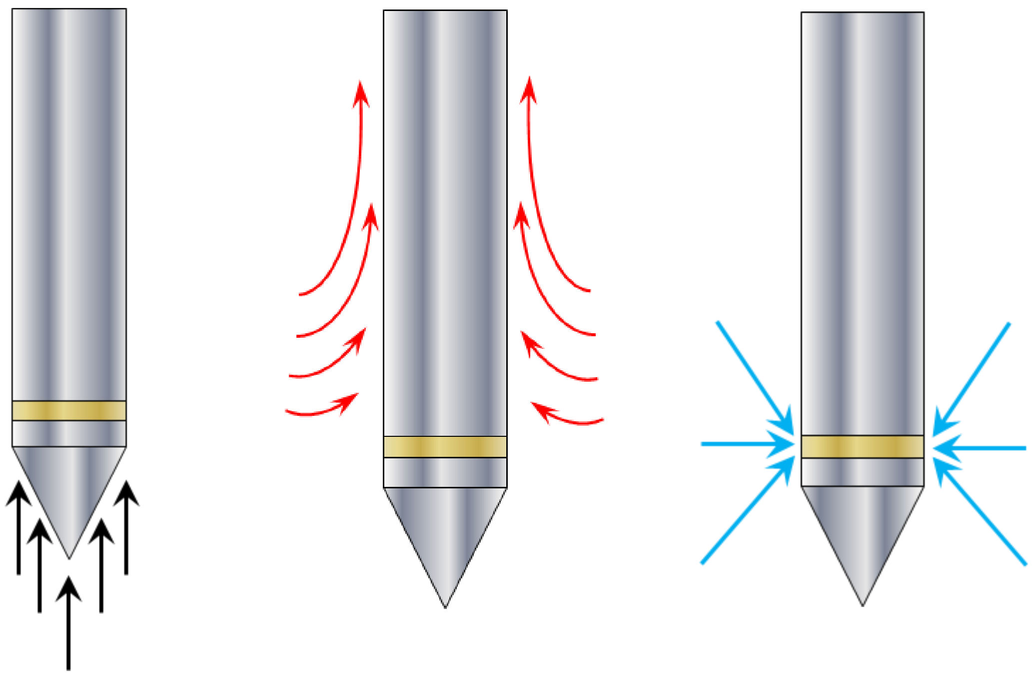
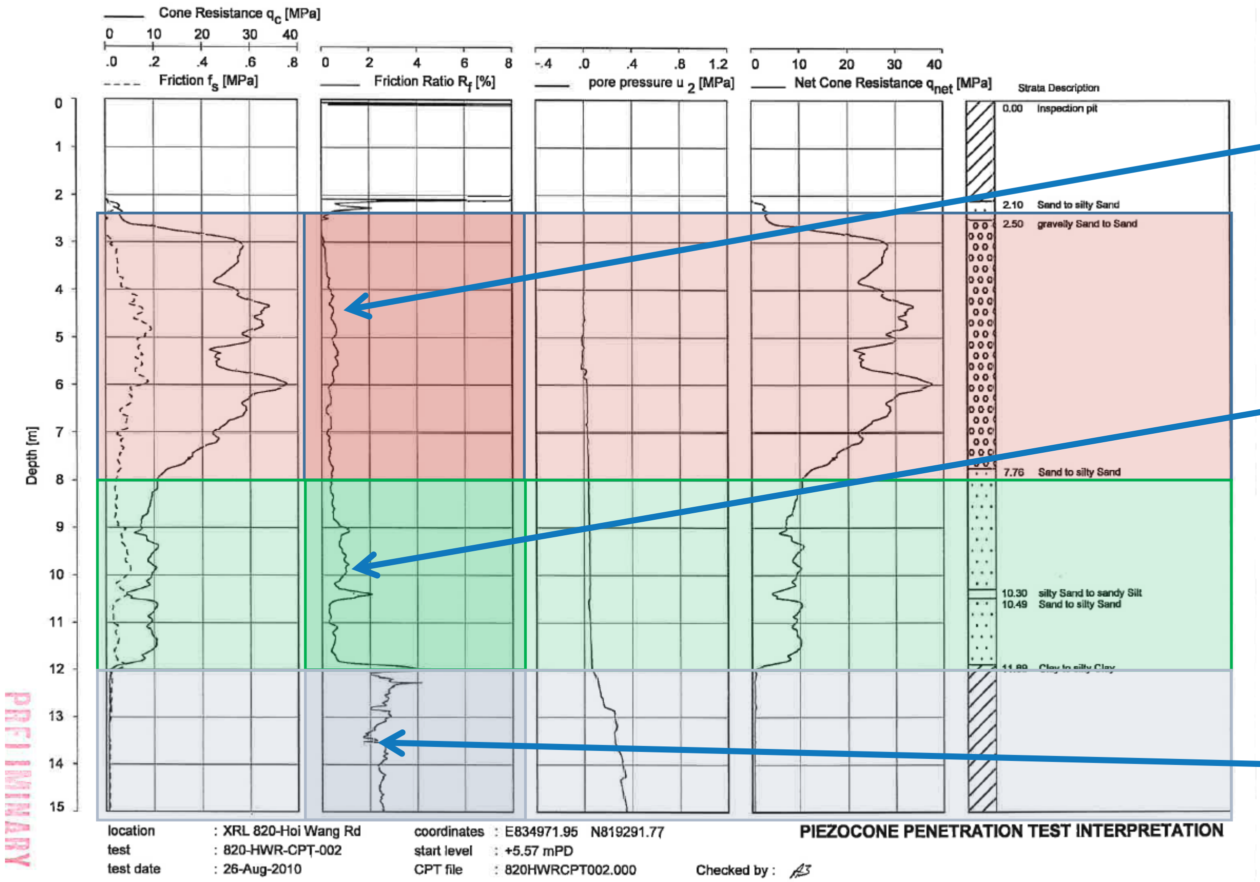


CPT Data

Friction Ratio

- Friction ratio (R_f)
- % of total resistance from sleeve friction (f_s/q_t)
- Generally:
  - Low in granular material
  - High in cohesive materials
- Normally between 0.1-10%



Friction Ratio low in sands and gravels

Friction Ratio increases with an increase in finer grained material – silty sands

