Cambridge Self-Bore Pressuremeter

Session 6 – Using pressuremeter parameters in design

Applications to Engineering

- Generally speaking, the Pressuremeter should be used for High(er) Risk; High(er) Consequence projects where modelling is important

- Input into numerical models are superior to most methods in that they are consistent and reliable

- Damage or poor tests (unreliable data) is easily detected

Applications to Engineering

- Inputs are easily obtained for:
  - Linear Elastic models
  - Non-linear elastic models
  - Linear Elastic – Perfectly Plastic models
  - Non-Linear Elastic – Perfectly Plastic models
  - Permeability for transient analyses

Applications to Engineering

- Allows for direct determination of the subgrade reaction, k_s for lateral pile (p-y curve) determination
- Nothing compares for determining lateral stresses at depth in wall and excavation design
- Coupled with non-linear curve development, lateral deformations are well modelled
- Also the unload-reload modulus is superior for modelling ground response due to tunnelling

Understanding the Data

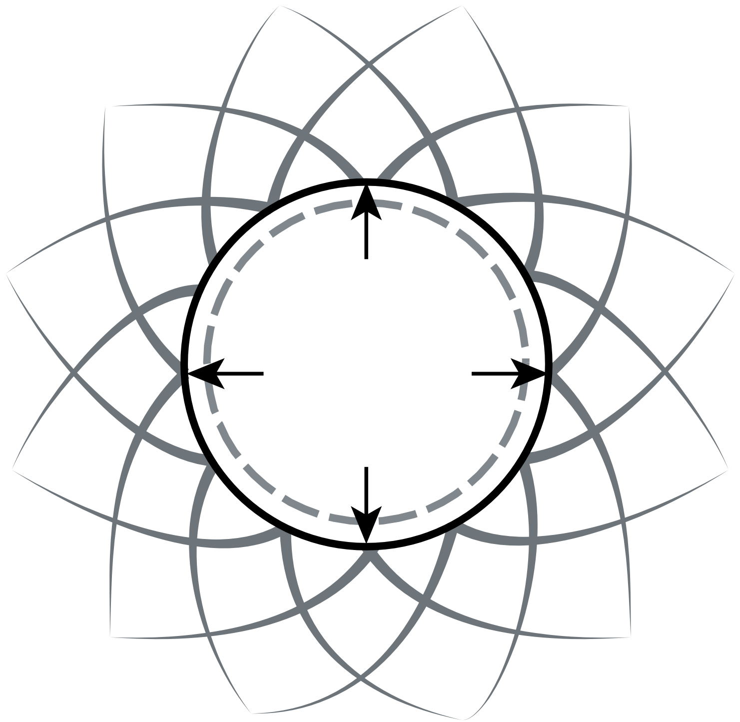
Multiple methods should be employed to provide an average strength with knowledge of the above to help complete the picture:

- Strengths will not be the same as the SVT or the DSS
- But strengths are not uniform throughout a site and therefore the information should be used judiciously
- They should be considered another data point to help designers make better, more informed decisions

Understanding the Data

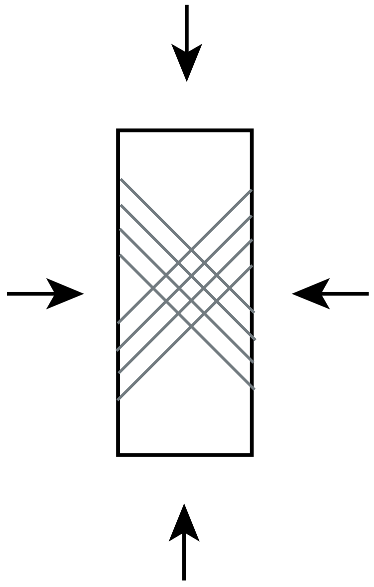
The parameters obtained are an ***average*** value as the volume of material tested is large relative to other tests

Pressuremeter Test



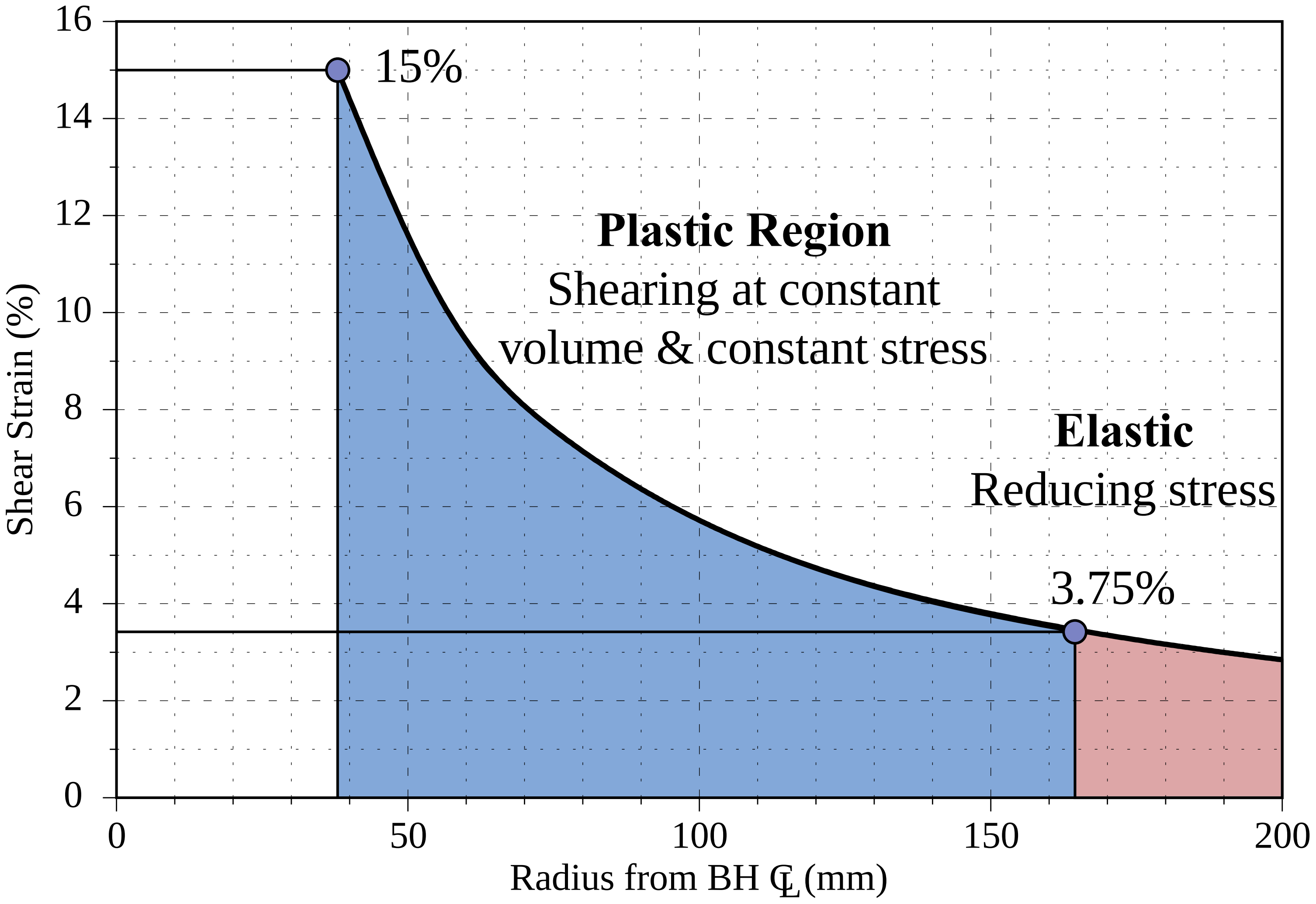
Shear stress decreases with distance from the cavity

