<u>Some</u> lessons learned from geotechnical site investigations

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Williamsburg, VA

2015

Two themes

- Need to identify soils with ‘*unusual*’ characteristics
- Case history to illustrate ‘*risk based*’ approach to site investigation

Site Investigation

- Natural deposits are often complex and erratic
  - *Needs a good geologic framework*
- Ground investigation provides approx. estimate of ground conditions
- Program should be flexible to maximize information
- Economic constraints often control

Major areas of uncertainty

- Natural variability
- Complex soil behavior
- Limitations of in-situ testing
- Difficulties obtaining truly undisturbed samples
- Limitations of laboratory testing

Stop using the SPT?

- Mayne et al (2009)
  - *"false sense of reality in the geot. engineer's ability to assess each and every soil parameter from the single N-value"*

Geot. engineers in the 21st century should progressively STOP using this crude, unreliable in-situ test

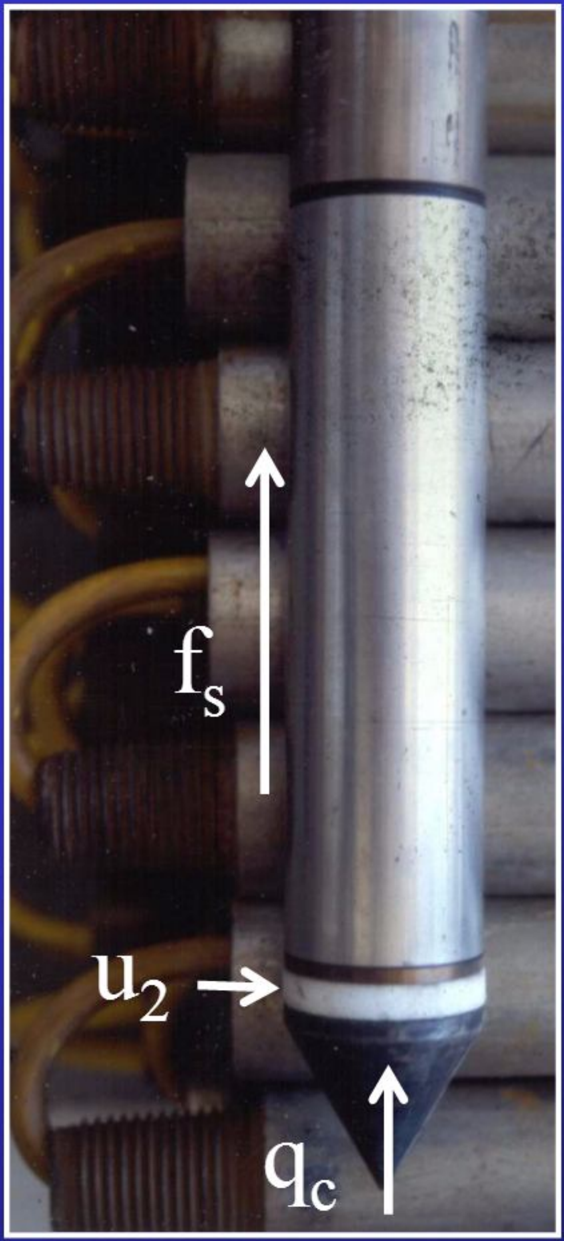
Cone Penetration Test (CPT)

ADVANTAGES:

- Fast and continuous profiling
- Repeatable and reliable data
- Economical and productive
- Strong theoretical basis for interpretation
- More than one measurement (q_c, f_s, u)
- Additional sensors (e.g. seismic V_s & V_p)

LIMITATIONS:

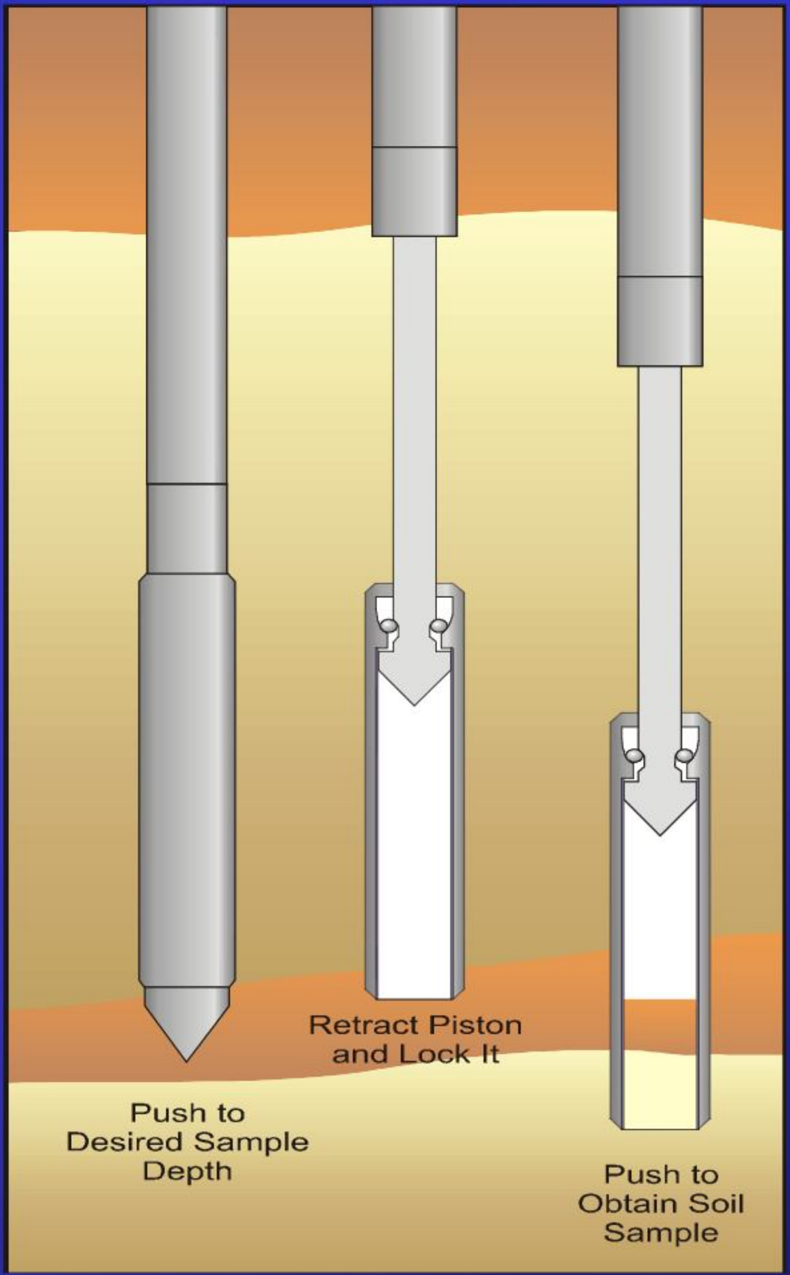
- Somewhat high capital investment
- Somewhat skilled operators
- No soil sample (during CPT)
- Penetration restricted in gravels/cemented layers (same as SPT)



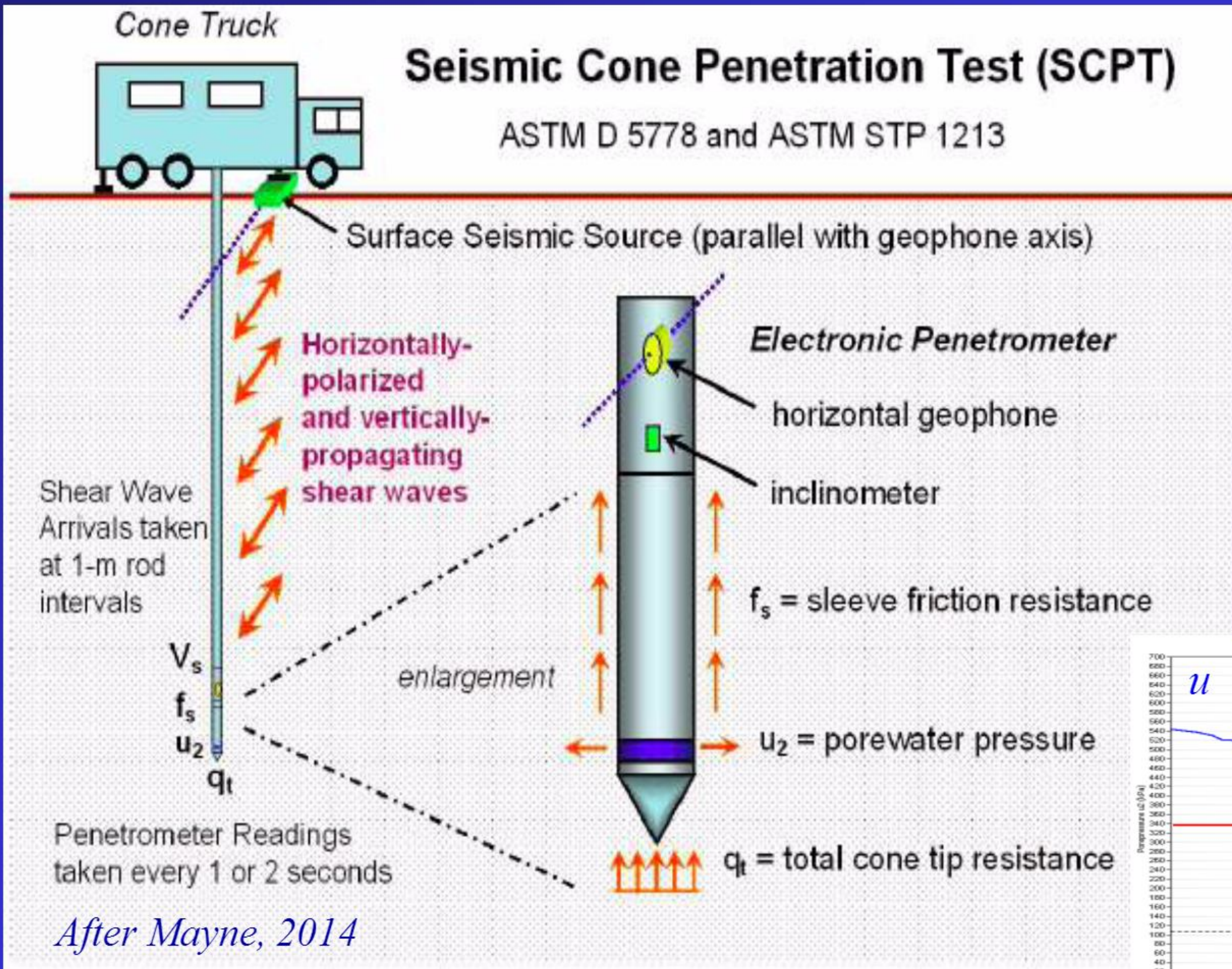
CPT Soil Sampling

Direct-push piston-type sampler

- Single-Tube System
- 300mm long x 28mm diameter sample
- Small disturbed sample (index testing only)



Seismic CPTu

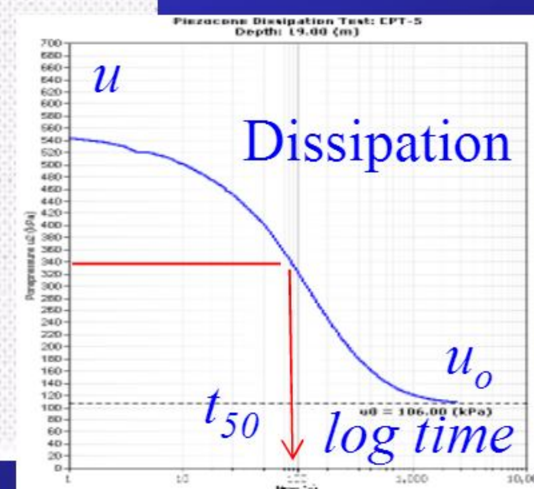


After Mayne, 2014

SCPTu

7 measurements!