Clay results in high friction ratio

Applications of CPT Data

Parameters Obtained

- Indirectly derived parameters:
  - Total vertical stress
    - $(\sigma_{vo} = \sum \gamma\ (dry + wet))$
  - Effective vertical stress
    - $(\sigma'_{vo} = \sigma_{vo} - u_0)$
  - Net cone resistance
    - $(q_n = q_t - \sigma_{vo})$
  - Pore pressure ratio
    - $(B_q = (u_2 - u_0) / (q_t - \sigma_{vo}))$
  - Normalized cone resistance
    - $(Q_t = (q_t - \sigma_{vo}) / \sigma'_{vo})$
  - Normalized friction ratio
    - $(F_r = f_s / (q_t - \sigma_{vo}))$
- Advanced derived parameters:
  - Soil classification
  - Internal friction angle: Frictional / coarse grained soils
  - Relative density: Frictional / coarse grained soils
  - Undrained shear strength: Fine grained / cohesive soils
  - Soil behavior type index
  - Equivalent SPT N60 value
- Depending on software used more parameters may be available!

Applications of CPT Data

Suitability of Parameters

Soil Type	D_r	Ψ	K_o	OCR	S_t	s_u	ϕ'	E,G*	M	G_0*	k	c_h
Sand	2-3	2-3	5	5			2-3	2-3	2-3	2-3	3-4	3-4
Clay			2	1	2	1-2	4	2-4	2-3	2-4	2-3	2-3

Table 4 Perceived applicability of CPTu for deriving soil parameters

1=high, 2=high to moderate, 3=moderate, 4=moderate to low, 5=low reliability, Blank=no applicability, * improved with SCPT

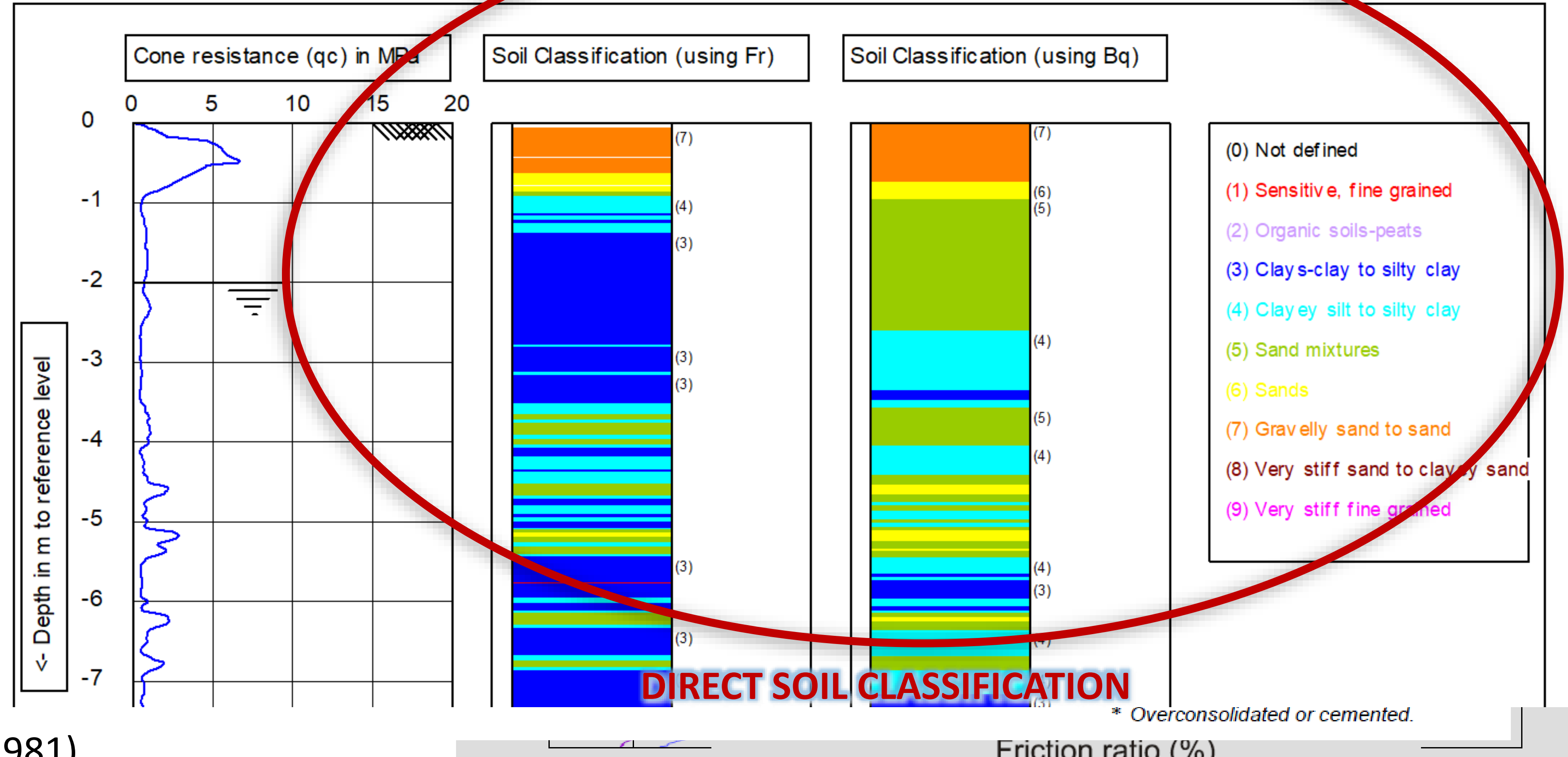
Applicability of using CPTU data for soil parameters according to Robertson (Guide to CPT, 2015)

Applications of CPT Data

Use of CPT Data

- Stratification
  - Interpretation characteristics
  - soft vs hard, dr
- Soil classification
  - Use of empirica
  - parameters co profiles
- Soil design paramet
  - Use of empirica
  - sand or clay → be obtained