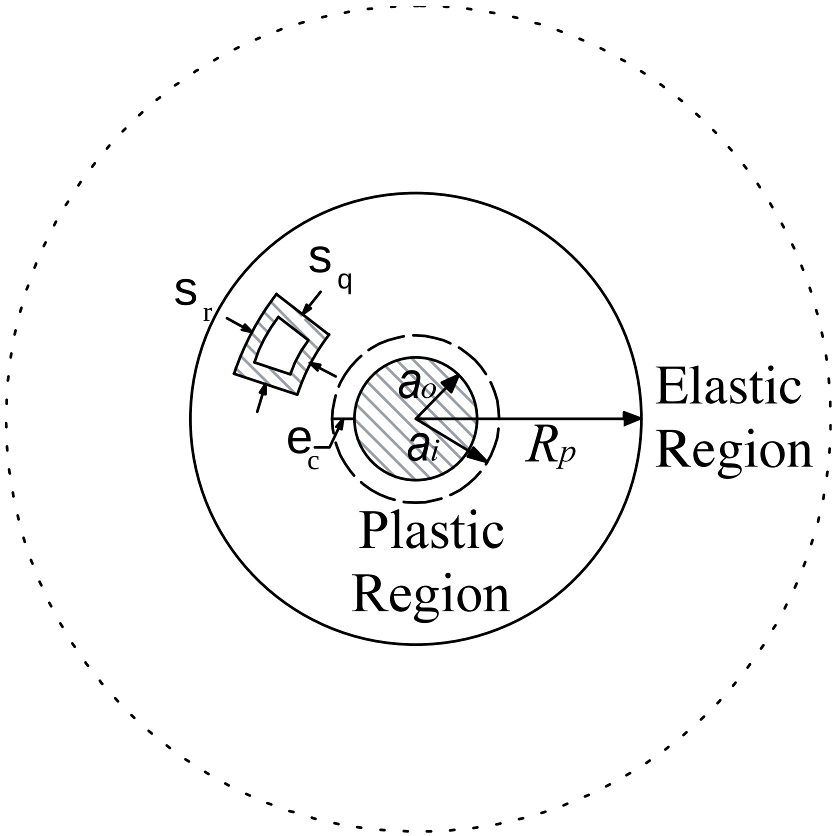
Triaxial Test



Shear stress is constant in the sample

Understanding the Data



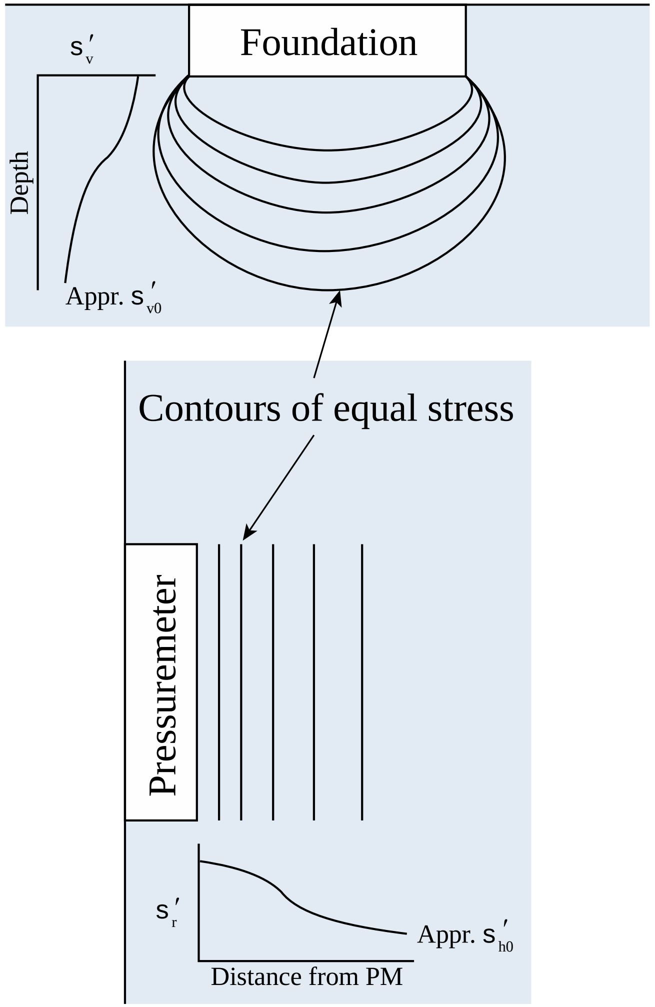


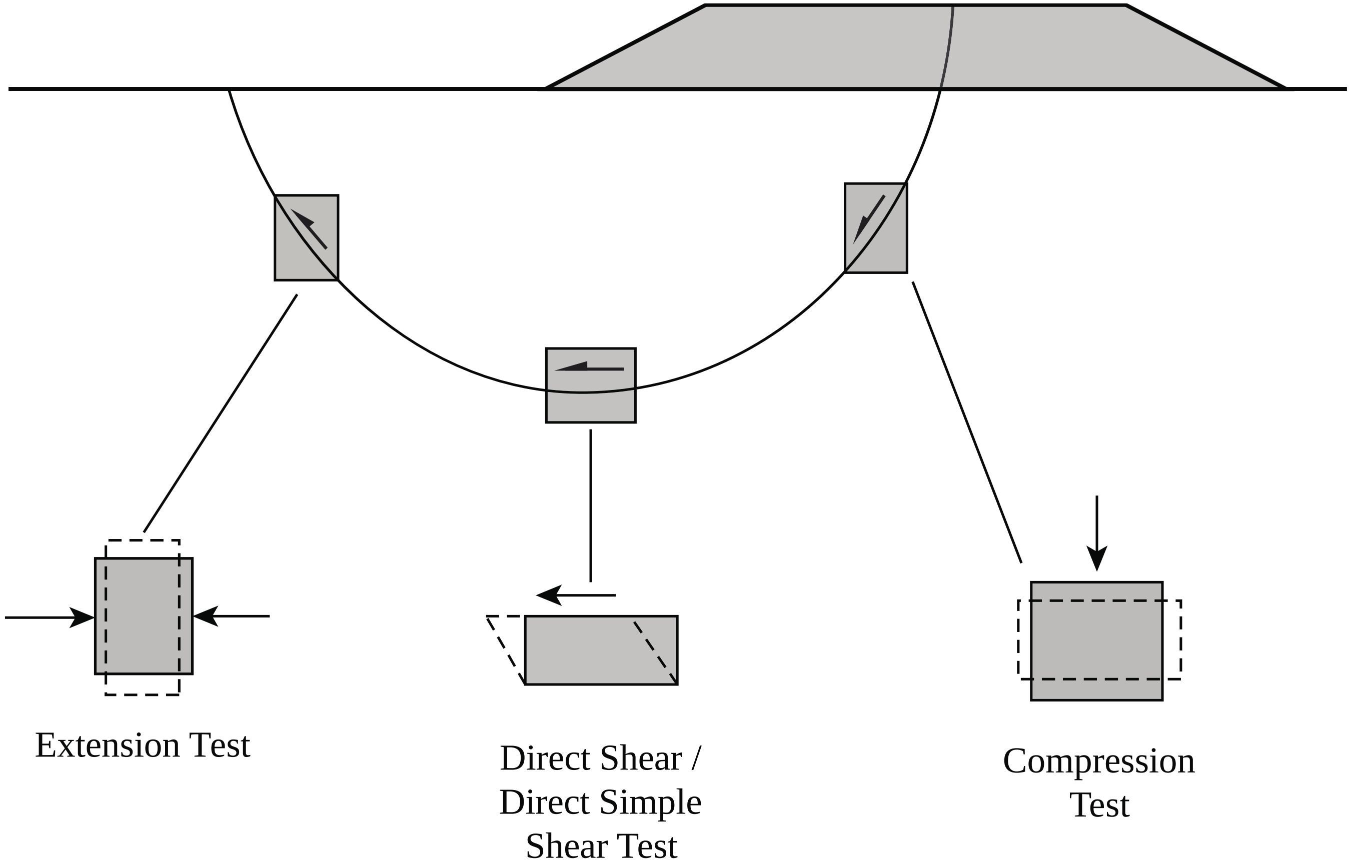
Shallow Foundation Design

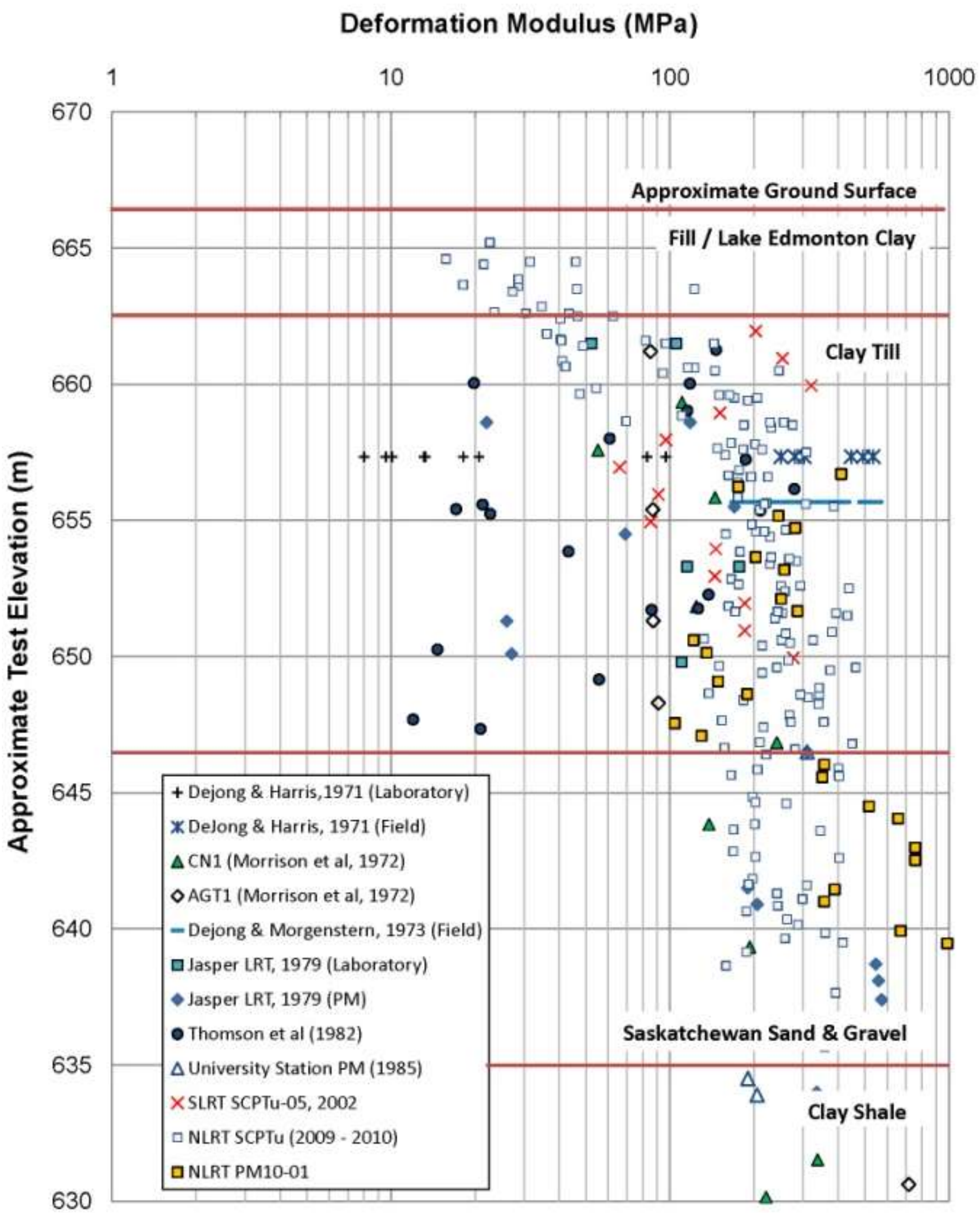
Originally, the bearing capacity of foundations was designed using empirical relationships related to the limit pressure

- These relationships were based on historical performance and not on calculated results
- Advanced methods of strength analysis have permitted the direct calculation of an average shear strength that is relatable to general bearing capacity failure as both are functions of cavity expansion
- Use of the modulus also allows for calculation of settlements for SLS design