- q_t
- f_s
- u_2
- $V_s\ (V_p)$
- t_{50} (diss)
- u_o (diss)
- (i)



Non-textbook – 'unusual' soil

- Most existing published experience/research based on "*well-behaved - ideal*" soil
  - *Young, uncemented: uniform clay and clean silica sand*
- Limited published experience/research on non-textbook "*unusual*" ground
  - stiff fissured clays, soft rock, calcareous soils, man-made ground, older and/or cemented soils

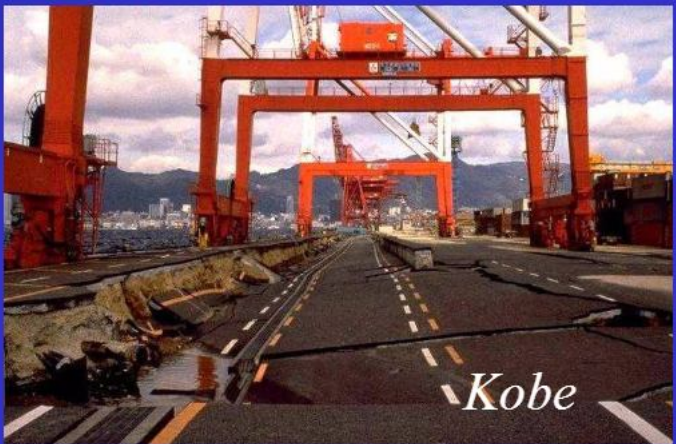
Microstructure often used to describe soils with '*unusual*' characteristics

Seismic (cyclic) Liquefaction

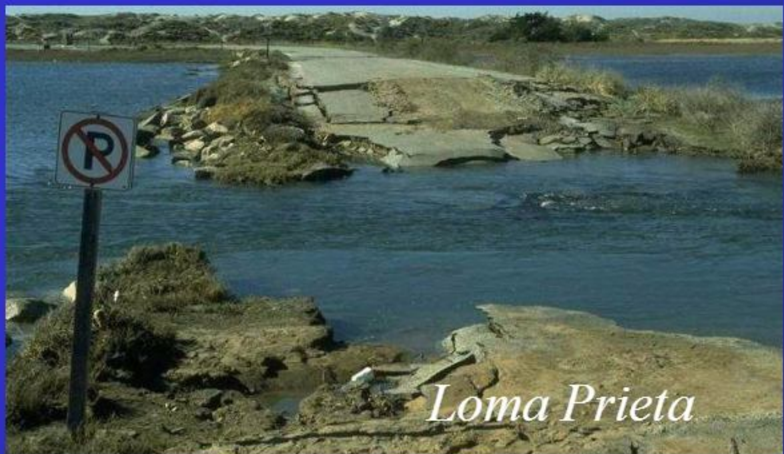
Many major earthquakes with significant soil liquefaction

Common soil features

- Young (Holocene-age)
- Non- plastic or low-plastic
- Uncemented
- Silica-based sandy soil
- Little or no stress history ($K_o \sim 0.5$)



Kobe

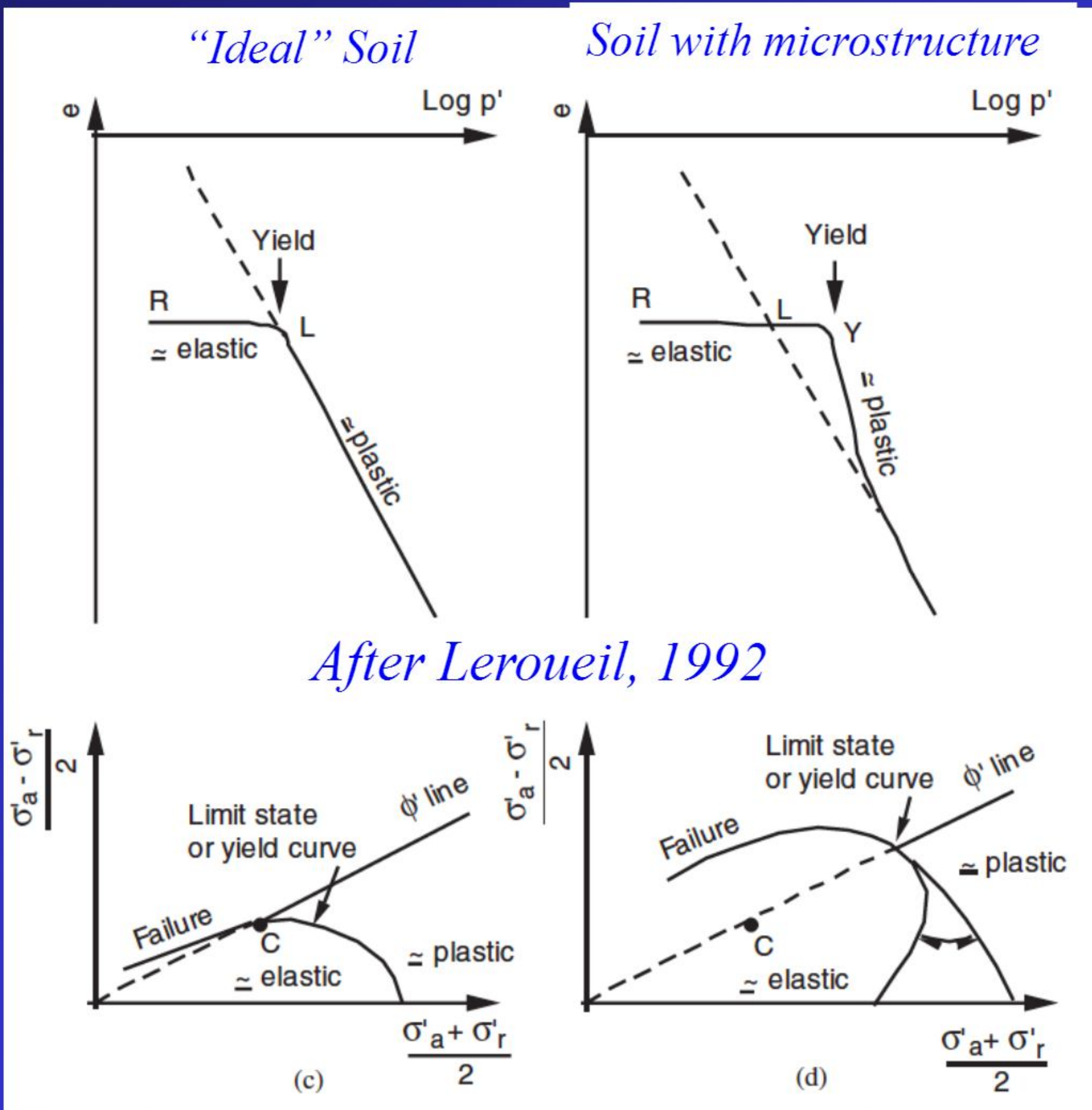


Loma Prieta

Christchurch

What is microstructure?

- Common causes:
  - Aging
  - Bonding (cementation)
  - Weathering
  - Cold welding
  - Stress & strain history
- How to identify:
  - Background geology (e.g. age, mineralogy, history)
  - Sampling & lab. testing
  - In-situ testing – *SCPT & SDMT*



Schematic behavior of 'ideal' and 'structured' soils

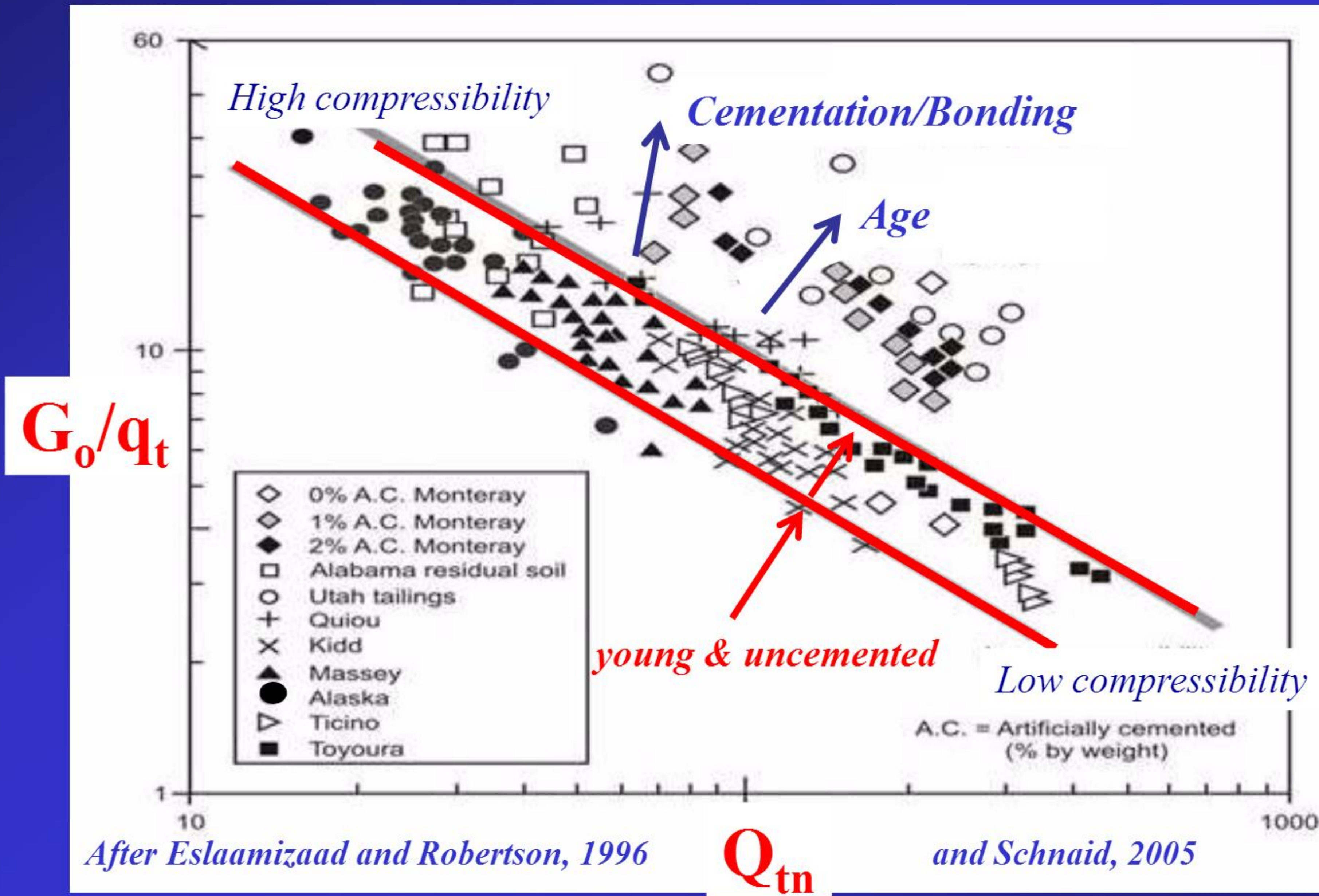
Stiffer at small strains
Larger 'elastic' region
Similar at large strains