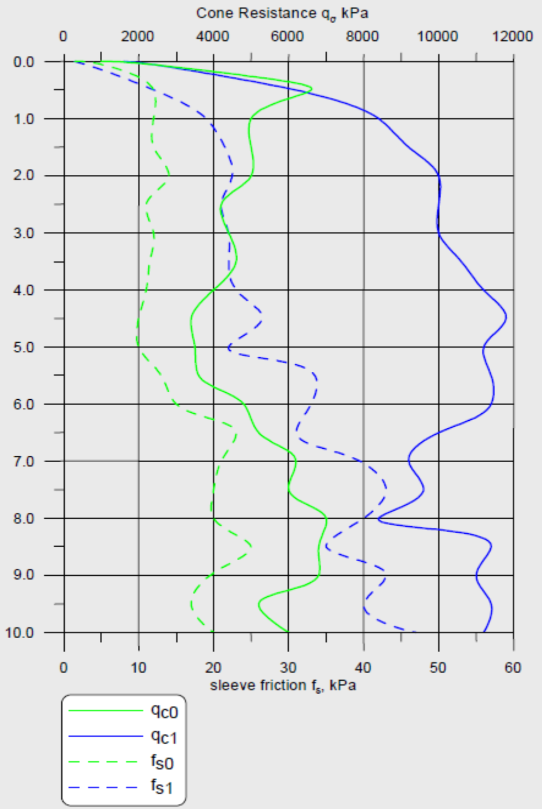
Soil classification cha cone
q_c and f_s data
(Douglas and Olsen, 1981)



Applications of CPT Data

Typical Applications

- Any geotechnical problem in soils testable by CPT
- (Pile) foundation design
- Settlement prediction
- Compaction control (land reclamations)
- Embankment and dike profiling
- Stability issues (mine tailings)
- Seismic survey (liquefaction analysis)
- Environmental issues
- Pipe line / cable routing
- Wind turbine foundations



Changi airport, Singapore

Cone resistance and sleeve friction before and after compaction

(Massarsch and Fellenius, 2002)

State of CPT in Hong Kong

Overview

- Generally healthy and competitive CPT market in Hong Kong
- Reclamation projects driving the CPT market
- CPTs (generally) compliant with international standards
- Many local contractors with CPT capability, growing understanding
- Engineers, designers, end clients less understanding
- Hong Kong is behind most CPT markets in terms of advanced/specialised testing
    - Seismic CPT, Soil Moisture Probe, Digital Cone etc.

CPT in Hong Kong – Ongoing

- HKIA – 3RS
  - Pre and Post improvement CPTs
  - Paired with ground improvement such as DCM
  - Delineating surface of competent strata
  - 3 Manta-200, 1 Manta-100, 3 Fox-200, 1 Shark in operation
  - Interesting signatures such as negatively shifted hydrostatic gradient
  - Strength of CPTu carrying out analysis in consolidating soils

CPT in Hong Kong – Upcoming

- HKIA 3RS
  - When the reclamation comes above water
  - 1000s of land CPTs
  - Many local contractors
- Tung Chung Development
  - 2400 marine CPTs
  - Buildking Samsung JV
- Shek Kwu Chau
  - Reclamation for incinerator
  - 170 marine CPTs in first round
  - China Harbour Engineering Company

CPT in Hong Kong

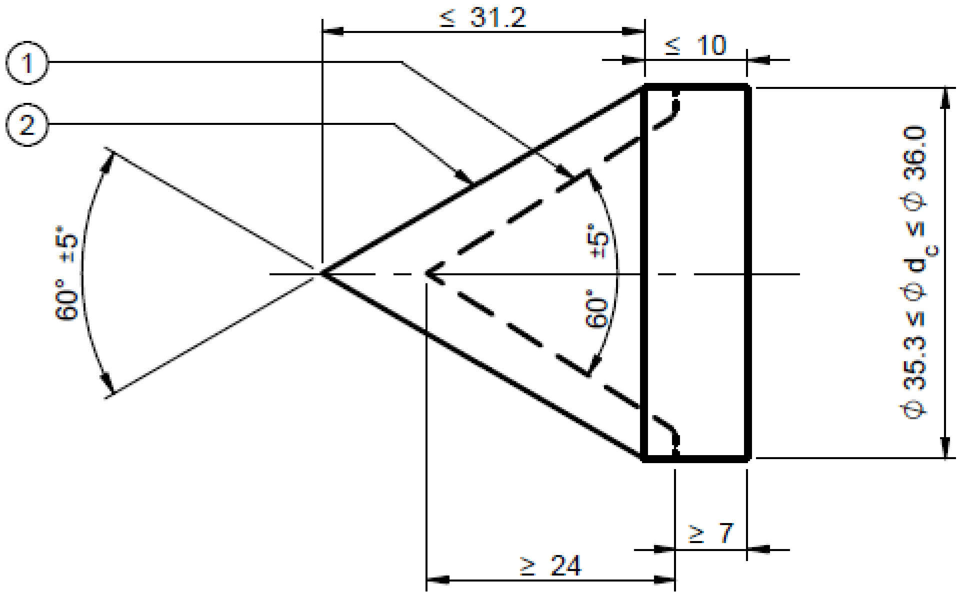
Challenges

- Operational error (not Hong Kong specific)

Data Quality

Operational Sources of Error

- Cone condition
  - *Zero readings*
  - *Straightness*
  - *Cleanliness*
  - *Water and dirt seals*
  - *Wear*
- Piezocone saturation
  - *Filter (replaced?)*
  - *Cone / pressure chamber*
- Temperature influences
- Penetration speed (20 mm/s)
- Large inclination
- Zeroing location (reference readings)
- Malfunctioning depth measurement