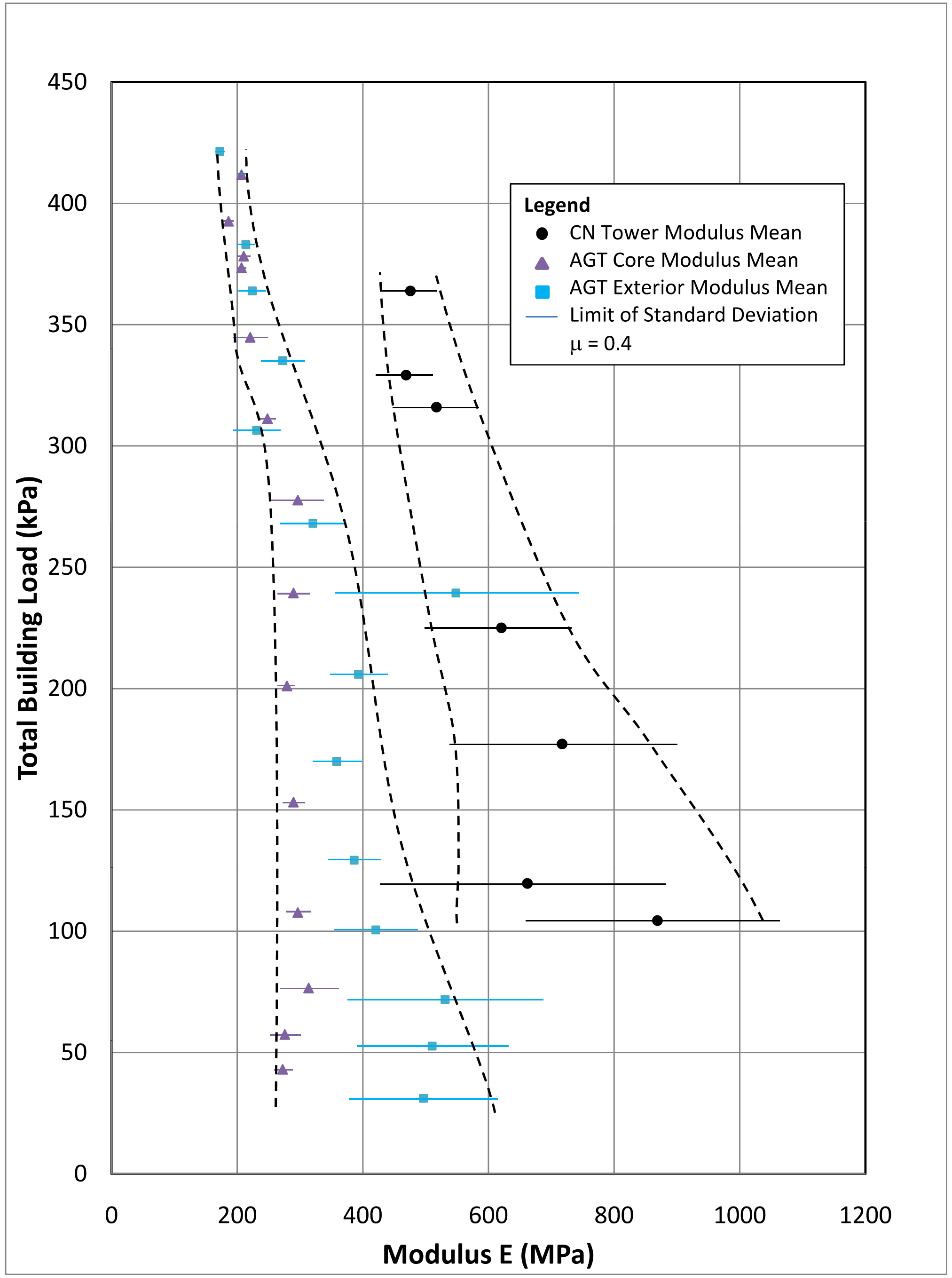
The Pressuremeter Test and BC





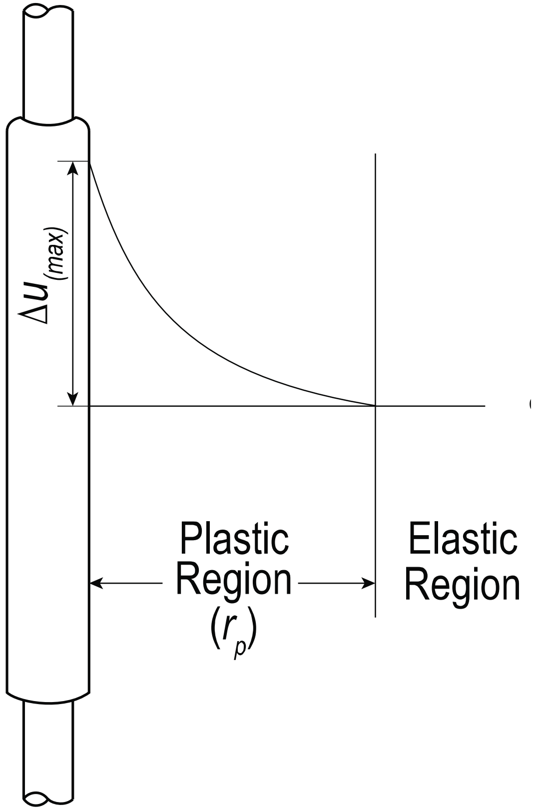


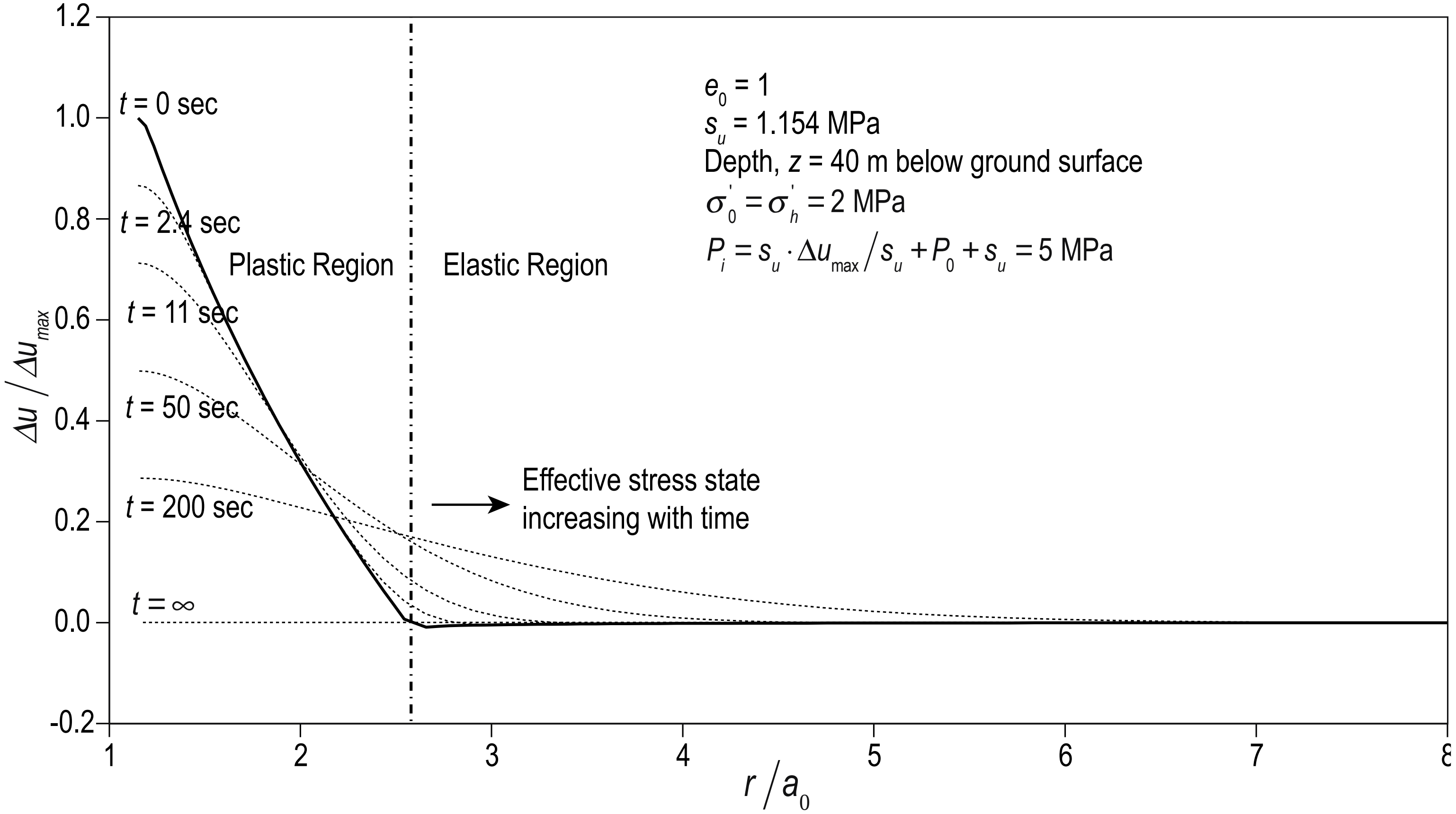
Deformation Modulus (MPa)
1
10
100
1000
670
665
660
655
650
645
640
635
630
Approximate Test Elevation (m)
Approximate Ground Surface
Fill / Lake Edmonton Clay
Clay Till
Saskatchewan Sand & Gravel
Clay Shale
Dejong & Harris,1971 (Laboratory)
DeJong & Harris, 1971 (Field)
CN1 (Morrison et al, 1972)
AGT1 (Morrison et al, 1972)
Dejong & Morgenstern, 1973 (Field)
Jasper LRT, 1979 (Laboratory)
Jasper LRT, 1979 (PM)
Thomson et al (1982)
University Station PM (1985)
SLRT SCPTu-05, 2002
NLRT SCPTu (2009 - 2010)
NLRT PM10-01



450
400
350
300
250
200
150
100
50
0
Total Building Load (kPa)
0
200
400
600
800
1000
1200
Modulus E (MPa)
Legend
CN Tower Modulus Mean
AGT Core Modulus Mean
AGT Exterior Modulus Mean
Limit of Standard Deviation
μ = 0.4

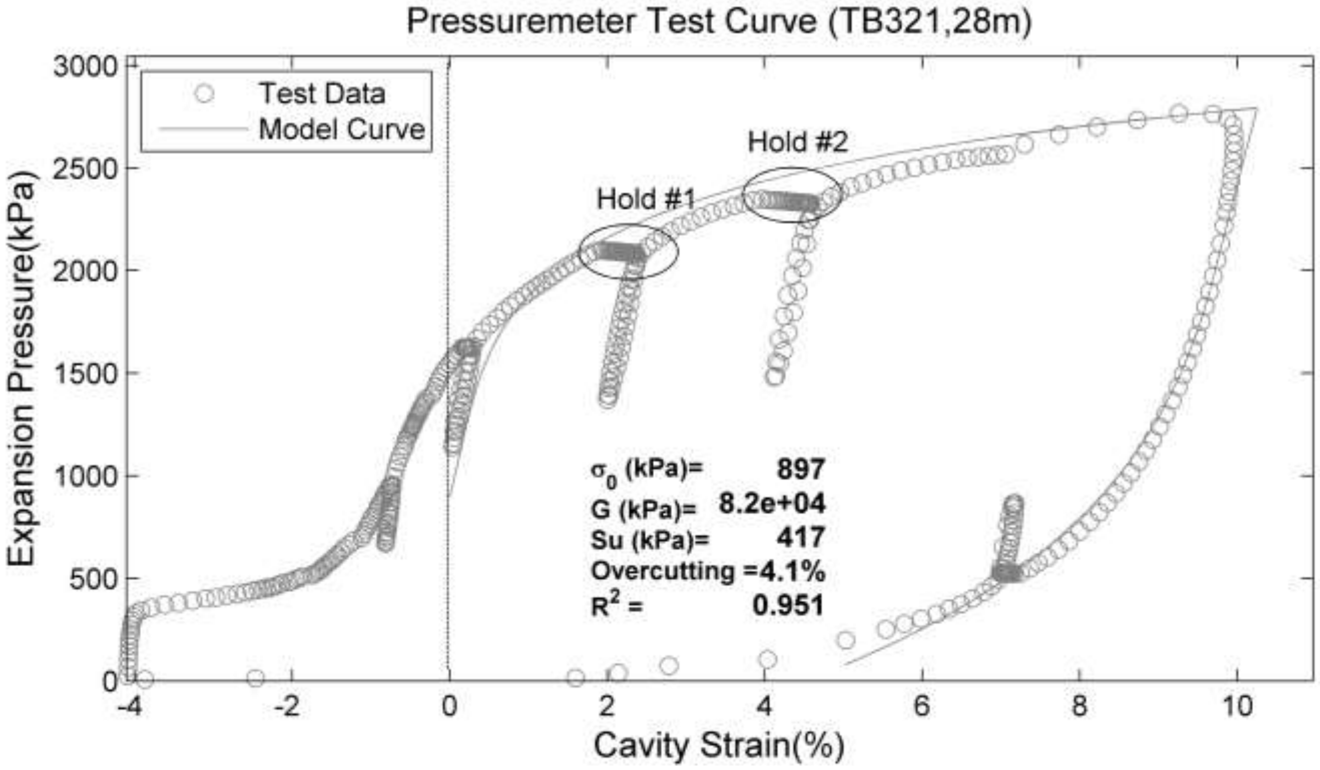
Settlements and Consolidation

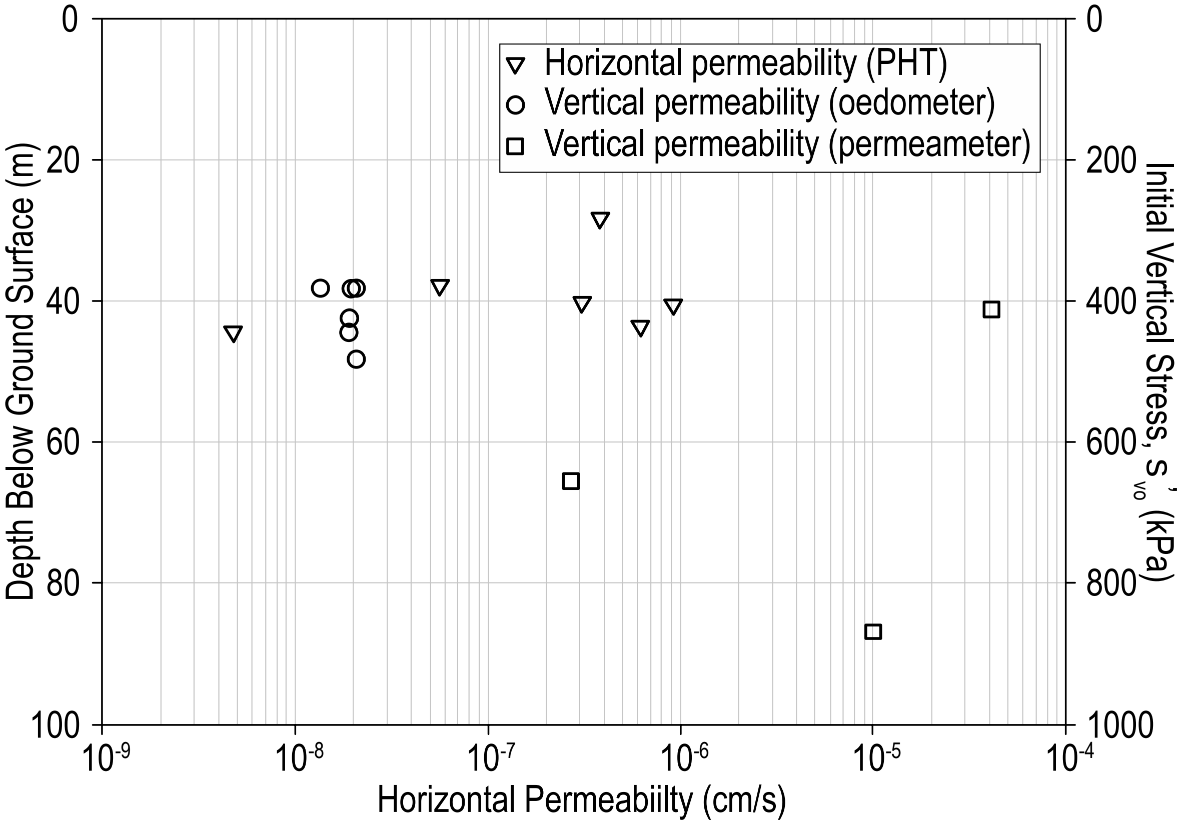




If excess pore-water pressure is recorded at the end of the loading or test is in a stiff clay, consolidation parameters (k_h, m_h) may be accurately determined