SCPT

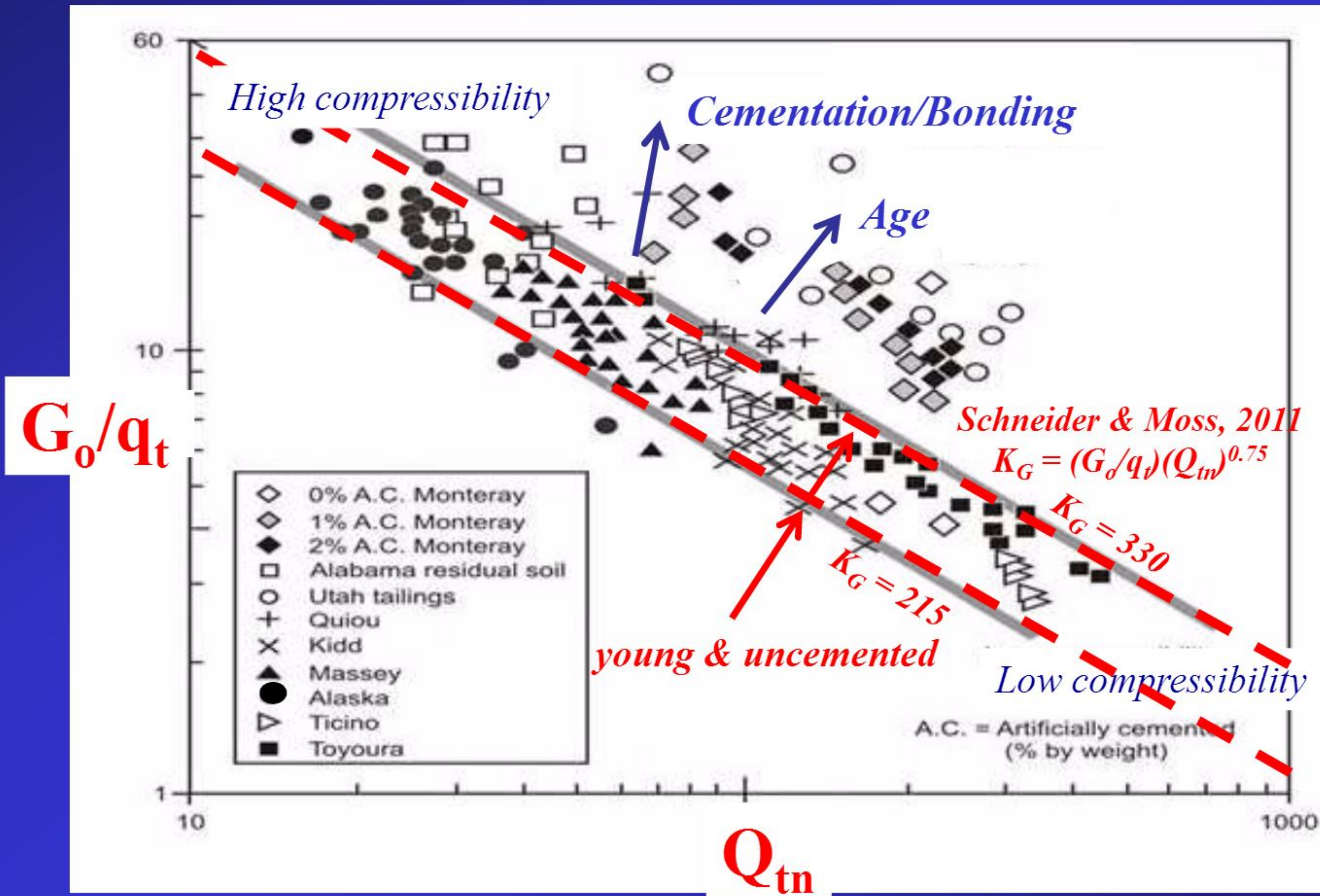
- *Shear wave velocity - V_s (small strain measure)*
  - controlled mainly by: state (relative density & OCR), effective stresses, age and cementation
- *CPT tip resistance - q_t (large strain measure)*
  - controlled mainly by: state (relative density & OCR), effective stresses, and to lesser degree by age and cementation

Strong relationship between q_t and V_s, but depends mainly on *microstructure (i.e. age and cementation)*

Rigidity Index $I^*_{ro} = G_o / q_t$



Normalized Rigidity Index, K_G

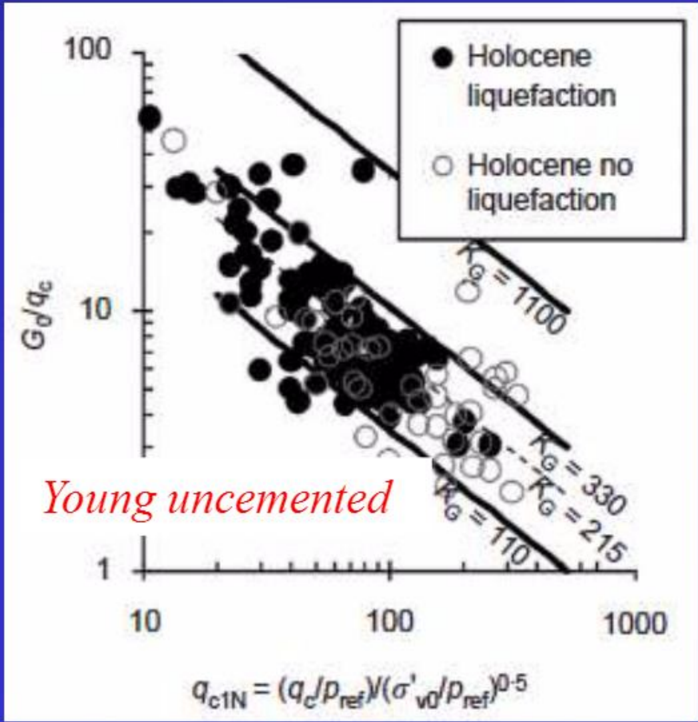


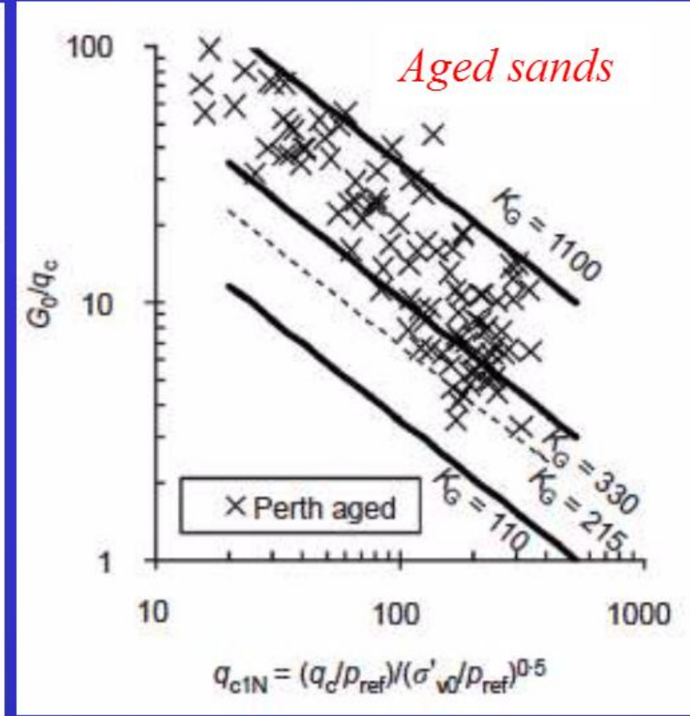
Normalized Rigidity Index, K_G

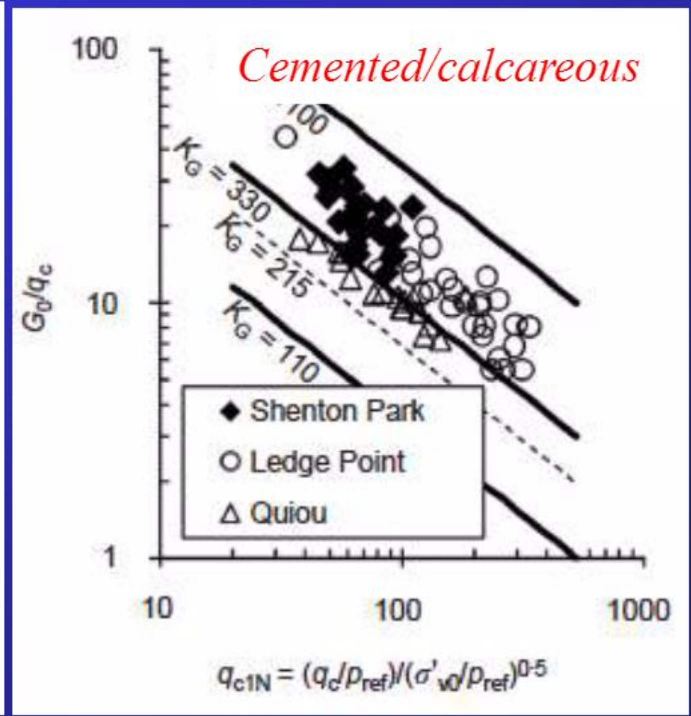
Normalized Rigidity Index, K_G *(Schneider & Moss, 2011)*

$$K_G = (G_o/q_t)(Q_{tn})^{0.7}$$

- If $K_G > 330$ aged and/or cemented
- If $K_G < 330$ young & uncemented







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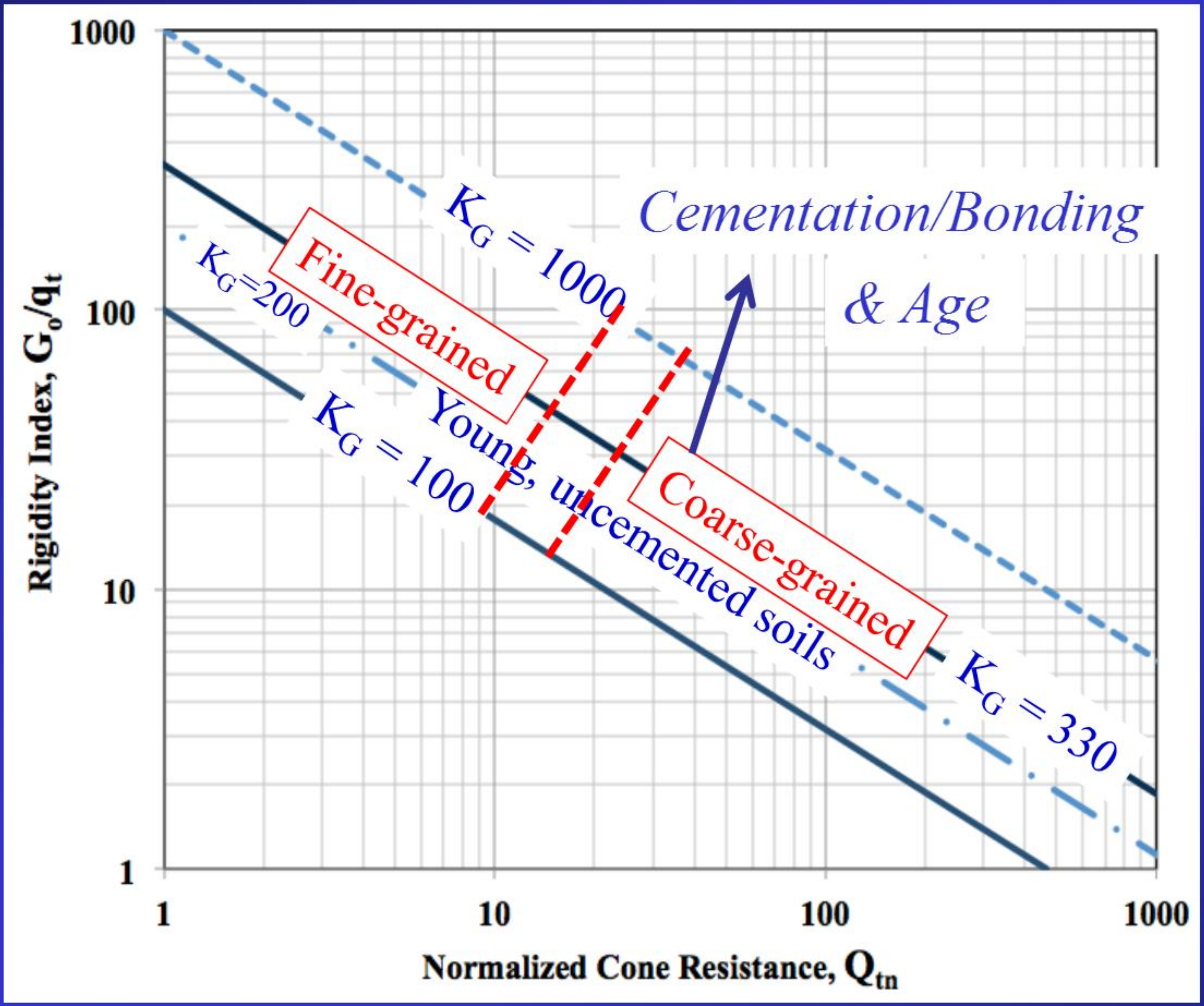