1. minimum shape of the cone tip after wear
2. maximum shape of the cone tip

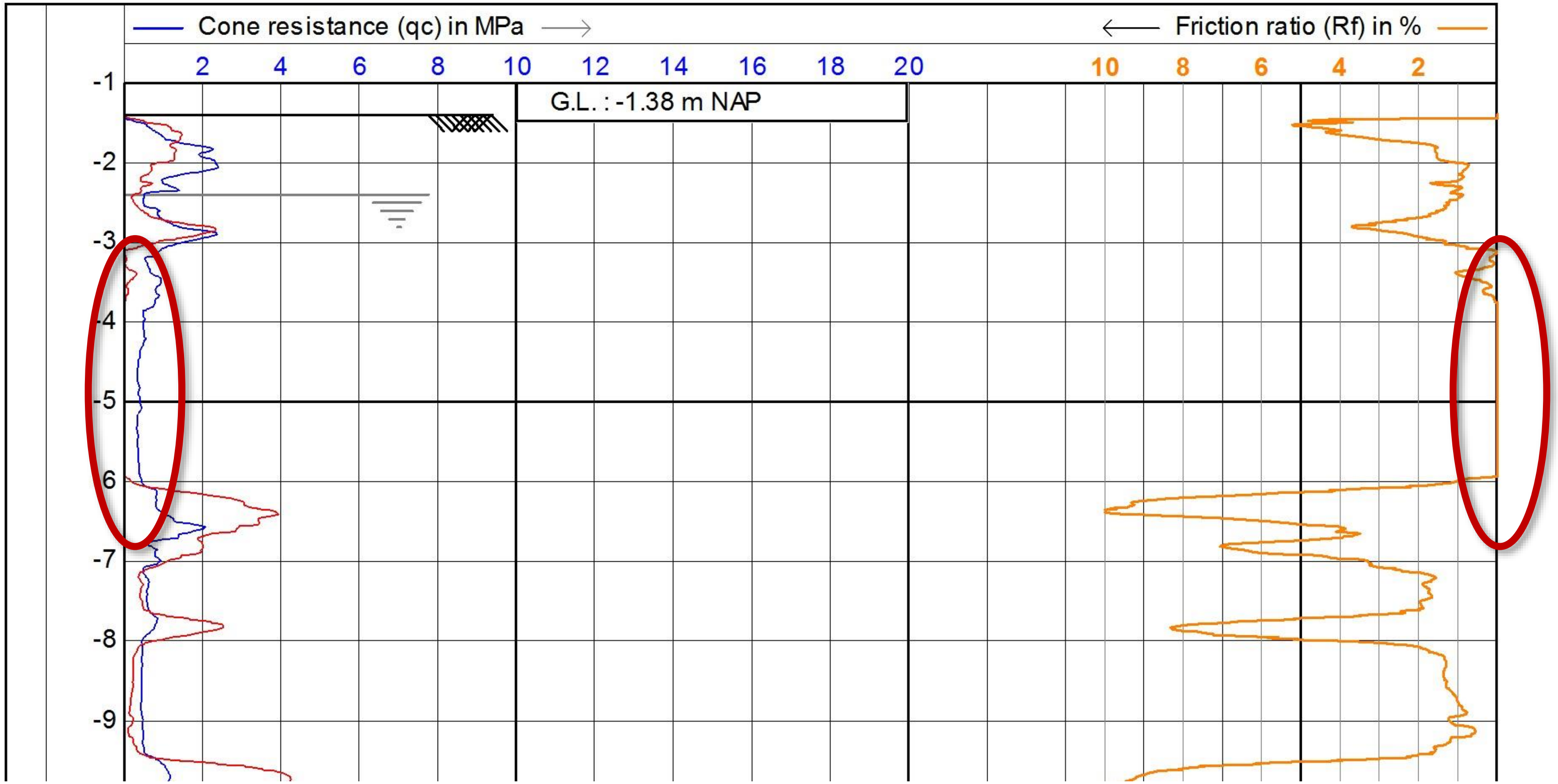
Data Quality

Warning Signs

- Gaps in readings
- Negative and/or “zero” friction readings

Data Quality

Warning Signs



Data Quality

Warning Signs

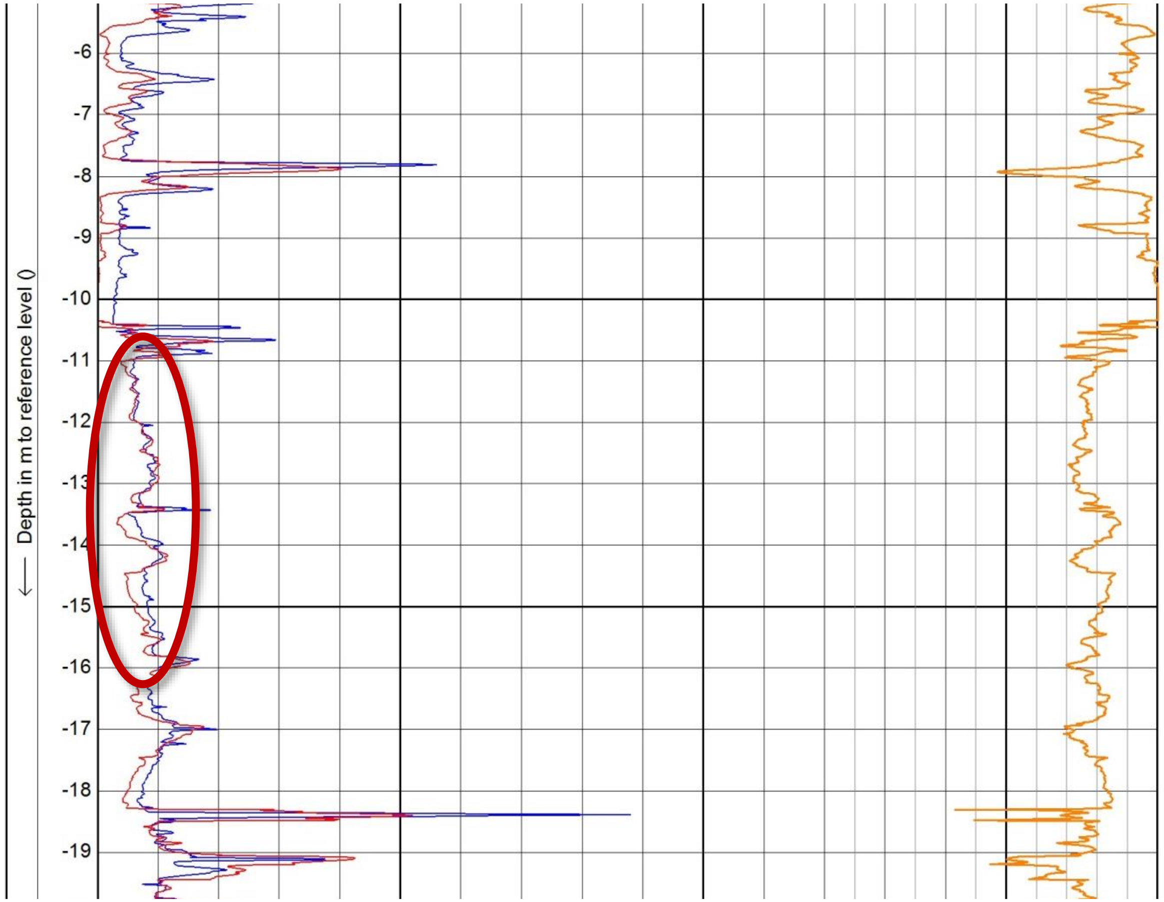
Data Quality

Warning Signs

- Gaps in readings
- Negative and/or “zero” friction readings
- Friction readings following cone resistance pattern