Settlements and Consolidation





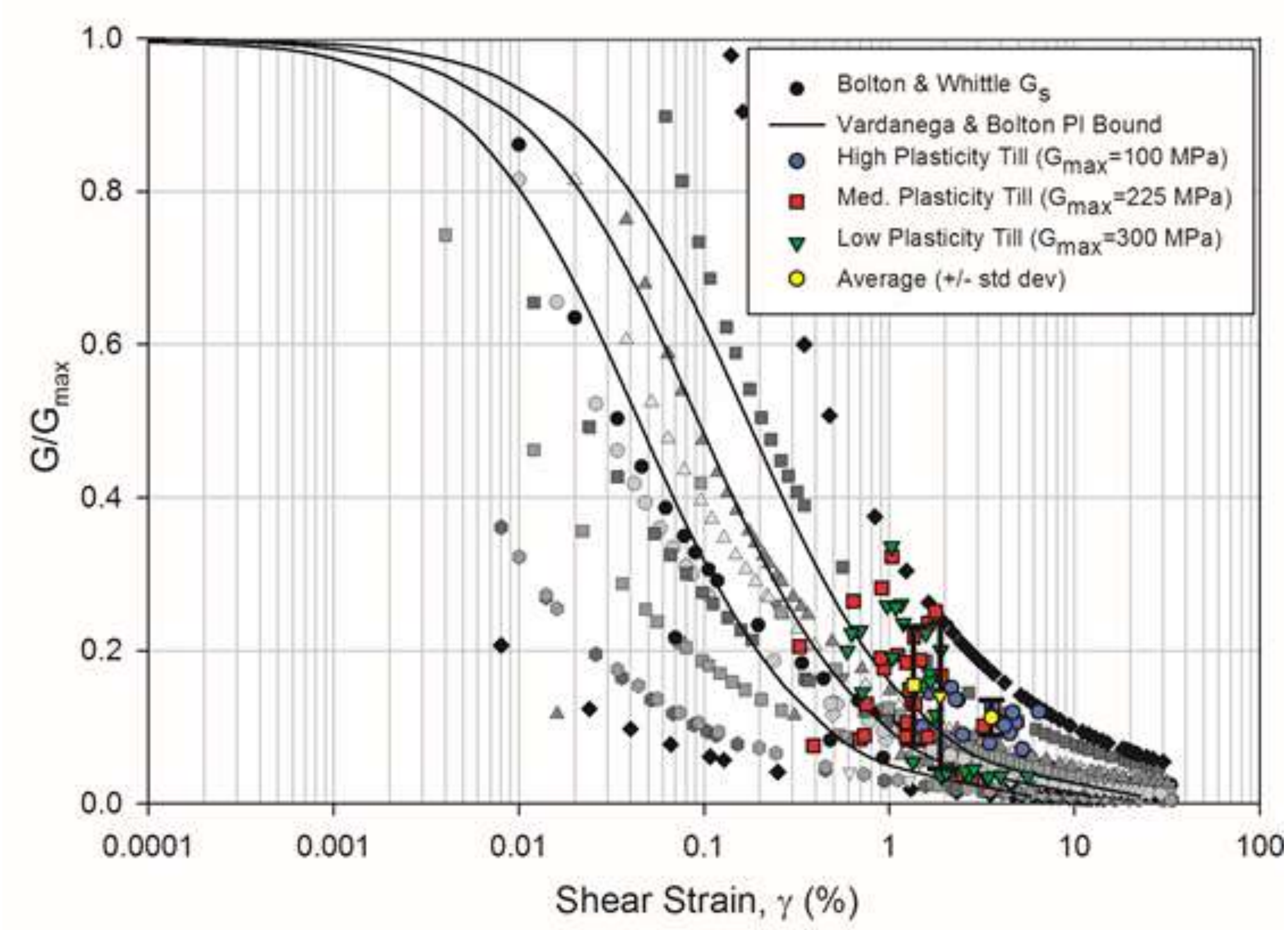
Comparison of the hold test data indicates that the PMT predictions are far more consistent than lab tests and agree well with oedometer

Shear Modulus and Stiffness

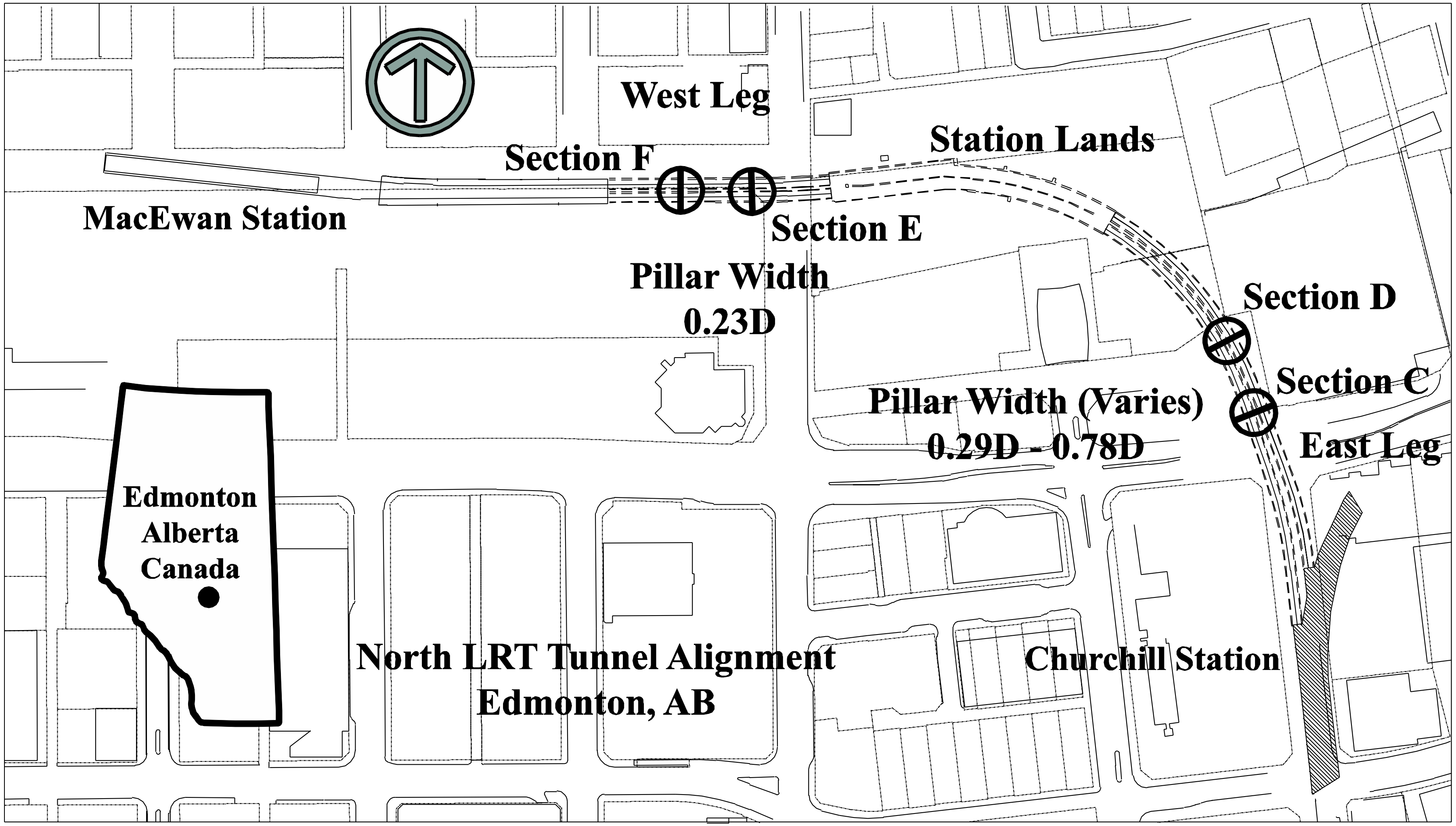
The measured stiffness is unparalleled:

- To date, there is no better way to evaluate the stiffness of a soil within the range of most engineering applications
- Because stiffness is the first characteristic to degrade during sampling, it is the least accurate parameter
- Many studies have shown that settlement predictions using $G_{u\text{-}r}$ proved superior when compared to lab data
- Movements in walls are well represented and measurements of stress has shown that active states may not be reached in many cases

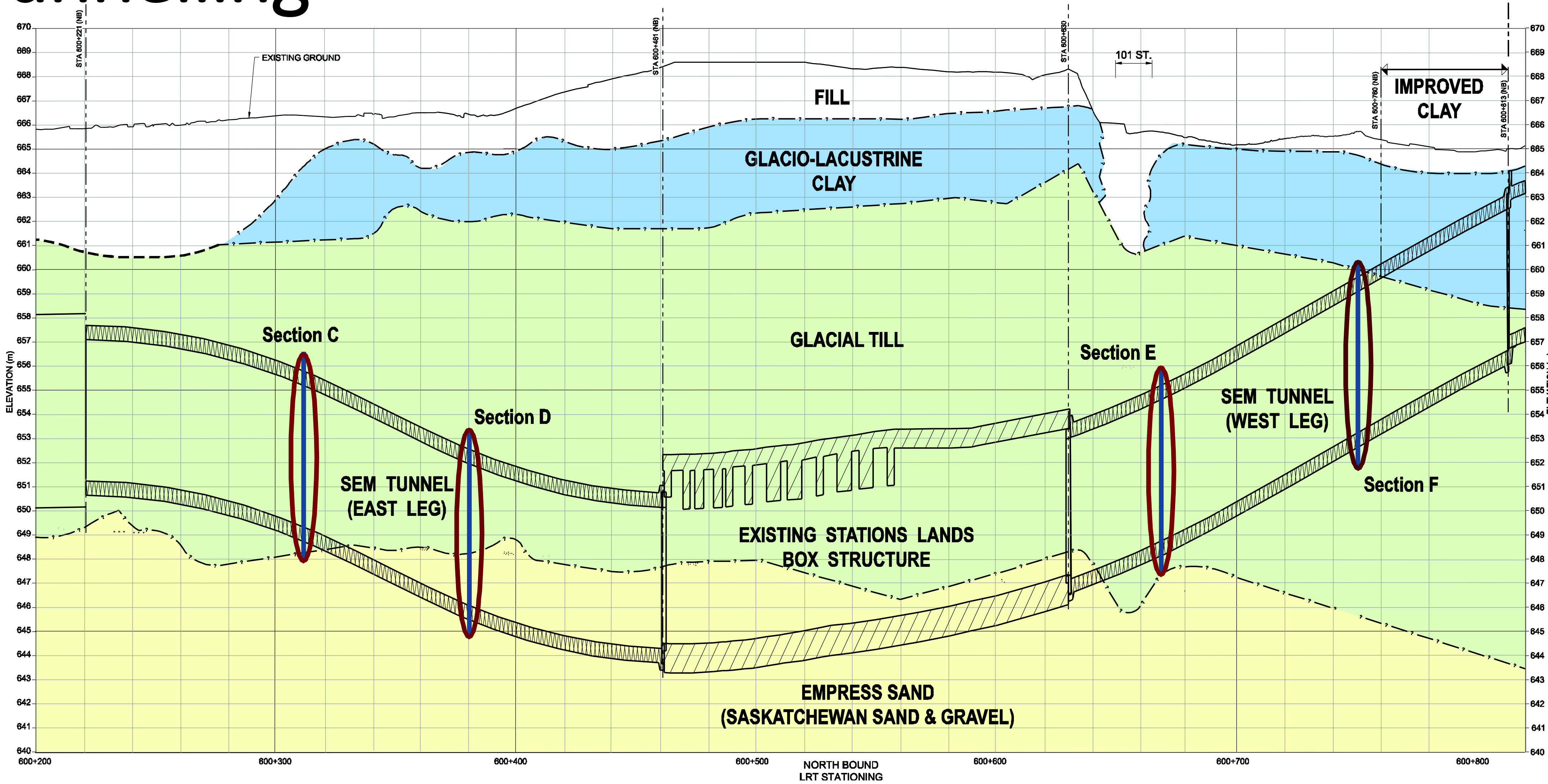
Shear Modulus and Stiffness



Tunnelling


West Leg
Station Lands
Section F
MacEwan Station
Section E
Pillar Width
0.23D
Section D
Section C
Pillar Width (Varies)
0.29D - 0.78D
East Leg
Edmonton
Alberta
Canada
North LRT Tunnel Alignment
Edmonton, AB
Churchill Station