Generalized CPT-Vs relationship to estimate microstructure in soil

Soils with significant microstructure $K_G > 330$

Cyclic Resistance Ratio for AGED soils

Andrus et al, 2009 + Hayati & Andrus, 2009

Based on MEVR *(Measure to Estimated V_s Ratio)*

$$MEVR = V_{s(measured)} / V_{s(estimated\ from\ CPT)}$$

–If MEVR > 1.0 aged and/or cemented

–If MEVR = 1.0 very young (~23 yrs)

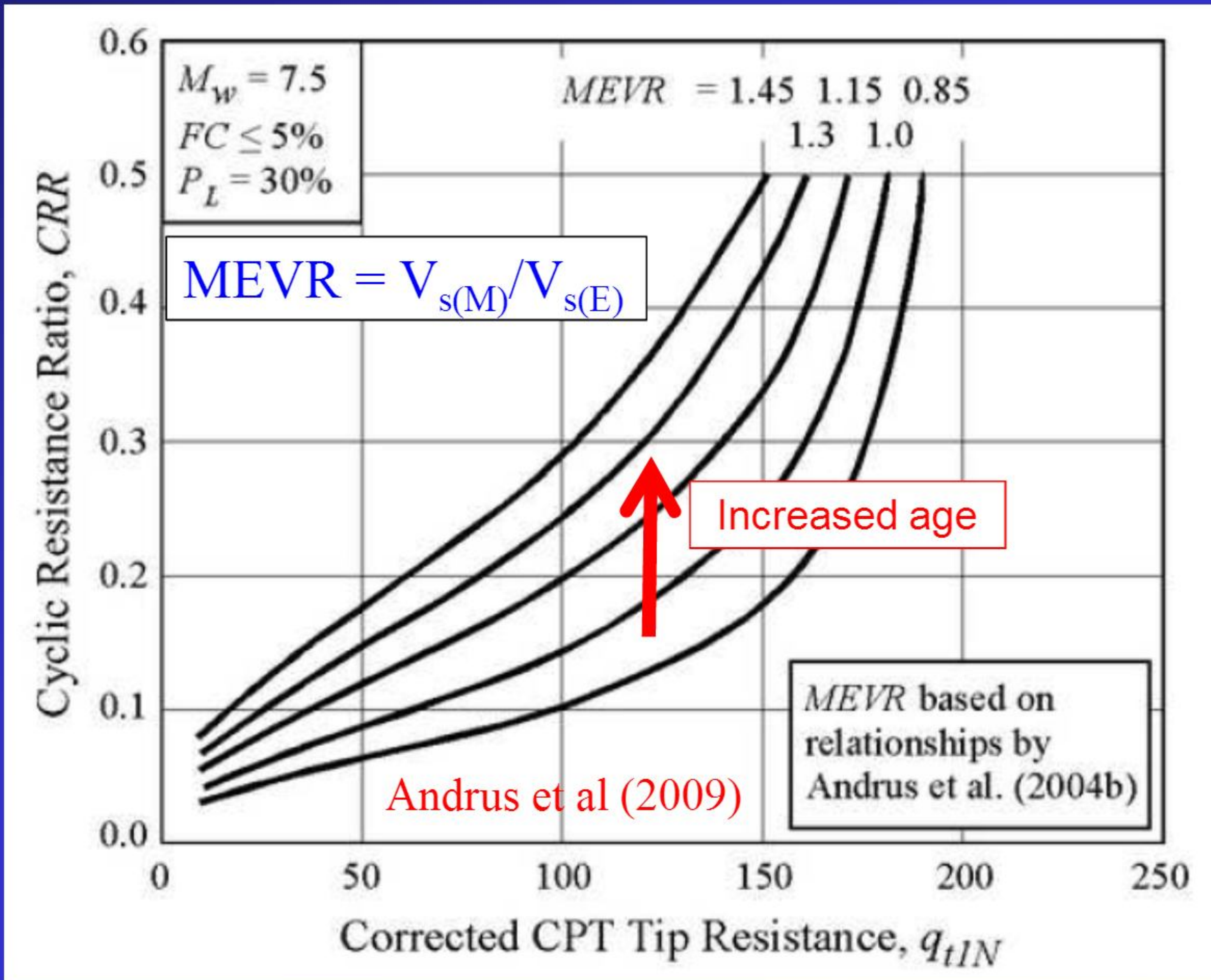
$$CRR_{Deposit} = CRR\ K_{DR}$$

$$K_{DR} = 1.08\ MEVR – 0.08$$

Difference between *'geologic-age'* and *'behavior-age'*

e.g. past soil liquefaction events can re-set age clock?

Age correction based on V_s (MEVR)



Age correction based on measured V_s

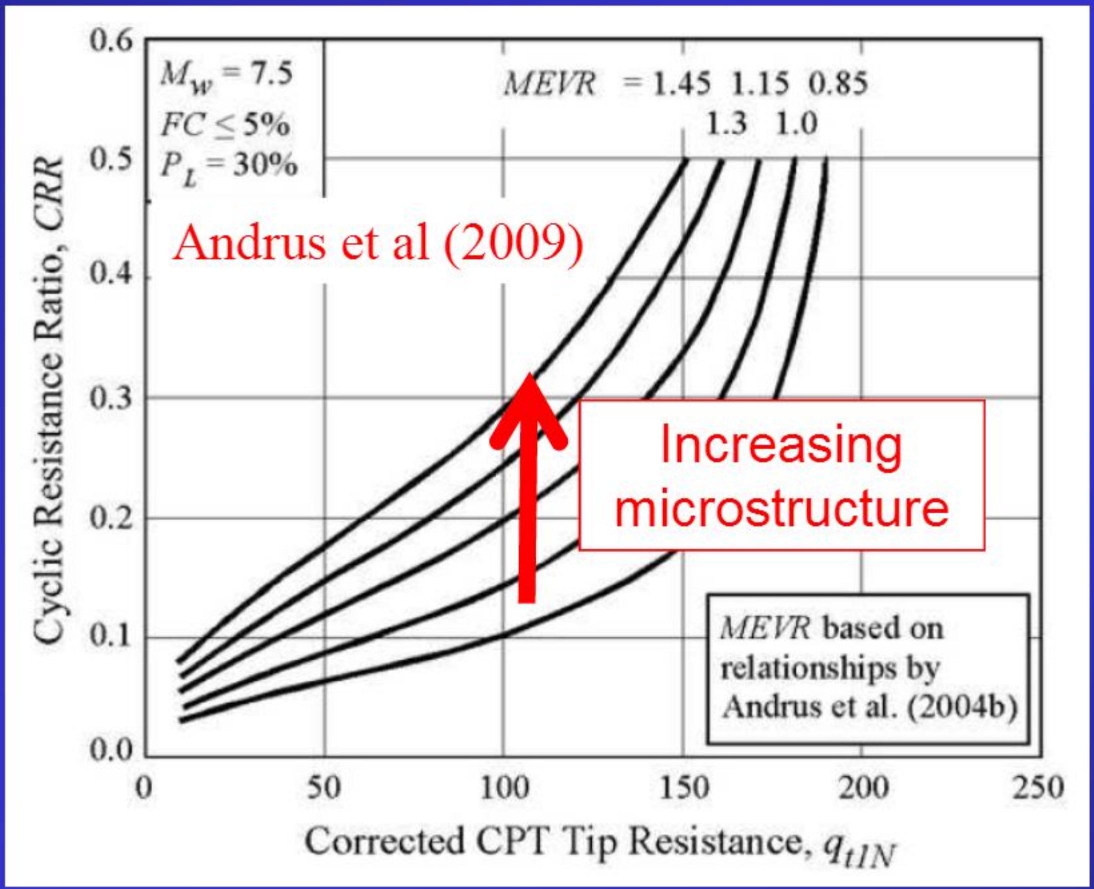
Estimate $V_{s(E)}$ from CPT

SCPT gives both CPT and V_s

MEVR & Norm. Rigidity Index (K_G)

Similarity between MEVR and K_G

$$MEK_G = K_{G(Measured)} / K_{G(Estimated)}$$



For liquefaction cases:

$K_{G(E)} \sim 200$

$$MEK_G = K_{G(m)}/200$$

$$MEK_G = (MEVR)^2$$

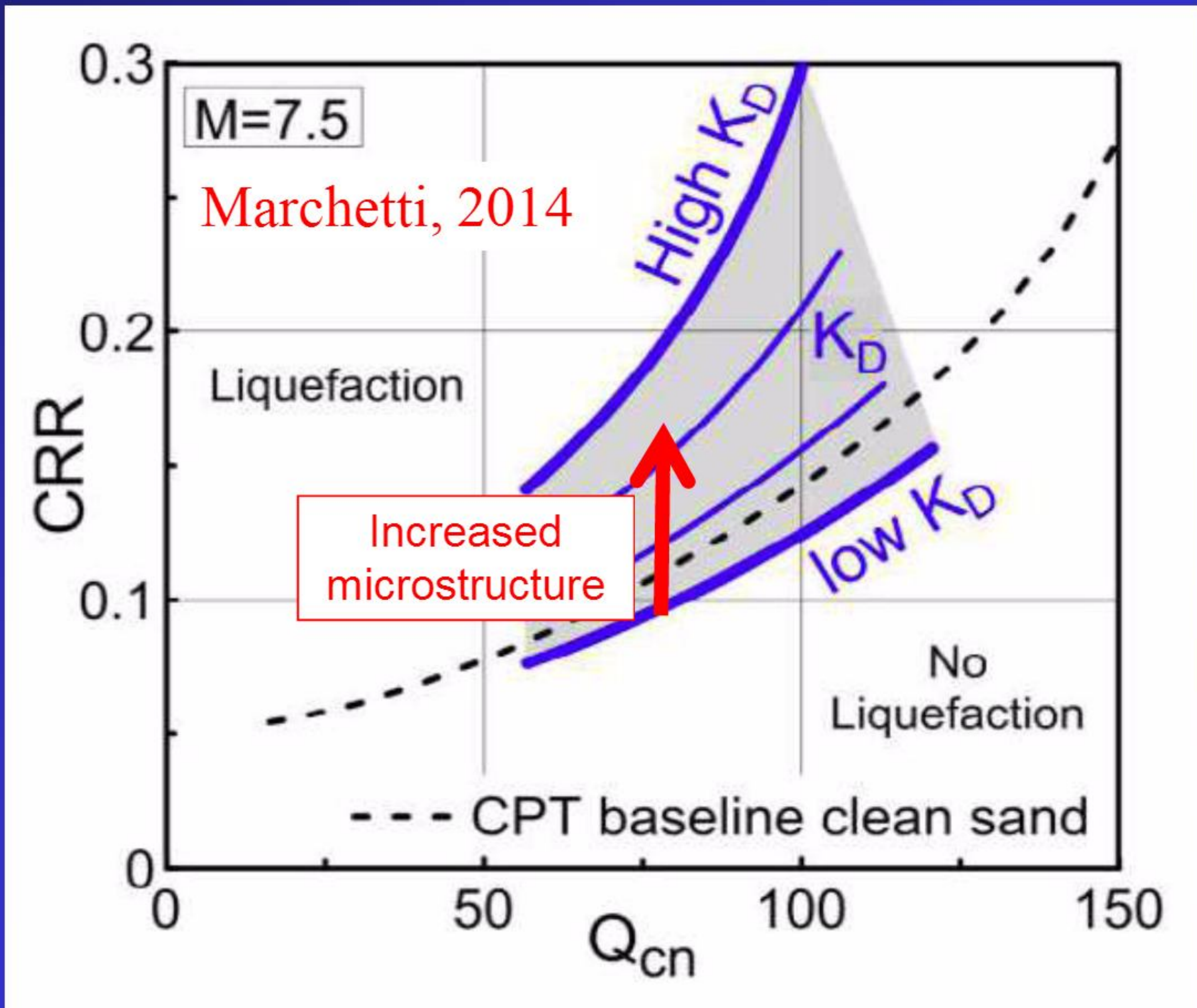
If CPT and V_{s1} give different interpretation – which one is correct?

Main factors are either aging or cementation

- V_{s1} appears to be correct for *aging* (Andrus et al 2009)
- Not so clear for soils with *light cementation*
  - if loading (e.g. CSR) exceeds threshold strain (estimated from G_o) – *cementation* may be destroyed and large strain response (Q_{tn}) may control (Schneider & Moss, 2011)

More research needed

Combined CPT and DMT



DMT K_D used to 'correct' for microstructure

K_D more sensitive to age, cementation, stress & strain history than Q_{tn}

Inadequate Site Investigation

Can arise from:

- Lack of awareness of importance of ground
- Too much focus on finance
- Insufficient time
- Lack of local geological experience