Data Quality

Warning Signs



Data Quality
Warning Signs

Geomil equipment

Data Quality

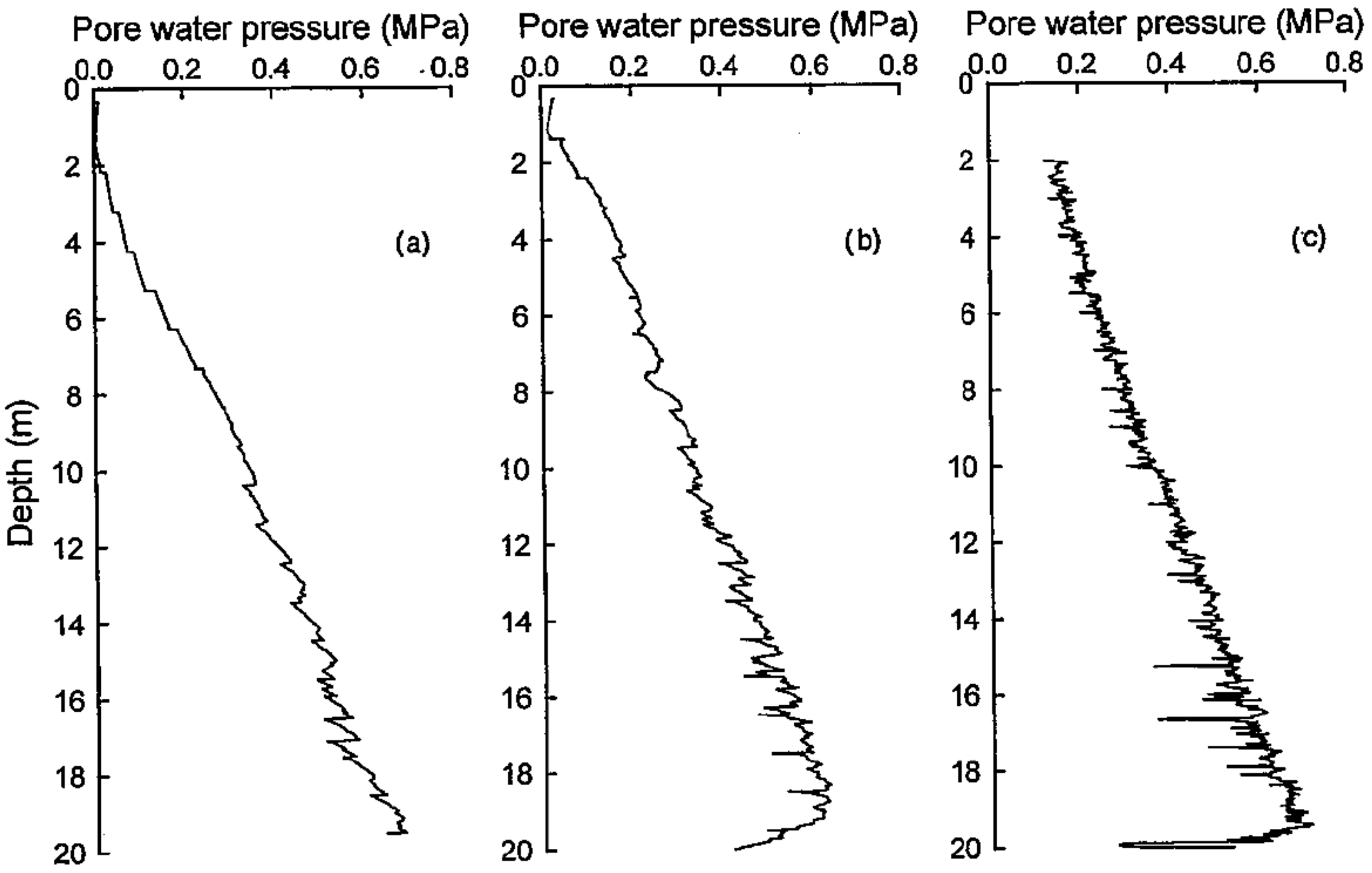
Warning Signs

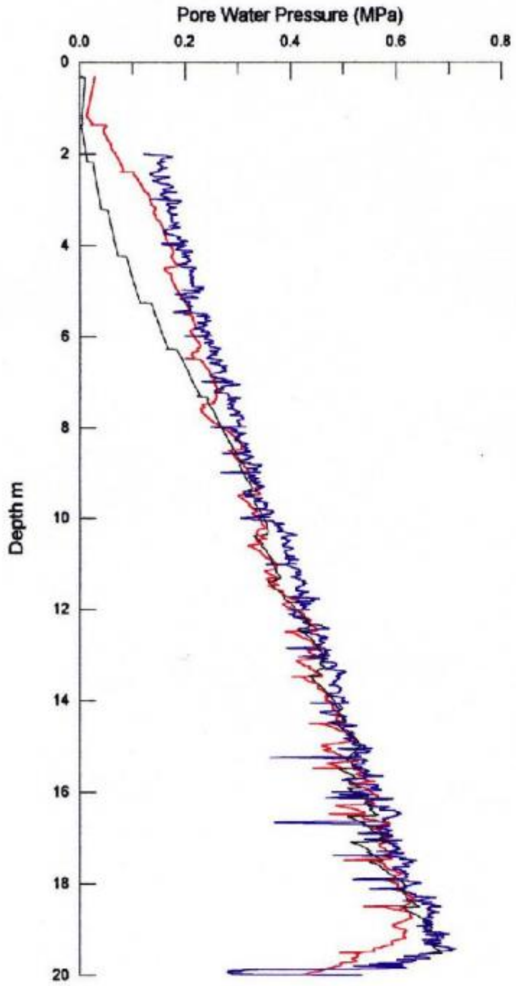
- Gaps in readings
- Negative and/or “zero” friction readings
- Friction readings following cone resistance pattern
- Sluggish pore pressure readings