Tunnelling


EXISTING GROUND
STA 600+221 (NB)
STA 600+461 (NB)
STA 600+630
101 ST.
STA 600+760 (NB)
STA 600+813 (NB)
IMPROVED CLAY
FILL
GLACIO-LACUSTRINE CLAY
GLACIAL TILL
Section C
Section D
Section E
Section F
SEM TUNNEL (EAST LEG)
SEM TUNNEL (WEST LEG)
EXISTING STATIONS LANDS BOX STRUCTURE
EMPRESS SAND (SASKATCHEWAN SAND & GRAVEL)
ELEVATION (m)
NORTH BOUND LRT STATIONING
600+200
600+300
600+400
600+500
600+600
600+700
600+800
640
641
642
643
644
645
646
647
648
649
650
651
652
653
654
655
656
657
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664
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666
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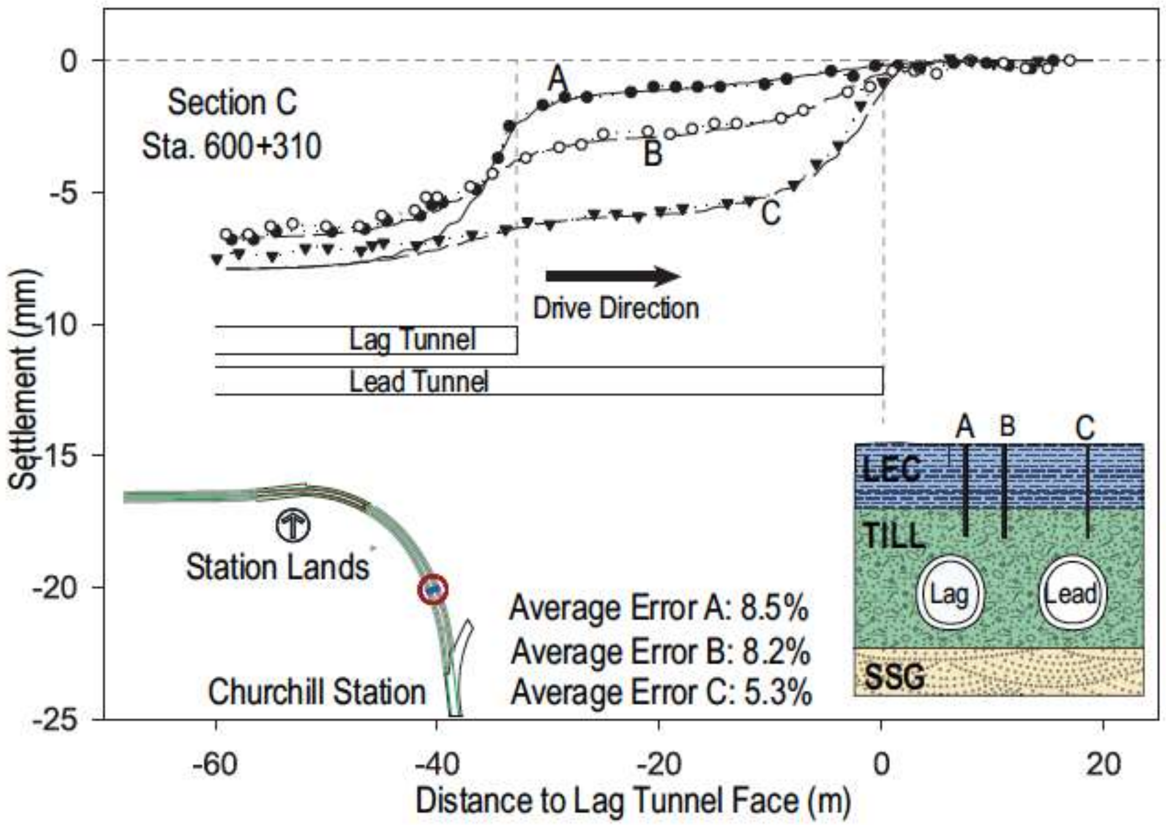
669
670

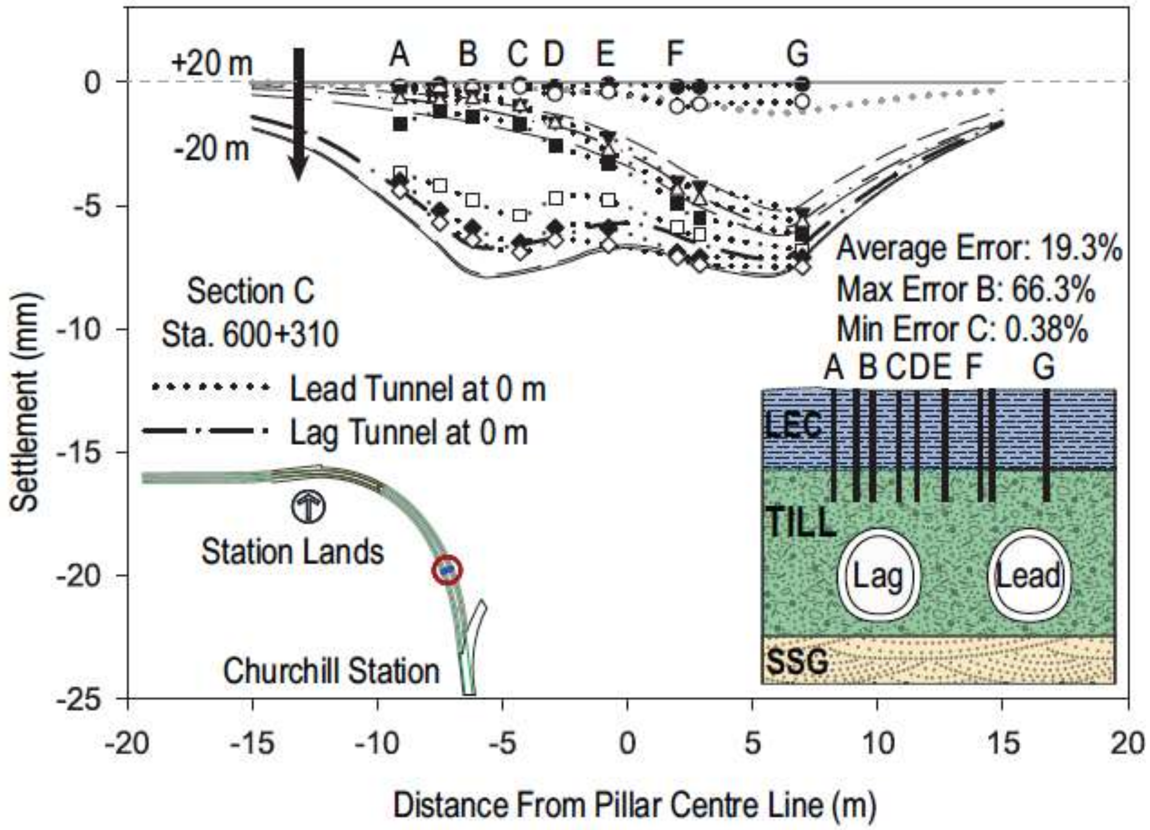
- Heavy reliance was placed on the PMT strength data when determining the overall face stability

- Considering the undrained strength of the till, a FoS for the unsupported face (provided undrained conditions controlled) was >3.0

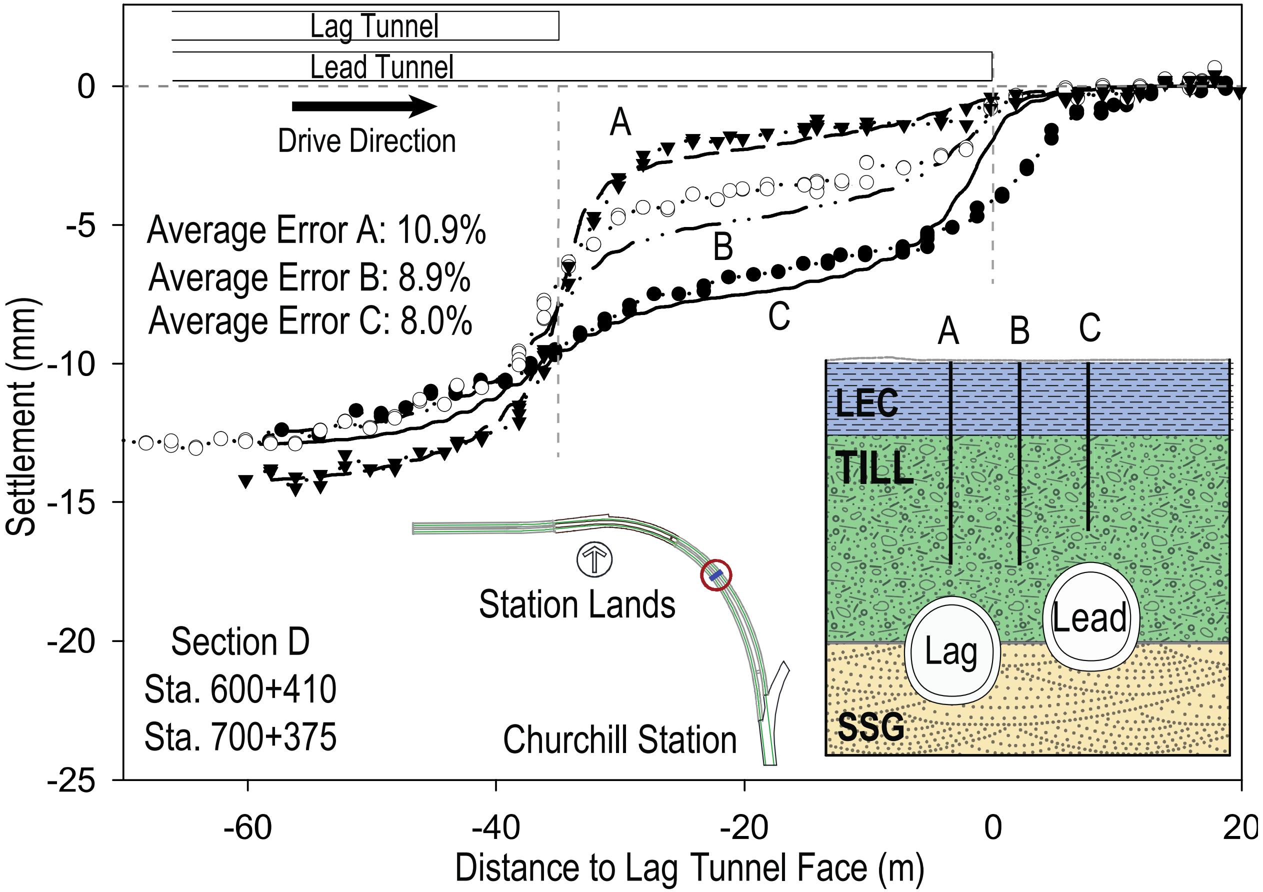
Parameter	No. of Data Points	Lowest Value	Mean	Highest Value	Standard Deviation
SPT 'N'	173	11	51	100*	18
Unconfined Compressive Strength	10	118	236	438	-
Effective Friction Angle (˚)	-	-	50	-	-
Cohesion (kPa)	-	-	37.5	-	-
Unit Weight (kN/m^3)	-	20	20.5	21	-
Coefficient of Lateral Earth Pressure (K_o)	-	-	0.75-0.85	-	-
Poisson's Ratio (υ)	-	0.33	-	0.49	-
Elastic Modulus (MPa)	-	90	120	150	-
PM Shear Modulus (MPa)	15	42.7	83.5	151.7	27.4
PM Undrained Shear Strength (kPa)	15	227	331	425	55
PM Effective Cohesion (kPa)	10	25	35.5	48	6.9
PM Effective Friction Angle (˚)	10	34	36	39	1.7
PM Lateral Earth Pressure (K_o)	15	0.7	0.85	0.87	-
Natural Moisture Content (%)	238	5	15	45	3
Sand (% Passing)	9	32	37	42	3
Silt (% Passing)	9	32	45	62	12
Clay (% Passing)	9	16	26	31	6
Liquid Limit (%)	15	25	35	42	6
Plastic Limit (%)	15	13	15	17	1
Plasticity Index (%)	15	12	19	25	5
Coefficient of Hydraulic Conductivity (cm/s)	-	1×10^{-7}	1×10^{-6}	1×10^{-5}	-