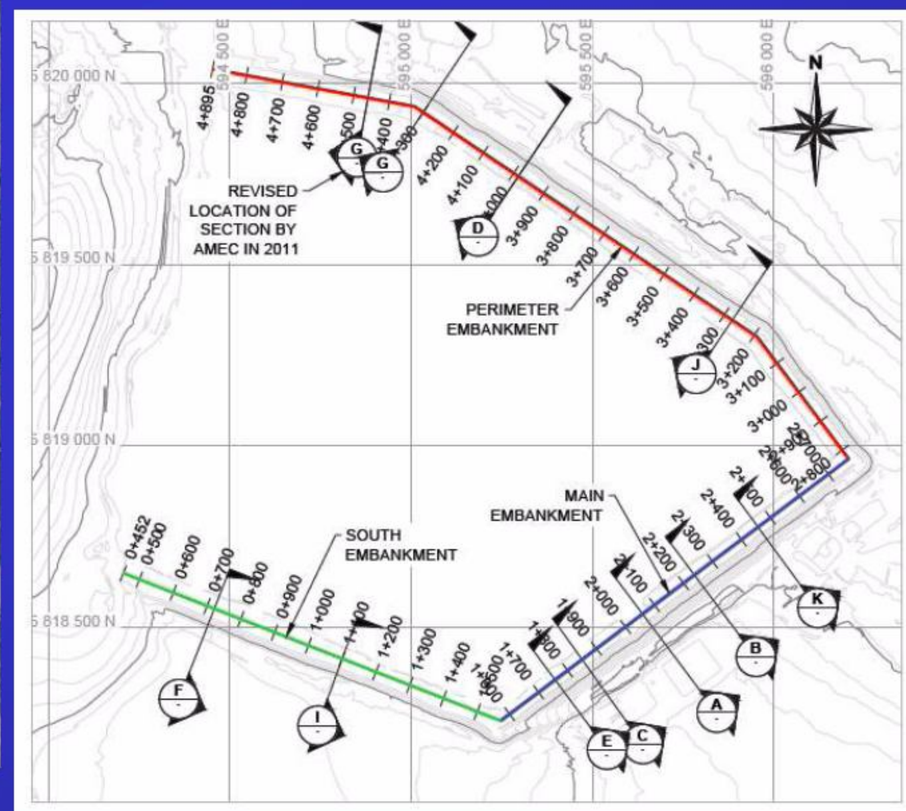
Results

- – Delays & failures
- – Increased costs

  Often far in excess of cost of site investigation

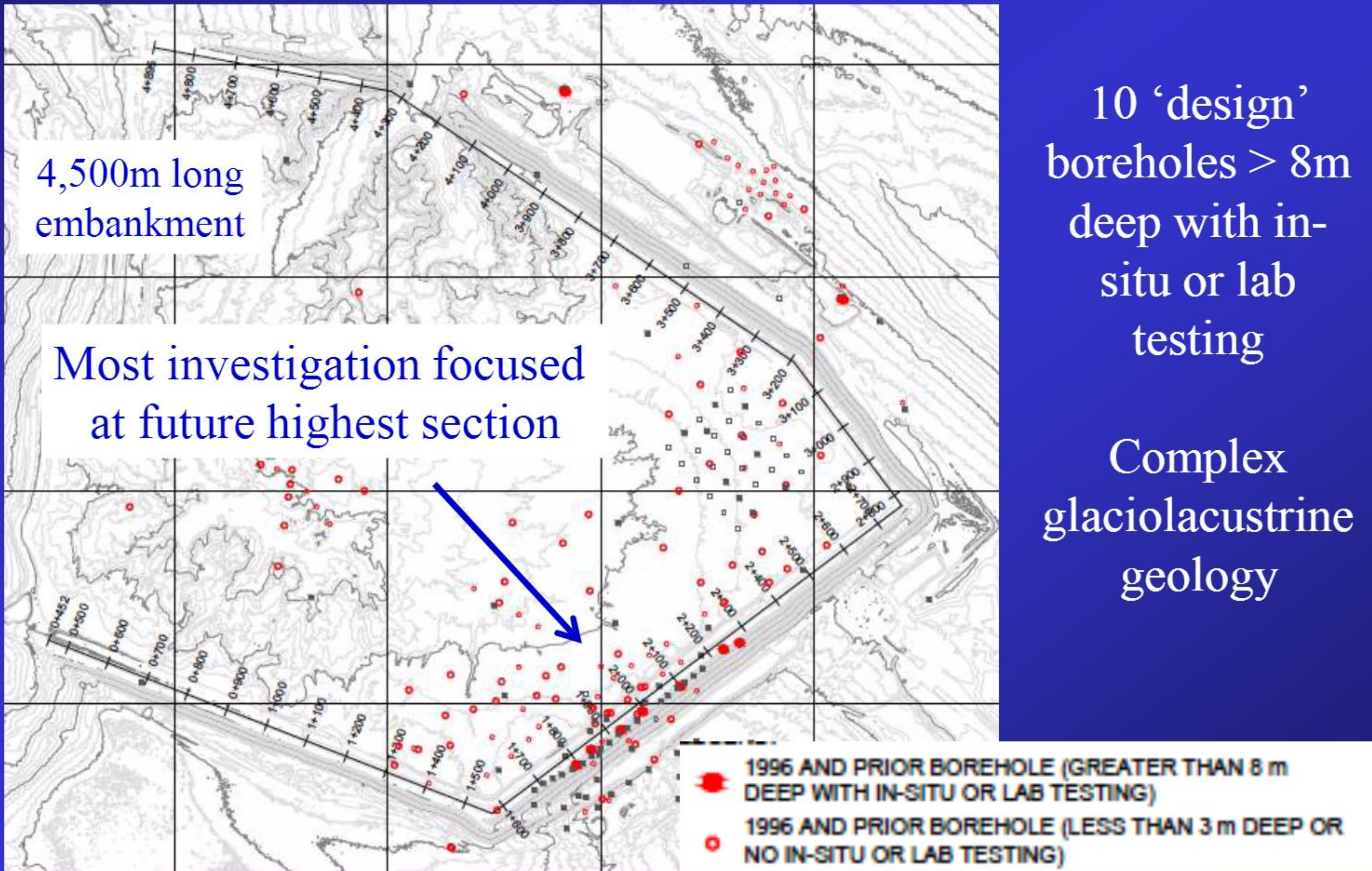
Tailings dam - failure

- Started 1996
- 4,500m long embankment
- Up to 55m high



https://www.mountpolleyreviewpanel.ca/final-report

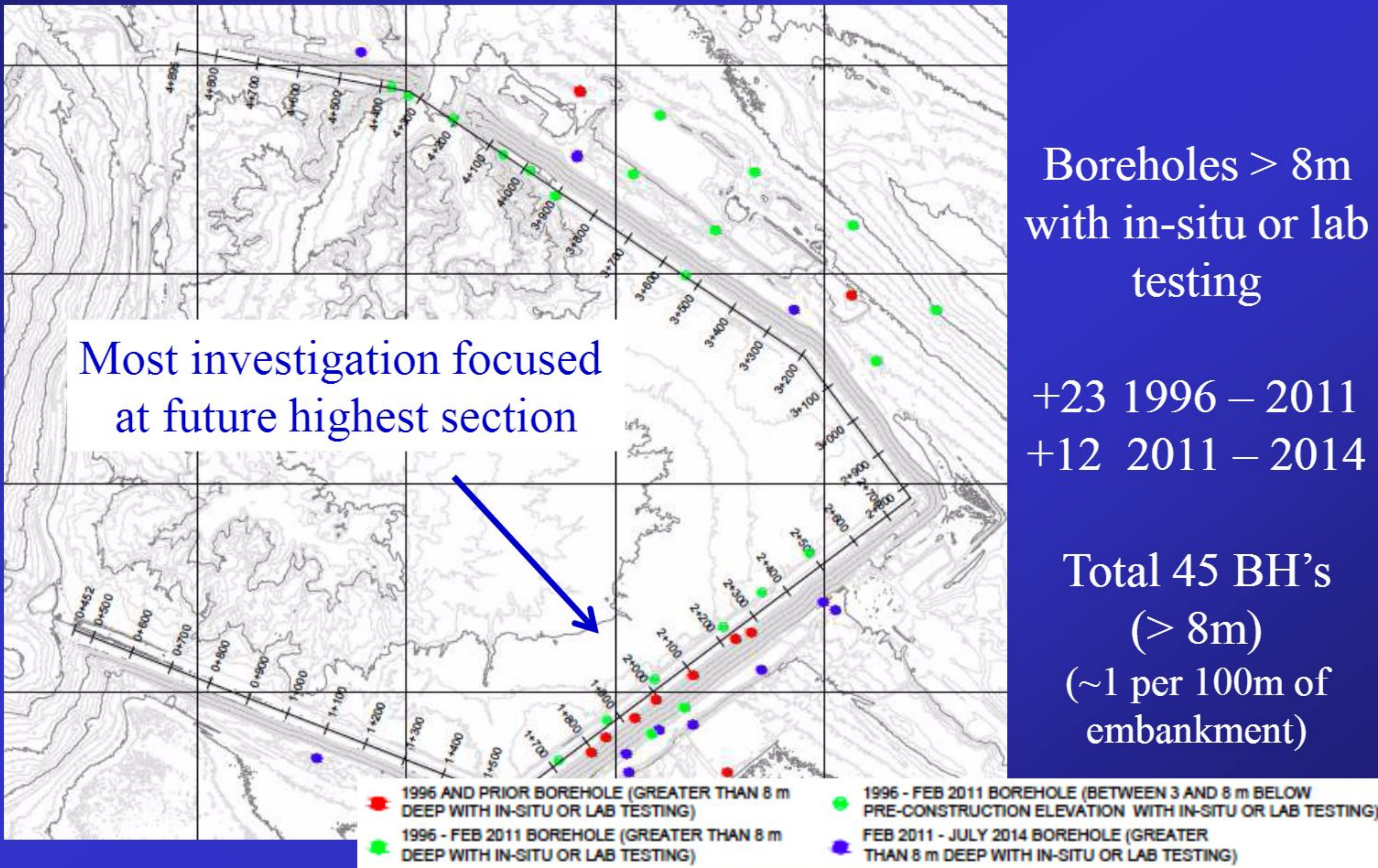
Early Design (pre-1996) SI



10 'design' boreholes > 8m deep with in-situ or lab testing

Complex glaciolacustrine geology

Post-1996 SI



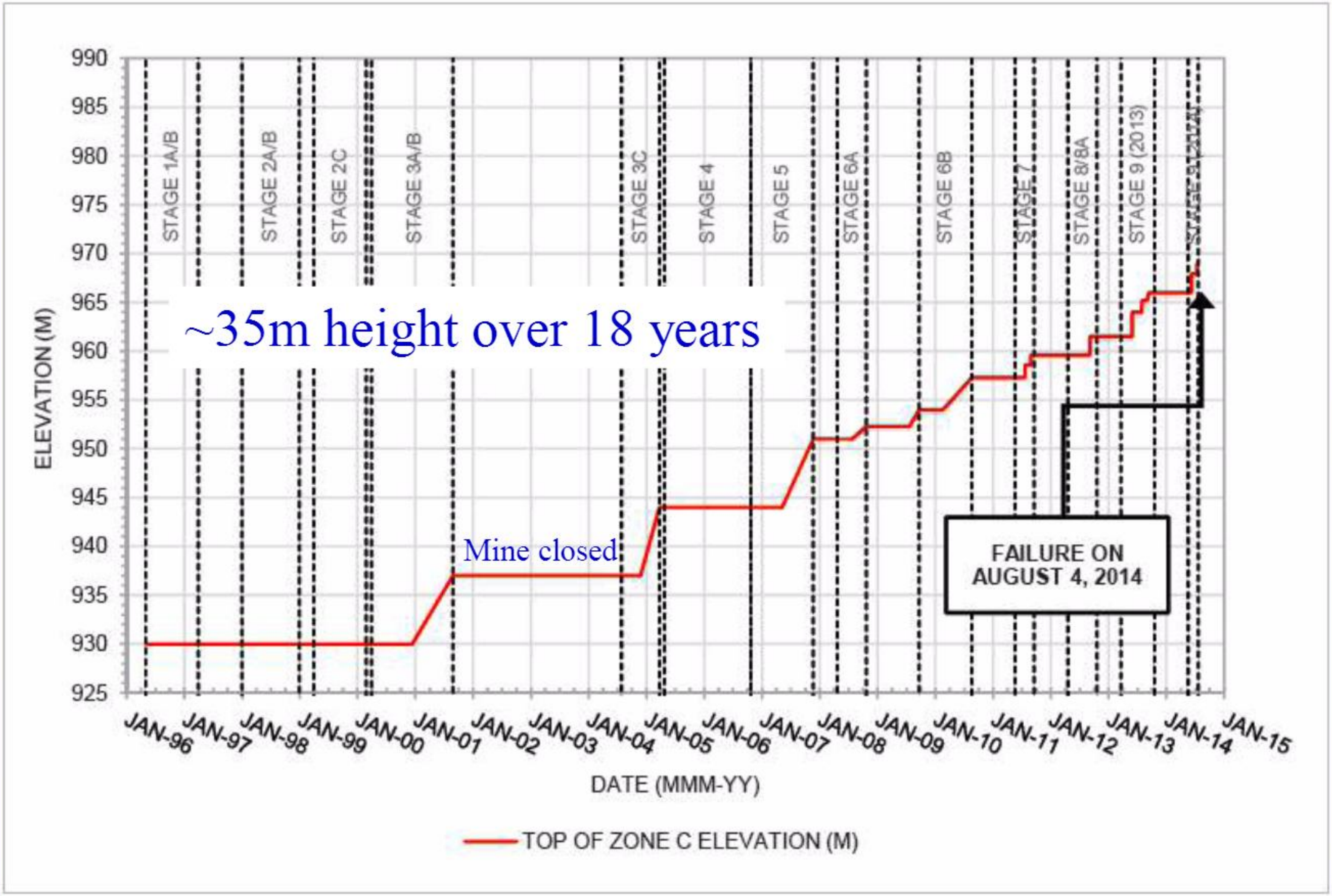
Most investigation focused at future highest section

Boreholes > 8m with in-situ or lab testing

+23 1996 – 2011
+12 2011 – 2014

Total 45 BH's (> 8m)
(~1 per 100m of embankment)

Construction history



Aug. 2014 Failure

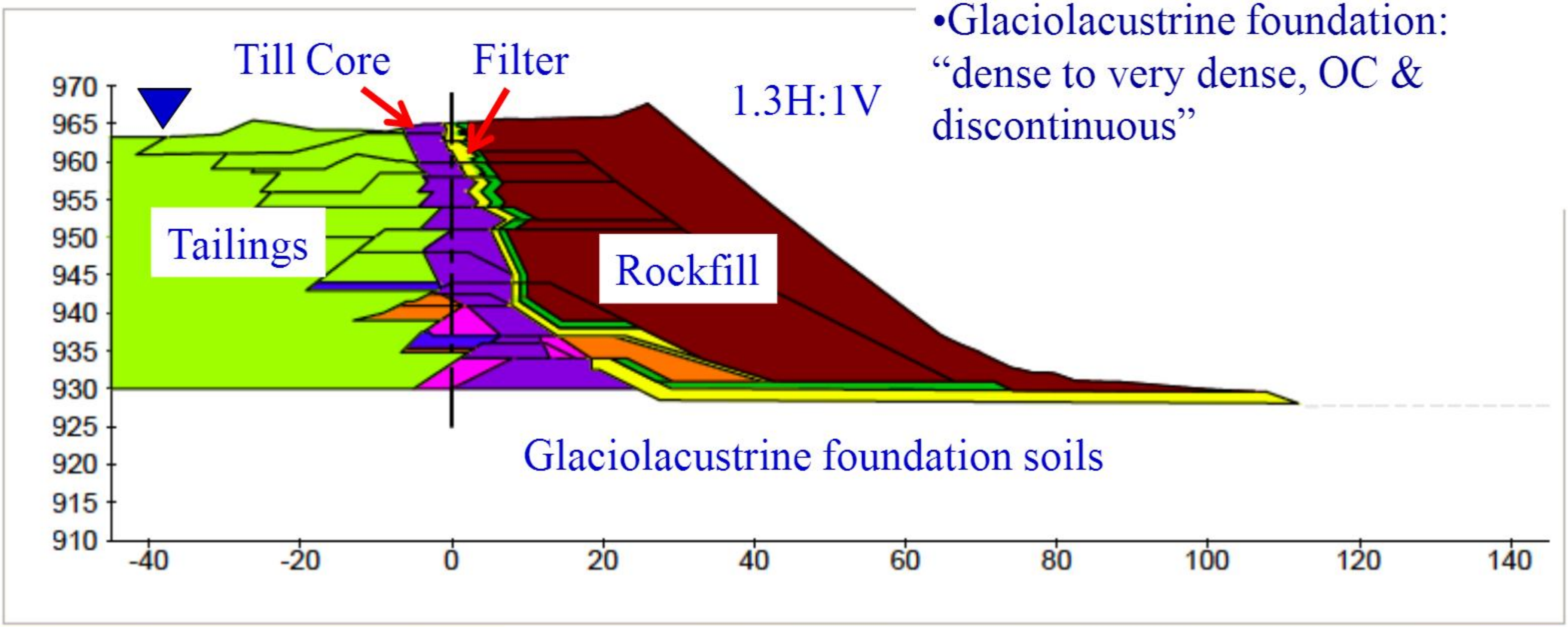
Failure was rapid and without warning

Perimeter Dam Section

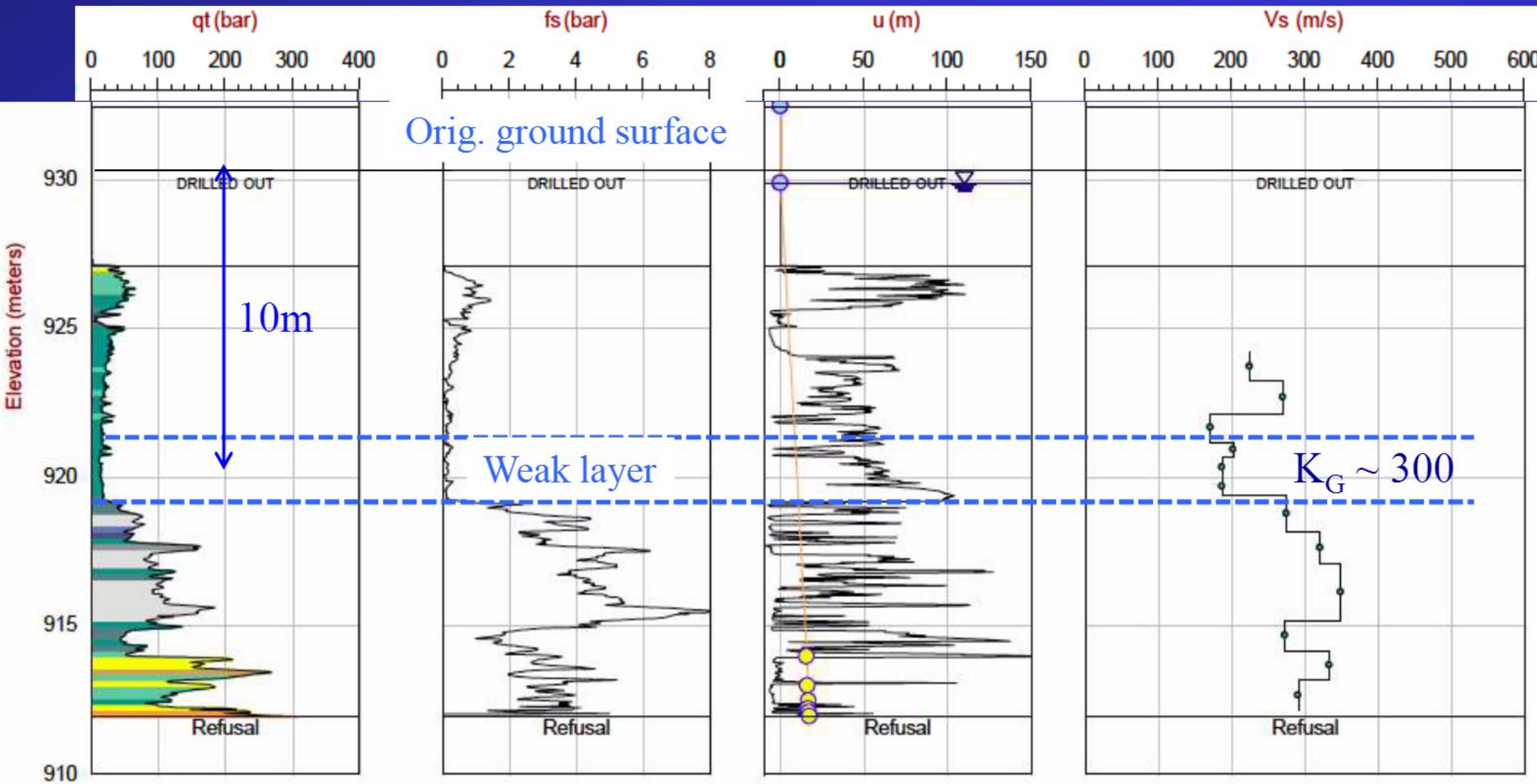
'Center-line' construction

Design assumptions:

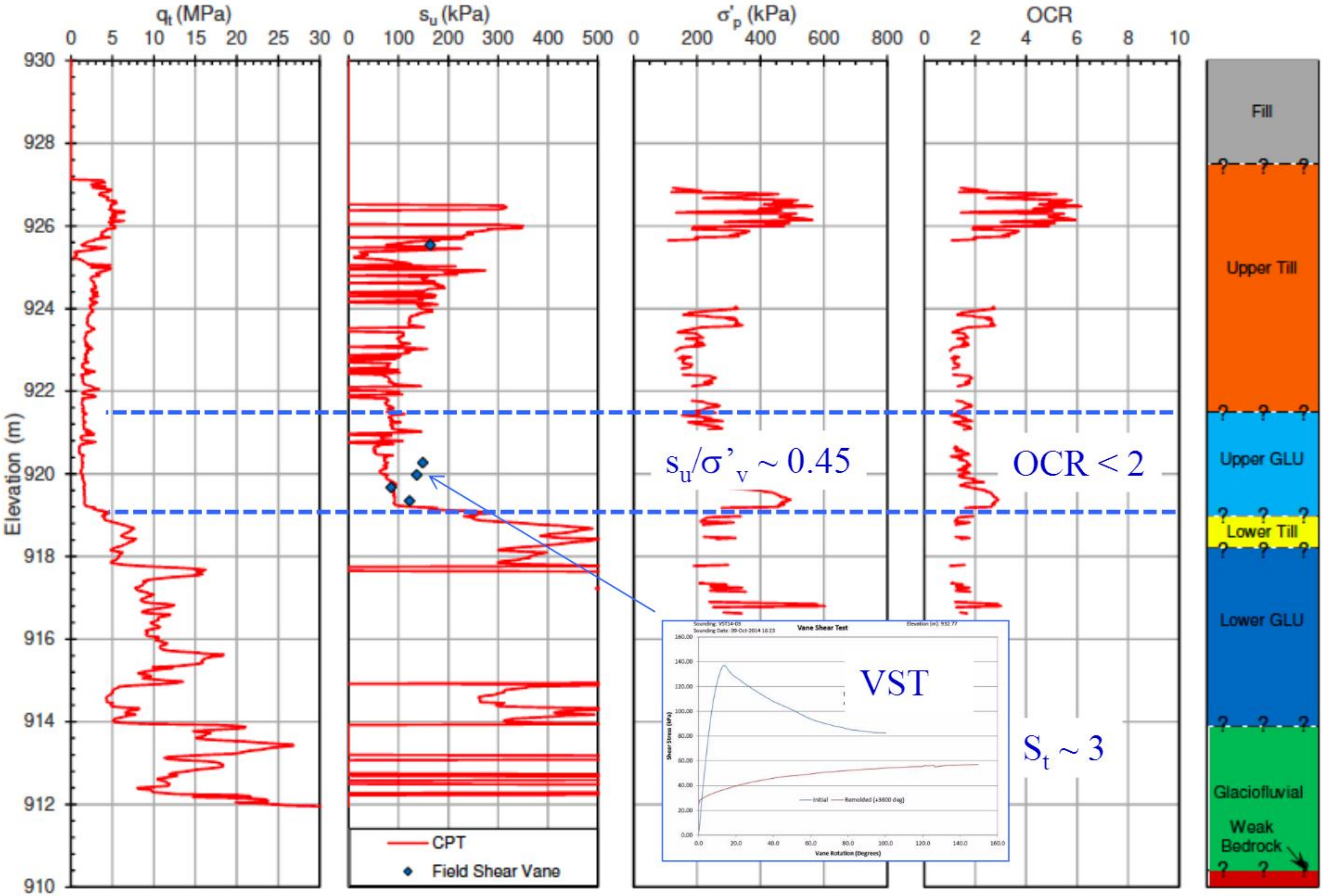
- Effective stress analyses
- Drained soil parameters
- Observational Method
- Glaciolacustrine foundation: "dense to very dense, OC & discontinuous"