Data Quality

Warning Signs

Geomil equipment





Data Quality

Warning Signs

- Gaps in readings
- Negative and/or “zero” friction readings
- Friction readings following cone resistance pattern
- Sluggish pore pressure readings
- Drifts in zero readings, either during a CPT or in between various CPT’s

CPT in Hong Kong

Challenges

- Operational error (not Hong Kong specific)
- Reliance on experienced si fu drillers (again happens everywhere)
- PS (Particular Specifications) largely copied from project to project

Challenges

Particular Specifications

- Particuliar specifications often handed down from project to project
- Specifications suitable for one project often not suitable for the next
- Common over specifications:
  - 200 kN pushing capacity
  - Application Class 1 tests
  - On site calibration set up
  - Changing filter each test
- Some over specifications cost production and therefore essentially reduce profit
- Some are not possible such as Class 1 tests in sands and mixed soils
- Some reduce resolution/sensitivity such as needing 100MPa cone

CPT in Hong Kong

Challenges

- Operational error (not Hong Kong specific)
- Reliance on experienced si fu drillers (again happens everywhere)
- PS (Particular Specifications) largely copied from project to project
- Insistence on Application Class 1 tests

Application Classes

Introduction

Application classes (ISO):

- Introduction of Application (Accuracy) Classes
- Class 1 : Most strict : design parameters in soft clays
- Class 4 : Least strict : profiling

Main purpose is to allow for differences in:

- Soil conditions
- Project requirements
- Use of results
- Stratigraphy only
- Engineering parameters
- National / regional traditions and experience

Table 2 — Application classes

Applic. Class	Test type	Measured parameter	Allowable minimum accuracy [a]	Maximum length between measurements	Use: Soil [b]	Use: Interpretation / evaluation [c]
1	TE2	Cone resistance	35 kPa or 5 %	20 mm	A	G, H
		Sleeve friction	5 kPa or 10 %			
		Pore pressure	10kPa or 2 %			
		Inclination	2°			
		Penetration length	0,1 m or 1%			
2	TE1 TE2	Cone resistance	100 kPa or 5 %	20 mm	A B C D	G, H* G, H G, H G, H
		Sleeve friction	15 kPa or 15 %			
		Pore pressure [d]	25 kPa or 3 %			
		Inclination	2°			
		Penetration length	0,1 m or 1 %			
3	TE1 TE2	Cone resistance	200 kPa or 5 %	50 mm	A B C D	G G, H* G, H G, H
		Sleeve friction	25 kPa or 15 %			
		Pore pressure [d]	50 kPa or 5 %			
		Inclination	5°			
		Penetration length	0,2 m or 2 %			
4	TE1	Cone resistance	500 kPa or 5 %	50 mm	A B C D	G* G* G* G*
		Sleeve friction	50 kPa or 20 %			
		Penetration length	0,2 m or 2 %			

NOTE For extremely soft soils even higher demands on the accuracy may be needed.

[a] The allowable minimum accuracy of the measured parameter is the larger value of the two quoted. The relative accuracy applies to the measured value and not the measuring range

[b] According to EN ISO 14688-2:
A Homogeneously bedded soils with very soft to stiff clays and silts (typically $q_c < 3$ MPa)
B Mixed bedded soils with soft to stiff clays (typically $q_c \leq 3$ MPa) and medium dense sands (typically 5 MPa $\leq q_c < 10$ MPa)
C Mixed bedded soils with stiff clays (typically 1,5 MPa $\leq q_c < 3$ MPa) and very dense sands (typically $q_c > 20$ MPa)
D Very stiff to hard clays (typically $q_c \geq 3$ MPa) and very dense coarse soils ($q_c \geq 20$ MPa)

[c] G profiling and material identification with low associated uncertainty level
G* indicative profiling and material identification with high associated uncertainty level
H interpretation in terms of design with low associated uncertainty level
H* indicative interpretation in terms of design with high associated uncertainty level

[d] Pore pressure can only be measured if TE2 is used.

Application Classes
Determining Class

LABORATORY CALIBRATION										
	Uncertainty analysis Maximum error of measured value (%)								Potential Uncertainty (kPa/Deg)	
Sensor	Resolution	Output stability	Repeatability	Linearity	Hysteresis	Zero drift	Dimensional	COMBINED UNCERTAINTY (%)	Temperature changes	Inclined load
Cone resistance	0.0031	0.0048	0.5623	0.1434	0.2742	0.0001	0.2800	0.70	1.20	0.3
Sleeve friction	0.0005	0.0009	0.5102	0.0067	0.4219	0.0009	0.1400	0.68	0.06	0.4
Pore pressure	0.0000	0.0001	0.2400	0.2784	0.3230	0.0002		0.49	0.5	

Example of results of a laboratory calibration of a piezocone and associated uncertainty analyses – Lunne et al 2014

Application Classes

Determining Class

Test procedure	
Saturation procedure used for pore water pressure system	Vacuum for 5 hours in glycerin oil
Air temp. before and after testing on deck	17°C / 17°C reference reading taken in a water bath
Probe location for deck reference readings	Deck in seawater bath
Time allowed for temperature compensation before reference readings on deck	Output values were monitored until stability was reached after 7 minutes
Probe preparation before reference readings on deck	Cone rinsed with seawater, sleeve friction rotated several times, dirt removed from gaps and seals by flushing
Probe location for pre- and post- test reference readings	Seafloor (Offset 0.2m)
Time allowed for temperature compensation on the seabed	Output values were monitored until stability was reached after 8 minutes
Observations during test (stone, sound, bent rods, cone preload etc.)	Dropped stone encountered at 5 m pore pressure sensor showed cavitation

Example of field records and field assessment of Application class – Lunne et al 2014