Tunnelling

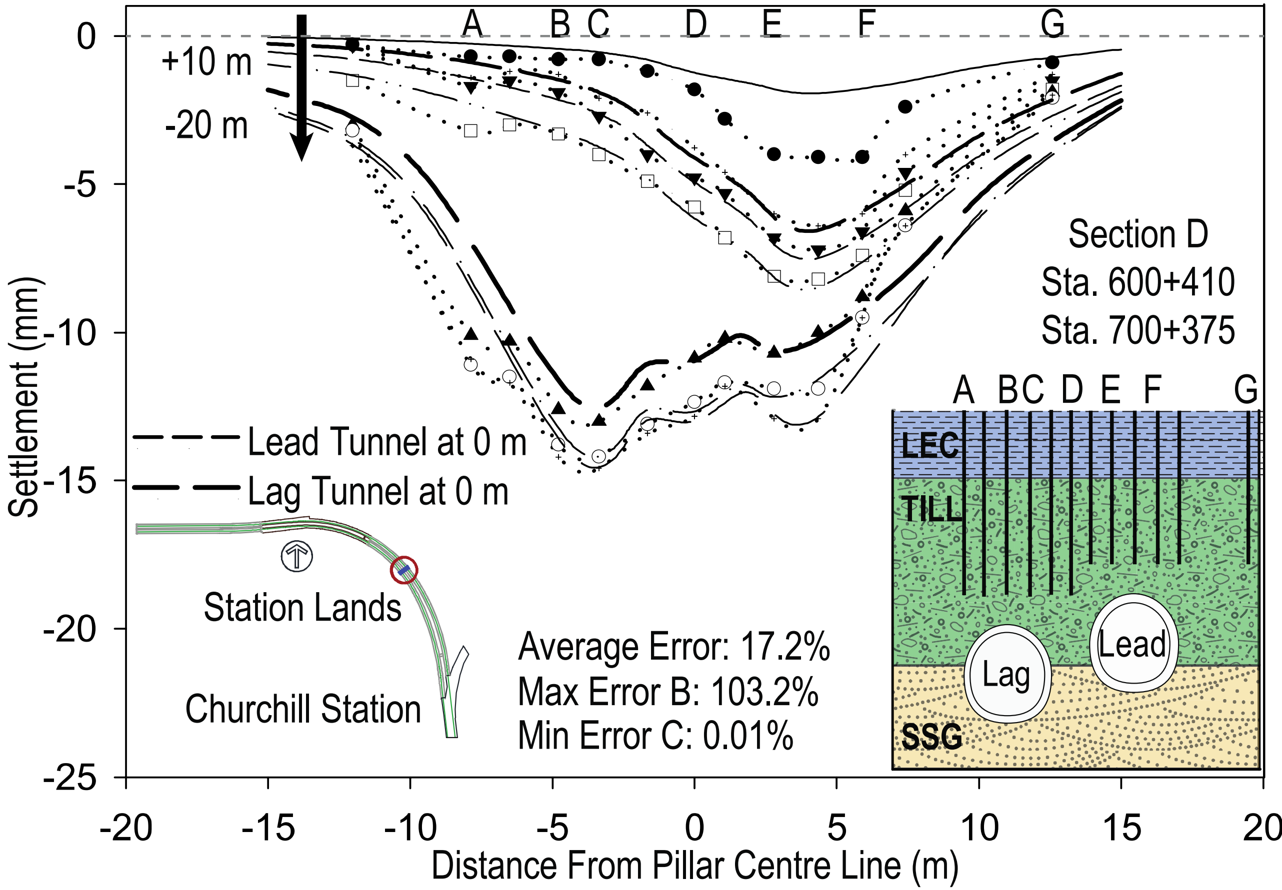

Section C
Sta. 600+310
A
B
C
Drive Direction
Lag Tunnel
Lead Tunnel
Settlement (mm)
Distance to Lag Tunnel Face (m)
Station Lands
Churchill Station
Average Error A: 8.5%
Average Error B: 8.2%
Average Error C: 5.3%
LEC
TILL
Lag
Lead
SSG


+20 m
-20 m
A B C D E F G
Section C
Sta. 600+310
Lead Tunnel at 0 m
Lag Tunnel at 0 m
Average Error: 19.3%
Max Error B: 66.3%
Min Error C: 0.38%
Settlement (mm)
Distance From Pillar Centre Line (m)
Station Lands
Churchill Station
LEC
TILL
Lag
Lead
SSG

Tunnelling



Lag Tunnel
Lead Tunnel
Drive Direction
A
B
C
Average Error A: 10.9%
Average Error B: 8.9%
Average Error C: 8.0%
A B C
LEC
TILL
Lag
Lead
SSG
Station Lands
Churchill Station
Section D
Sta. 600+410
Sta. 700+375
Settlement (mm)
Distance to Lag Tunnel Face (m)

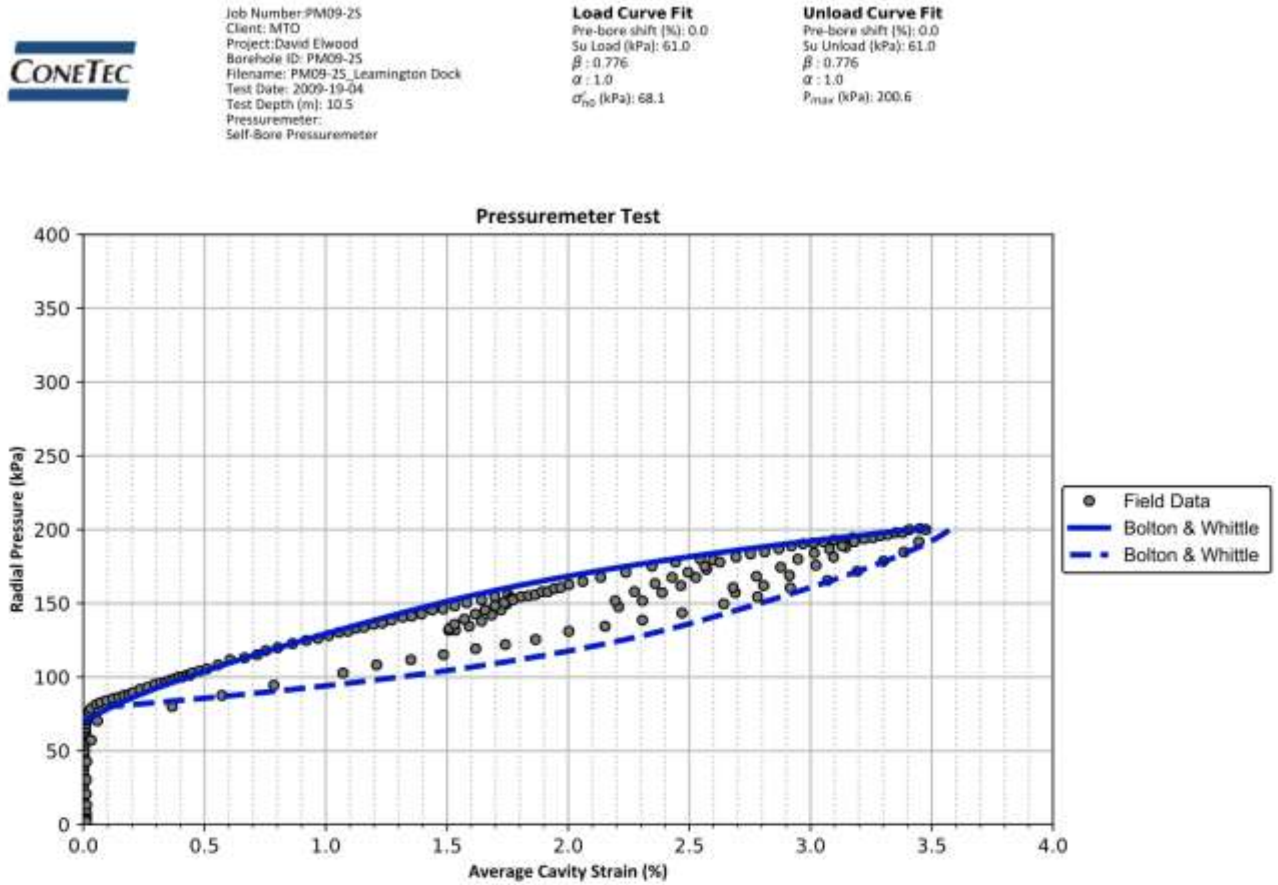


A B C D E F G
+10 m
-20 m
Section D
Sta. 600+410
Sta. 700+375
Lead Tunnel at 0 m
Lag Tunnel at 0 m
Station Lands
Churchill Station
Average Error: 17.2%
Max Error B: 103.2%
Min Error C: 0.01%
LEC
TILL
Lag
Lead
SSG
Settlement (mm)
Distance From Pillar Centre Line (m)

Lateral Deformations

- Lateral deformations of piles are best predicted directly calculating the lateral coefficient of subgrade reaction, k_s using the method of Suyama et al. (1982)
  - This requires entering the spring constant into structural software to determine the ground response due to lateral loading of piles
- Robertson et al. (1986) give empirical formulations for pressuremeter tests to determine p-y curves directly