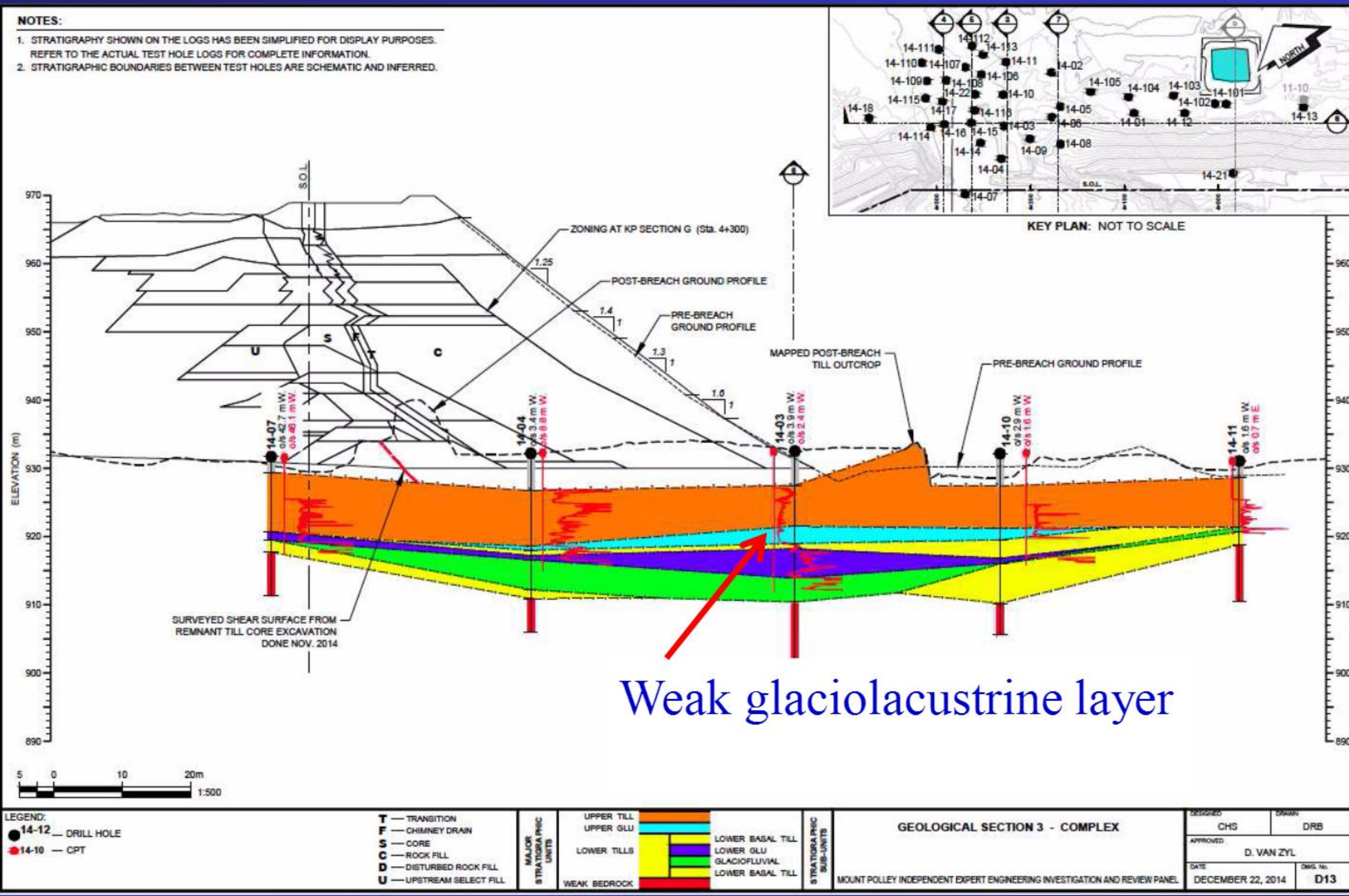
SCPTu profile in breach area



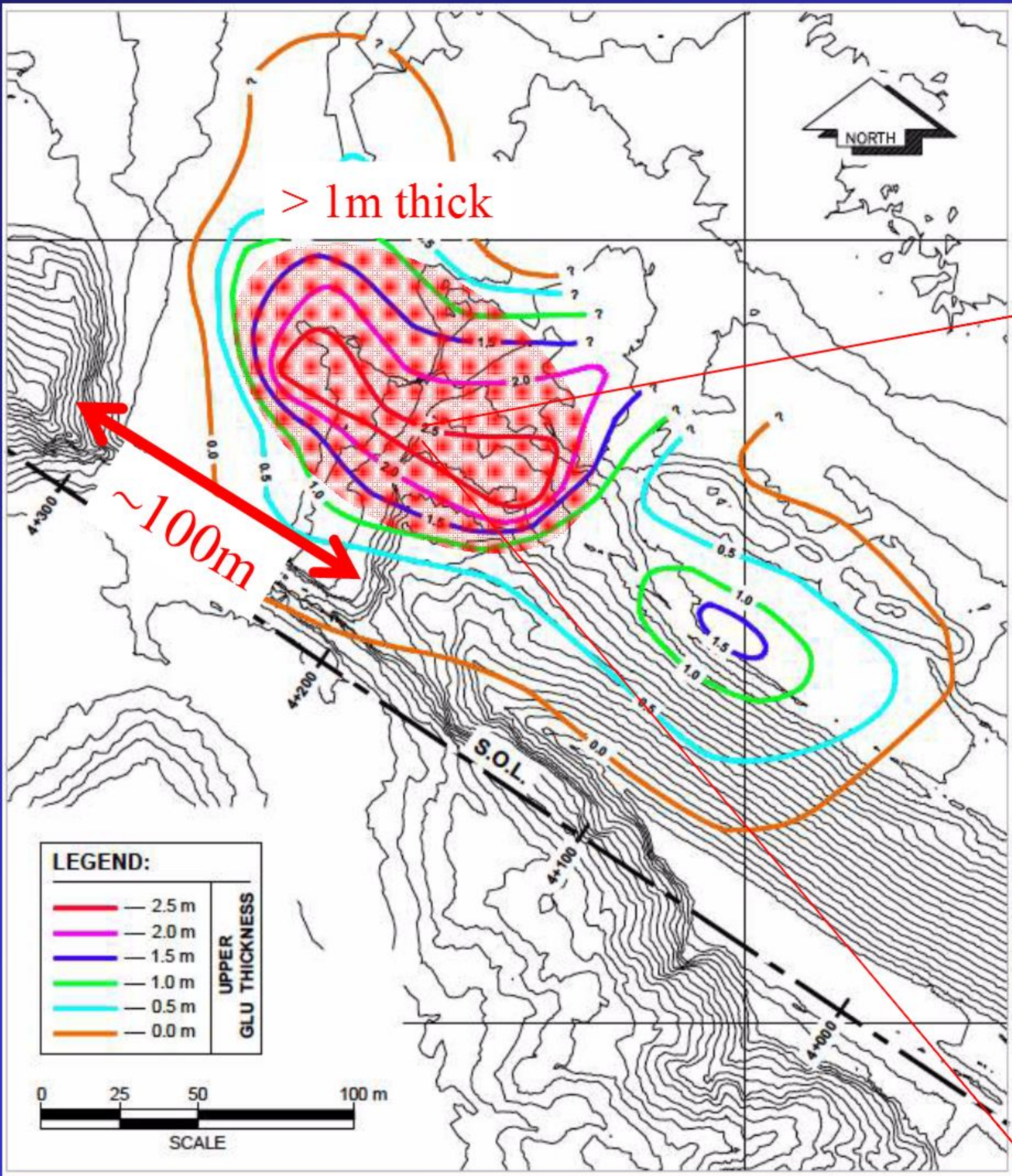
SCPTu in breach area

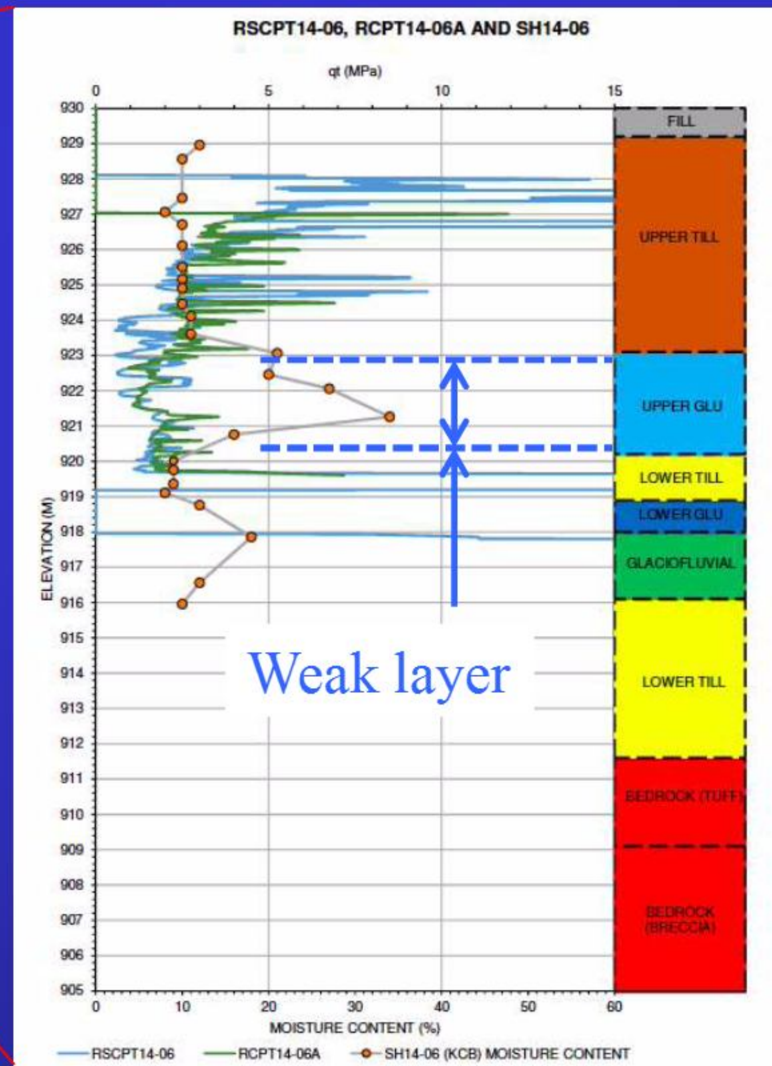


Geologic Section in breach

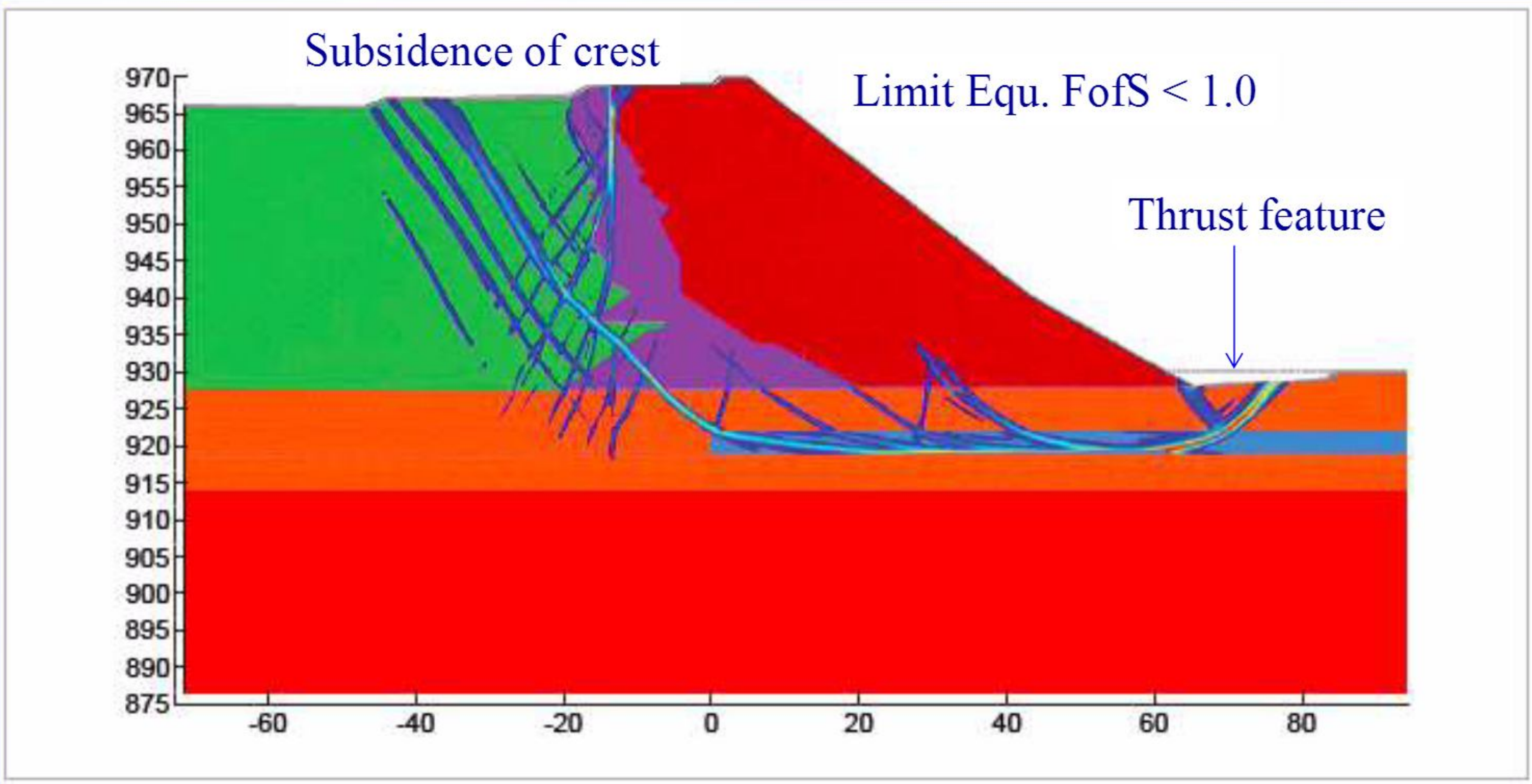


Thickness of weak glaciolacustrine layer





Failure analysis

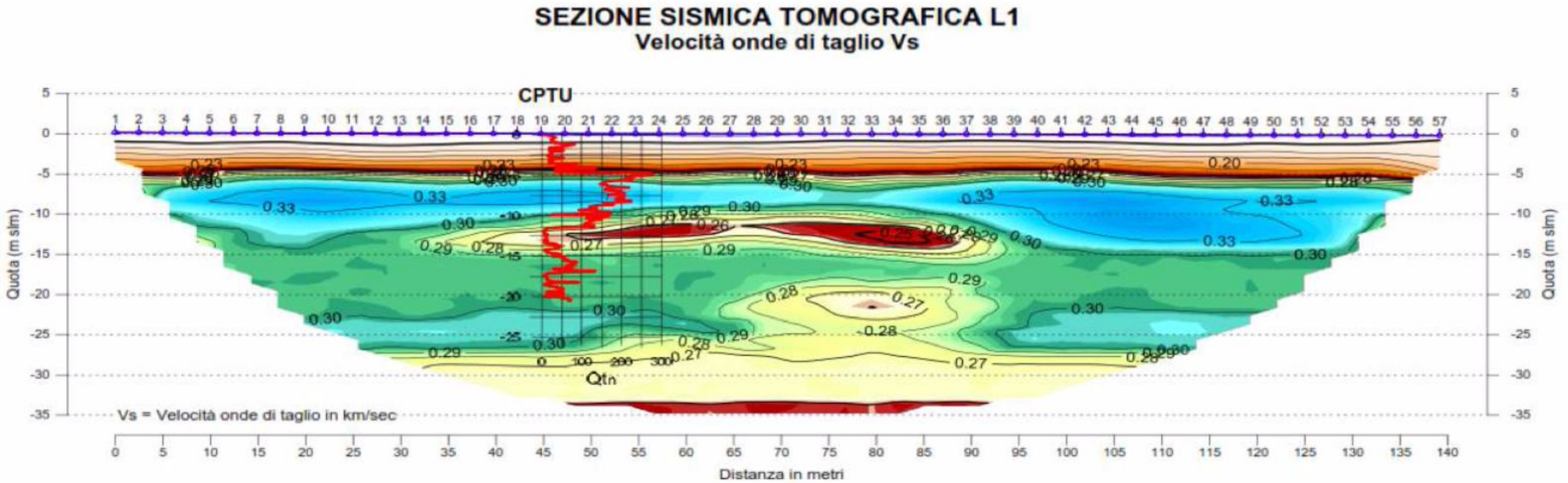


Plaxis analysis using undrained strength parameters in weak layer
Supported by limit equilibrium analysis

Failure - Report

- Weaker glaciolacustrine layer went undected
  - SI's not tailored to degree of geologic complexity
- Nature of strength behavior not appreciated:
  - Ignored change in OCR with embankment load
  - Ignored undrained strength characteristics
  - Lack of control on water balance & mine planning (rock fill)
  - Observation Method misapplied
    - difficult to install instruments & incapable of detecting critical conditions

Seismic Tomography



Need to incorporate more geophysics into North American site investigation practice

Geotechnical Risk

Sum of:

- Hazards (What can go wrong?)
  - including geologic complexity
- Probability of occurrence (How likely is it?)
- Consequences (What are the consequences?)
- Experience of engineer (What is local experience?)

What level of sophistication is appropriate for site investigation & analyses?

GOOD	**Precedent & local experience**	*POOR*
SIMPLE	**Design objectives**	*COMPLEX*
LOW	**Level of geotechnical risk**	*HIGH*
LOW	**Potential for cost savings**	*HIGH*

Traditional Methods → ***Simplified***

Advanced Methods → ***Complex***

Summary

- Level of sophistication in site investigation should be defined by overall risk
- Important to identify critical layers/zones and mechanisms
- Important to identify any '*unusual*' soil behavior characteristics

Questions?