Application Classes
Determining Class

Test results				
Corrections done during processing	Standard correction to cone resistance accounting pore water pressure effects. Depth corrected based on inclination measurements			
Inclination of probe relative to vertical	Maximum inclination 1°.			
Temperature changes during the test	Not applicable, no temperature sensor			
Evaluation of cone resistance profile	Good response of cone resistance. No anomalies have been detected.			
Evaluation of sleeve friction profile	Good response of cone resistance. No anomalies have been detected.			
Evaluation of pore pressure response profile	Very good reaction to changes in soil types. Cavitation was observed when drop stone encountered; pore pressure sensor recovered immediately.			
Reference readings	Cone resistance	Sleeve Friction	Pore water pressure	Comments
Deck reference readings (Before/After)	(12 / 52) kPa	(6 / 5) kPa	(-4 / -2) kPa	Large drift in cone resistance
Seabed/ downhole reference readings (Before/After)	(3752 / 3775) kPa	(7 / 15) kPa	(4996 / 5100) kPa	Clay adhere to cone after retraction

Example of field records and field assessment of Application class – Lunne et al 2014

Application Classes
Determining Class

Application Class analysis				
	Cone re-sistance	Sleeve Friction	Pore water pressure	Application Class
Required Application Class based on soil type	Class 1	Class 1	Class 1	Class 1
Application Class based on calibration	Class 1	Class 1	Class 1	Class 1
Dimensional difference	0	0		Class 1
Deck reference readings observed differ-ences (before and after)	40 kPa	1 kPa	2kPa	Class 2
Output stability for all sensors (Maximum range of oscillations)	4 kPa	0 kPa	2 kPa	Class 1
Uncertainty caused by Temperature changes	0	0	0	Class 1
Uncertainty caused by inclination	0.3	0.4	NA	Class 1
Achieved Application Class	Class 2.			
Causes of deviation from desired and achieved Application Class	Observed drift on the cone end resistance sensor. Test needs to be repeated with a different cone			

Example of field records and field assessment of Application class – Lunne et al 2014

CPT in Hong Kong

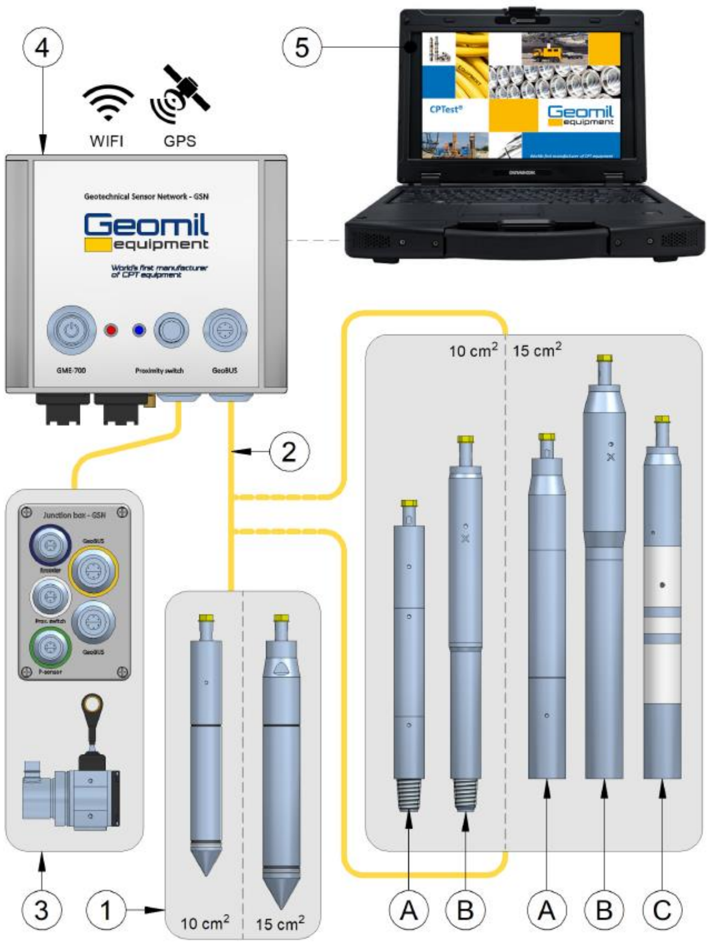
Challenges

- Operational error (not Hong Kong specific)
- Reliance on experienced si fu drillers (again happens everywhere)
- PS (Particular Specifications) largely copied from project to project
- Insistence on Application Class 1 tests
- Use of only standard CPTU testing
  - No specialist techniques used in Hong Kong
  - Tests such as Seismic CPT, Soil Moisture Probe, Video cones, widely used across Europe
  - Most specialist equipment has now been deployed in China

CPT in Hong Kong

Potential future developments

- Project specific requirements written before tendering stage which reflect the project conditions
- Specialist CPT data review panel
- Use of specialist CPT testing methods
  - Soil Moisture Probe (SMP)
  - Digital CPT
  - Seismic CPT (SCPT)
- Digital CPT (D-cone and GSN)
  - Analogue to digital conversion in cone
  - Calibrations stored on cone
  - Easier to add and swap modules (SMP, SCPT etc).



A standard Geotechnical Sensor Network (GSN) for CPT consists of:

1. Digital subtraction or compression type D-Cone
2. High quality GSN CPT cables in standard or custom lengths
3. Digital depth encoder
4. Digital data acquisition system GME-700 with GPS as standard and optional WiFi
5. Data acquisition software package CPTest