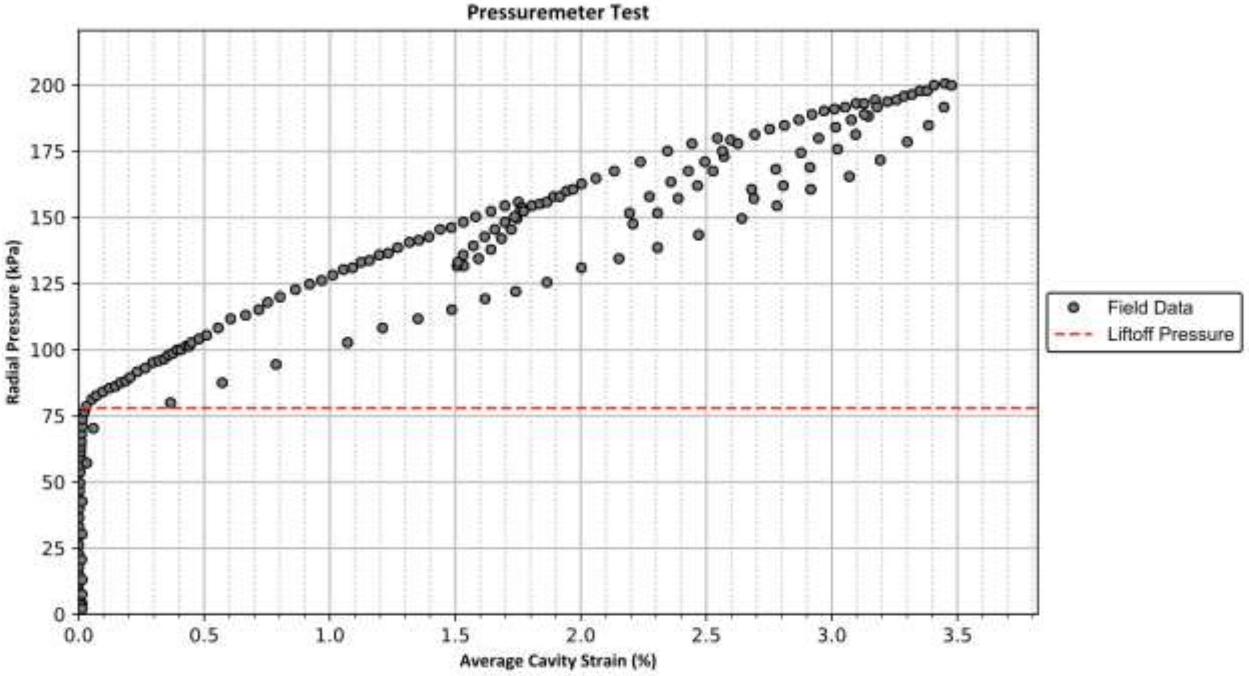
Lateral Deformations



Lateral Deformations

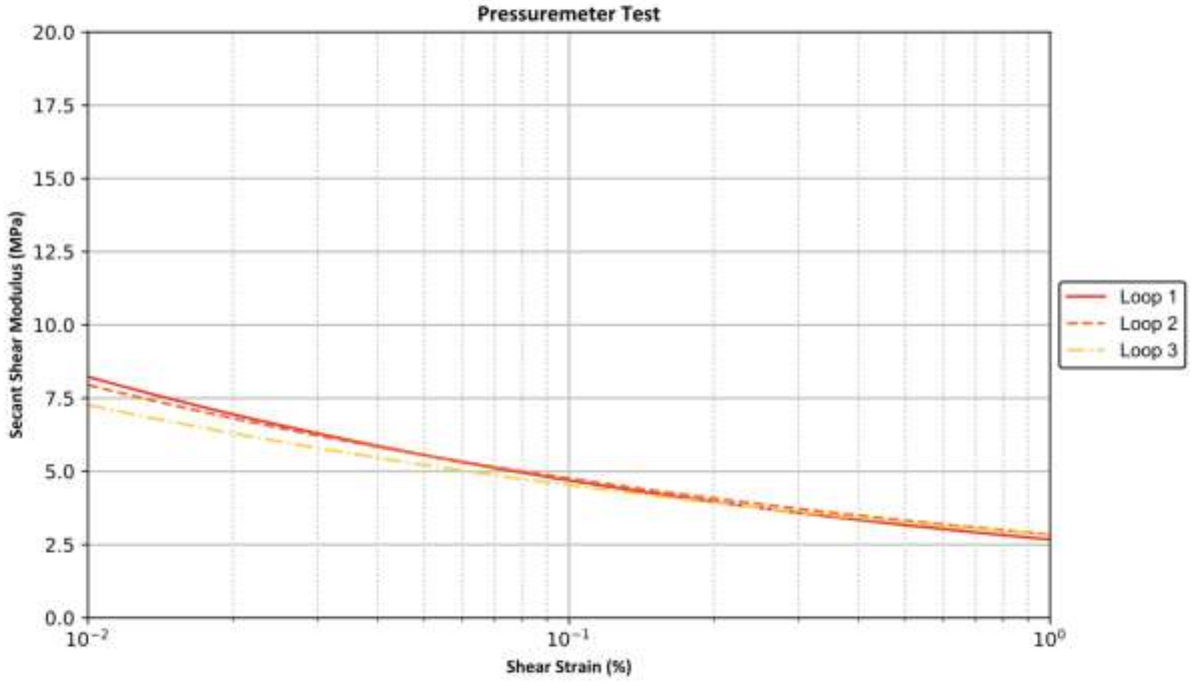
Job Number:PM09-25
Client: MTO
Project:David Elwood
Borehole ID: PM09-25
Filename: PM09-25_Leamington Dock
Test Date: 2009-19-04
Test Depth (m): 10.5
Pressuremeter:
Self-Bore Pressuremeter

Lift Off Pressure: 78.0kPa



Job Number:PM09-25
Client: MTO
Project:David Elwood
Borehole ID: PM09-25
Filename: PM09-25_Leamington Dock
Test Date: 2009-19-04
Test Depth (m): 10.5
Pressuremeter:
Self-Bore Pressuremeter

Loop 1: β :0.756: α :0.87
Loop 2: β :0.777: α :1.02
Loop 3: β :0.795: α :1.1



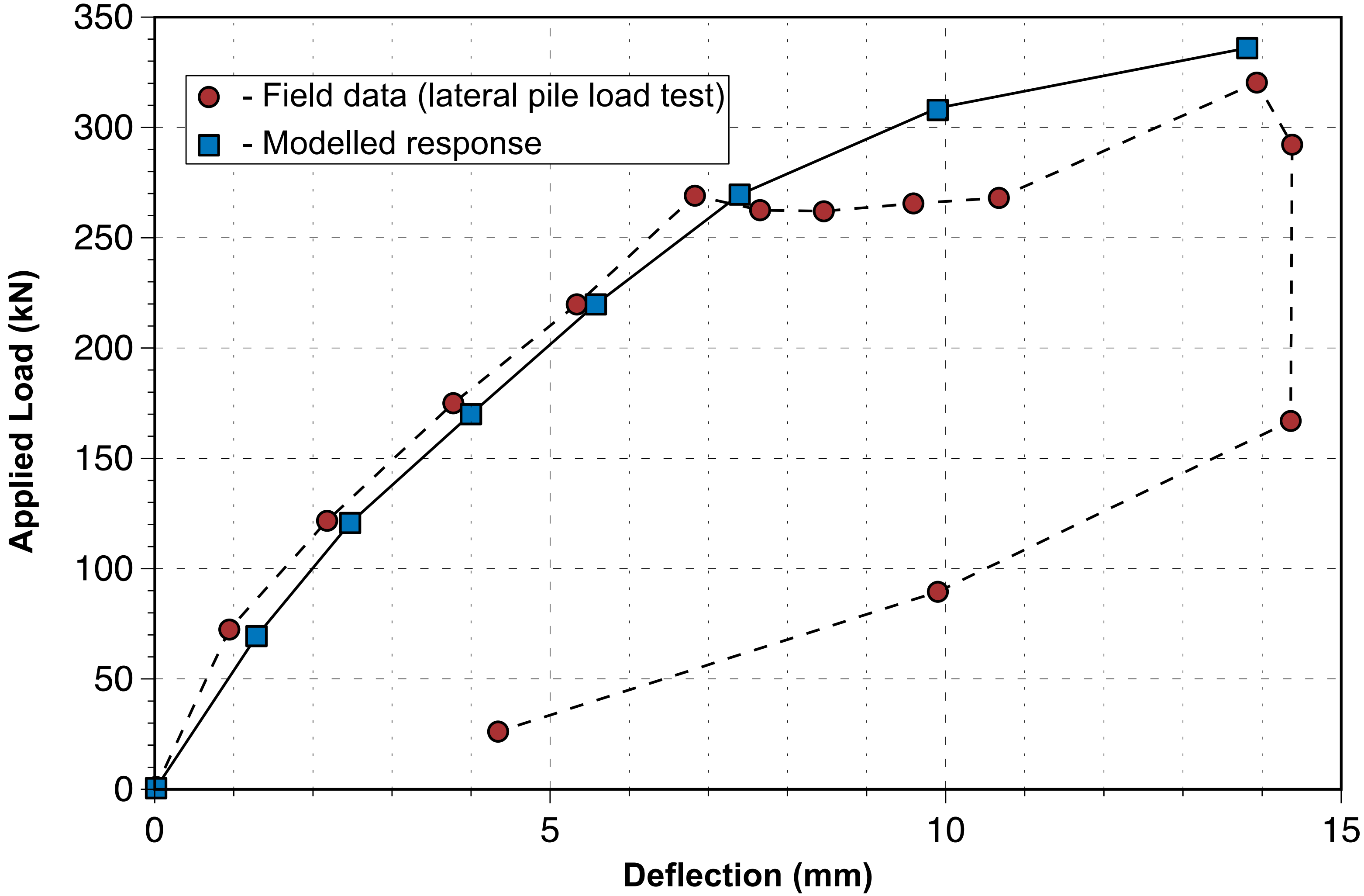
Lateral Deformations

Table 1
Summary of In-Situ Test Results

Borehole No.	Material Type	Depth (m)	Shear Vane		Pressuremeter			CPT(u)		Dilatometer		
			Undrained Shear Strength s_u (kPa)	Sensitivity	Elastic Modulus (kPa)	Friction Angle φ' (°)	Undrained Shear Strength s_u (kPa)	Equivalent Strain Elastic Modulus (kPa)	Friction Angle φ' (°)	Elastic Modulus (kPa)	Friction Angle φ' (°)	Undrained Shear Strength s_u (kPa)
09-01	Silty Sand to Sandy Silt	7.5	N/A	N/A	60,000	32°	N/A	30,000	28 - 30°	28,450	37°	N/A
		8.25	N/A	N/A	21,600	30°	N/A					
		8.8	N/A	N/A	36,000	30°	N/A					
	Silty Clay	10.5	75	2.3	26,400	29°	102.8	16,675	N/A	5,840	26°	31.0
		11.25	72	2.3	16,800	29°	95					
		12	72	2.2	16,450	28°	79.7					
		12.75	72	1.6	15,450	28°	78.2					
	Clayey Silt Till	15.3	N/A	N/A	360,000	38°	N/A	N/A	N/A	99,725	43°	N/A
09-02	Silty Sand to Sandy Silt	10.5	N/A	N/A	3,350*	30°	N/A	N/A	N/A	20,350	34°	N/A
		11.25	N/A	N/A	6,620	32°	N/A					
	Silty Clay	12.0	60	3.0	6,500	30°	80.8	16,450	N/A	4,400	14°	31.4
		12.75	64	3.2	6,820	29°	80.8					
	Clayey Silt Till	14.0	N/A	N/A	216,000	38°	N/A	N/A	N/A	67,400	38°	N/A

* - Sample likely disturbed during testing.