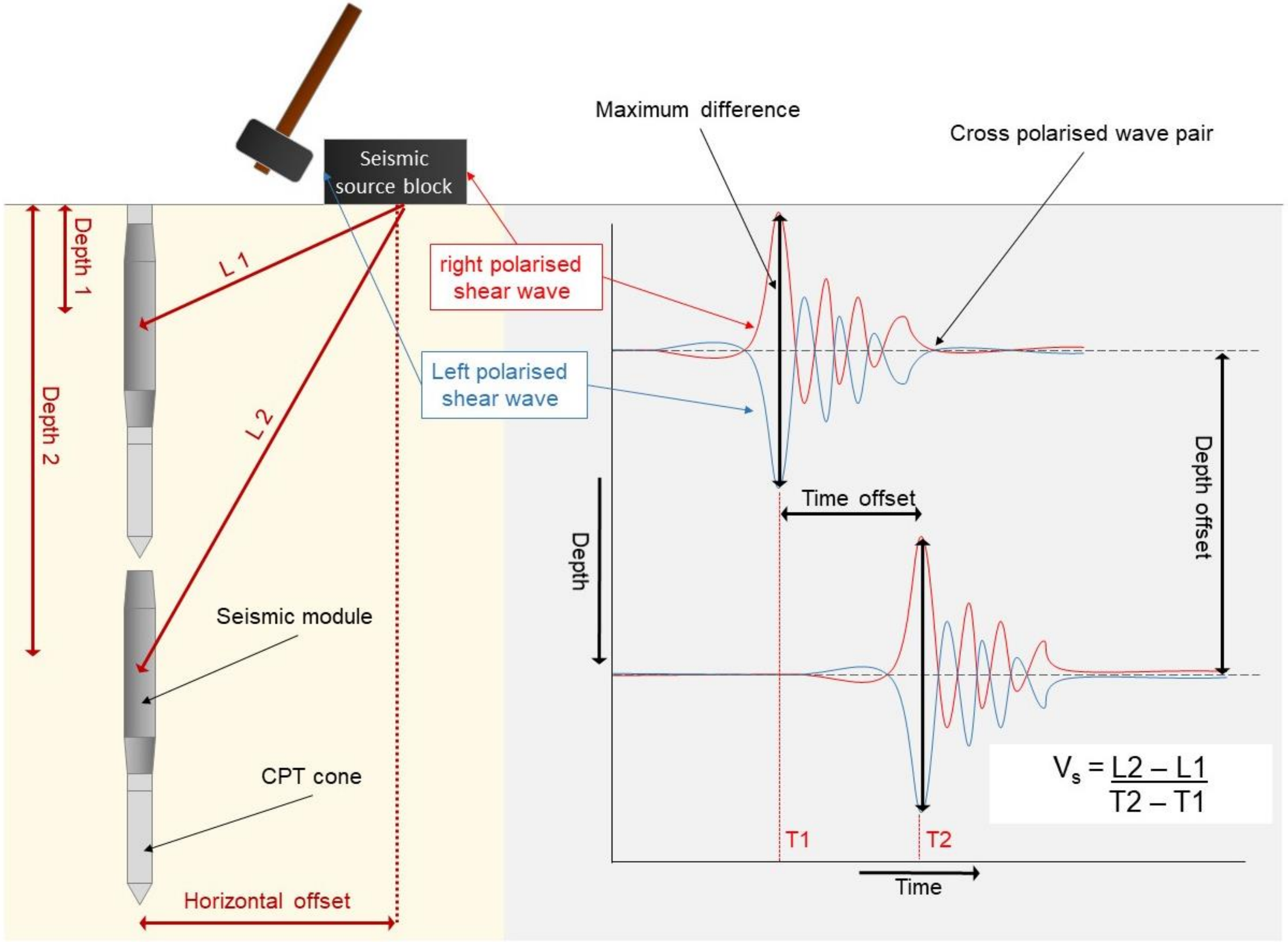
Optional add-ons:

- Wireless system
- Battery add-on (A) (for memory or wireless* use of cone)
- Seismic module (B)
- SMP (Soil Moisture Probe) module (C)
- Magnetometer module
- Dipole module
- Temperature sensor module
- Client specific module

Future of CPT in Hong Kong

Seismic CPT

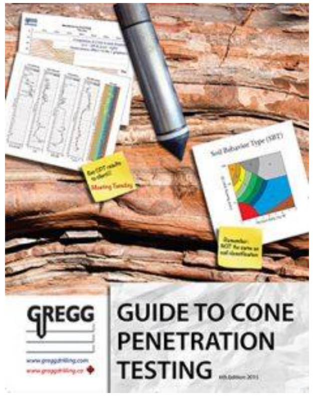
- Seismic CPT (SCPT) standard CPT plus measurement of shear (+/- push-pull) wave velocity
- CPT paused at regular intervals and surface waveform generated
- Equipment:
  - CPT cone
  - Seismic receiver
  - Seismic source generation
  - Data acquisition including seismic data treatment
- Small strain shear modulus G0 directly derived from shear wave velocity

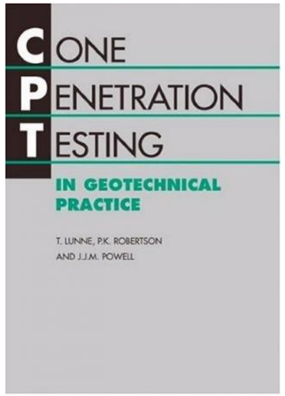


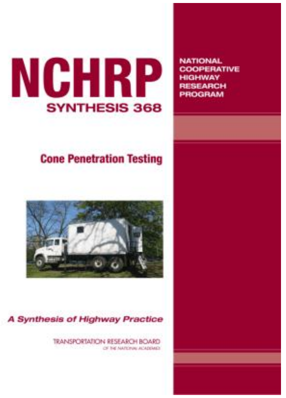
Future of CPT in Hong Kong

Recommended Reading

- Recommended Reading:
  - Guide to Cone Penetration Testing 6th Edition, 2015 – Peter Robertson
  - Cone Penetration Testing in Geotechnical Practice, 1994 Lunne, Robertson, Powell
  - NCHRP Synthesis 368 Cone Penetration Testing, 2007 Paul Mayne
  - American Standard, ASTM D5778 – 12 (2012)
  - ISO Standard, ISO 22476, Part 1 (2012)







Summary

Geomil equipment

- CPT great compliment to conventional GI
  - Fast, accurate, repeatable, well backed by scientific research, well founded parameters
- Growing use across the world
- Many parameters can be derived from CPT data
- Important to critically view CPT data to spot operational error and QC
- Some aspects such as application class are unreasonable in HK PS, poorly understood.
- Growing number of very capable contractors in Hong Kong
- Geomil in Hong Kong to support not only contractors but govt, engineers etc.
- Geomil supported by EPC in Hong Kong and China
- The future of CPT is very bright in Hong Kong with enthusiastic engineers and world class projects

Thank you

Any questions?