Lateral Deformations



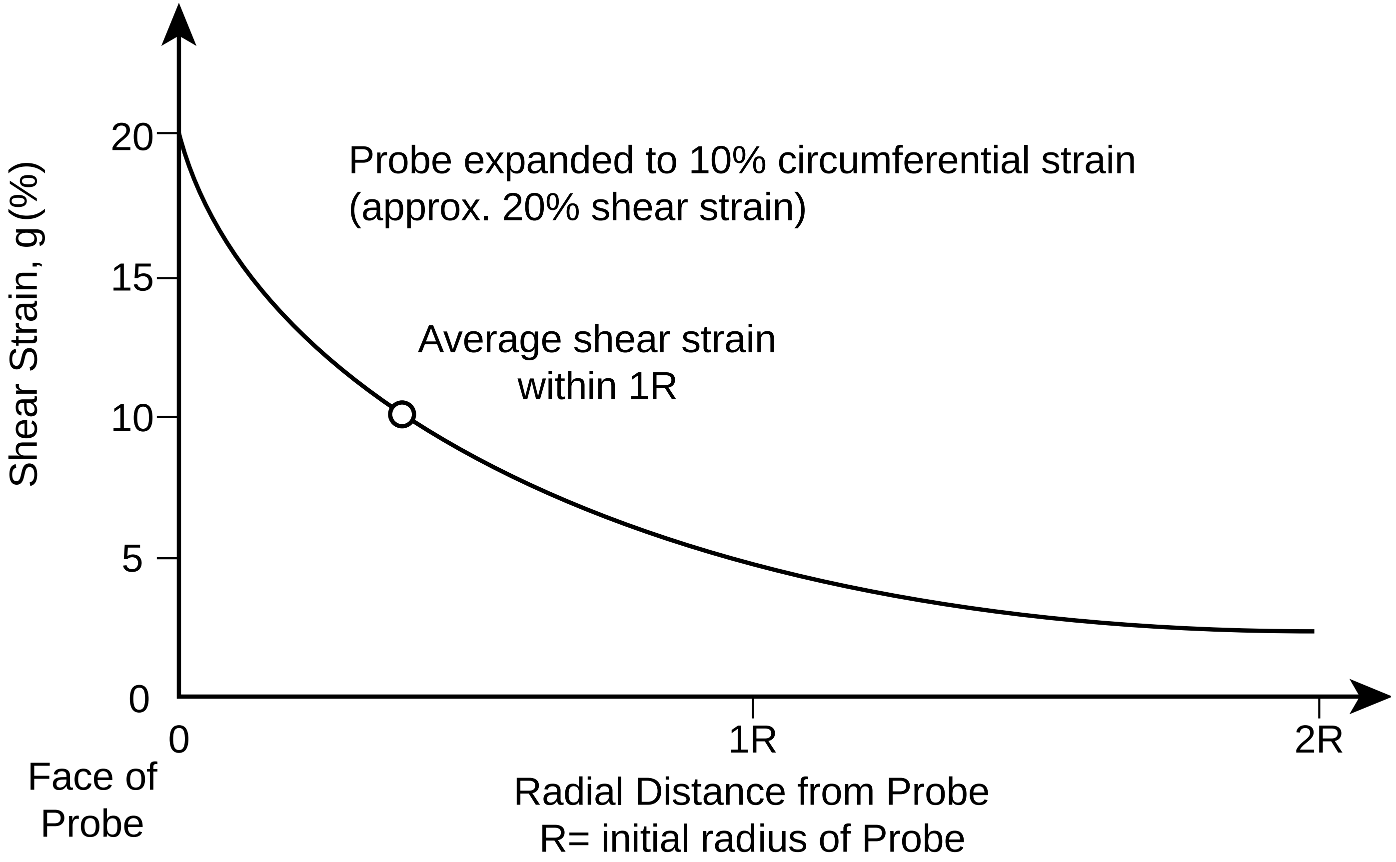
Loose Sands

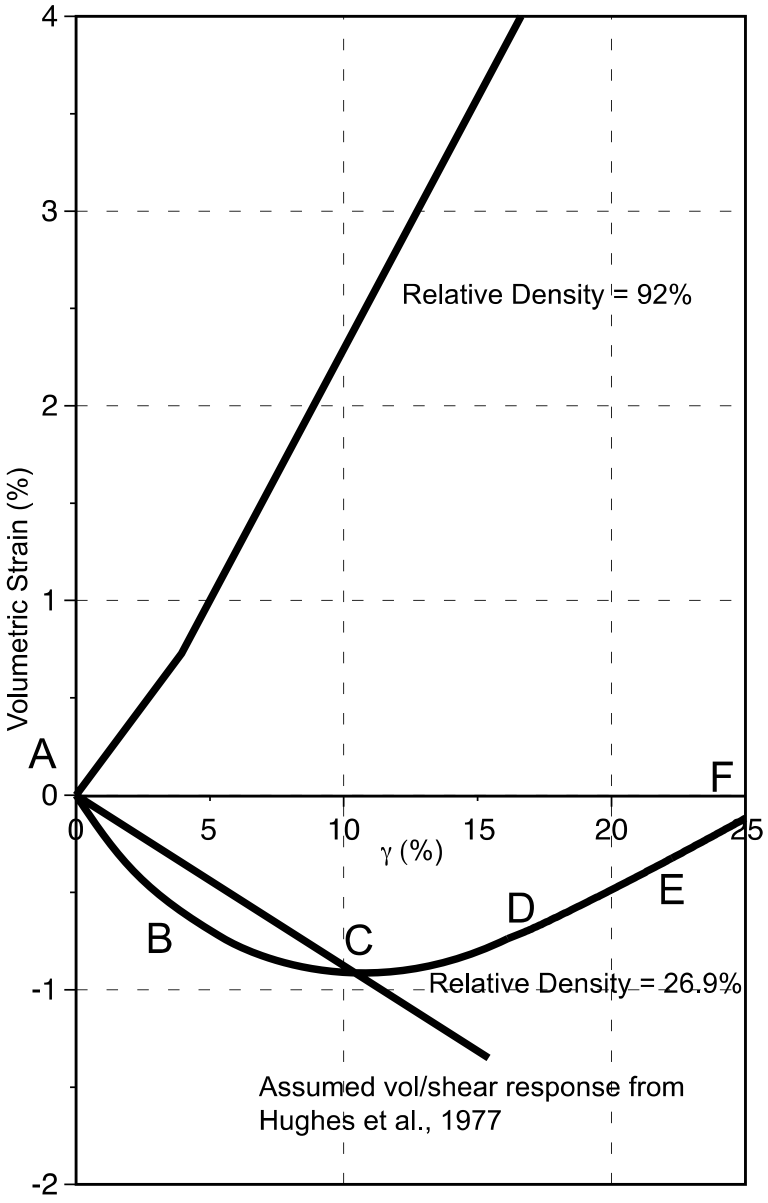
- WRT sands, the angle of friction is dependent on the installation method and degree of disturbance:
  - Care should be taken when evaluating the friction angle and dilation angle in pre-bored tests
  - SBPMT comes the closest to providing frictional data, though the values are still typically higher than triaxial and CPT values
  - Discrepancies are likely from difficulty in sampling, stress paths and rate effects

Loose Sands

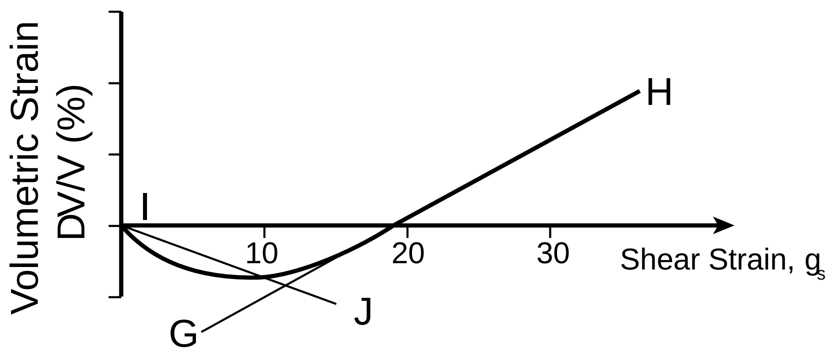
- Because loose sands are strain hardening, they require approximately 20-30% shear strain before peak strength is achieved
- This poses problems with the pressuremeter test in that the probe must strain more than this for peak strength (and critical state) to occur at the borehole wall
  - Currently, self-bore probes can strain approximately 14% radially or around 28% shear strain
  - The lack of strain means that the linear portion of the log-log plot may not be achieved

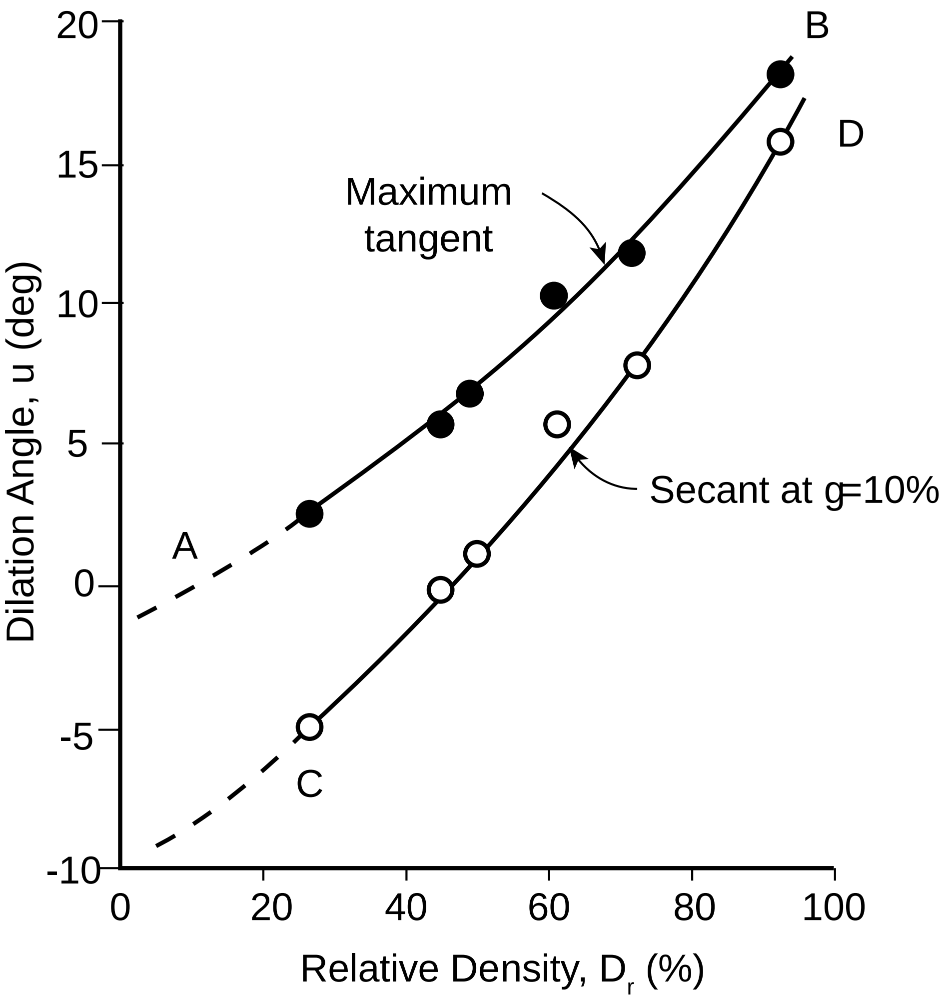
Liquefaction and Loose Sands



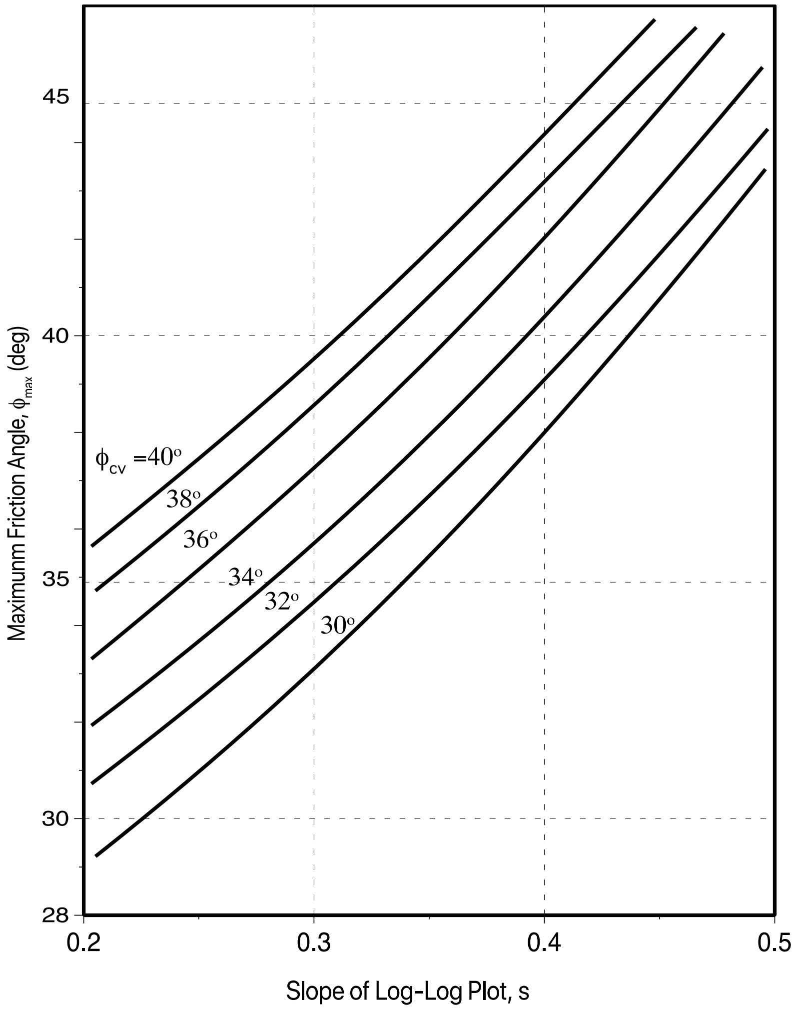


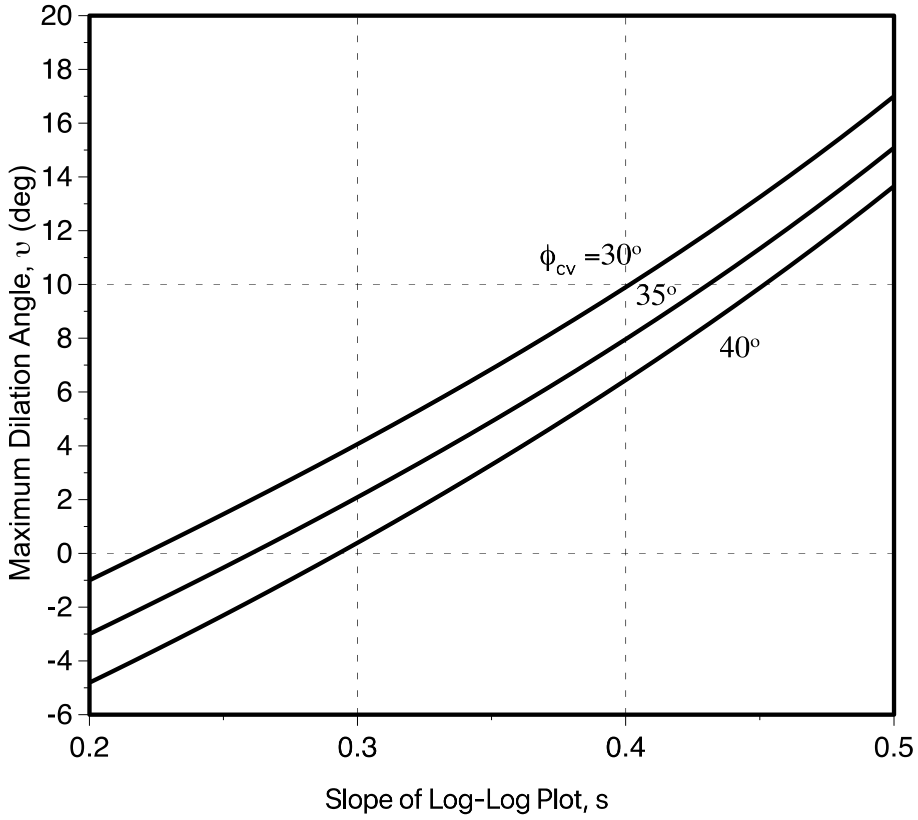
Liquefaction and Loose Sands

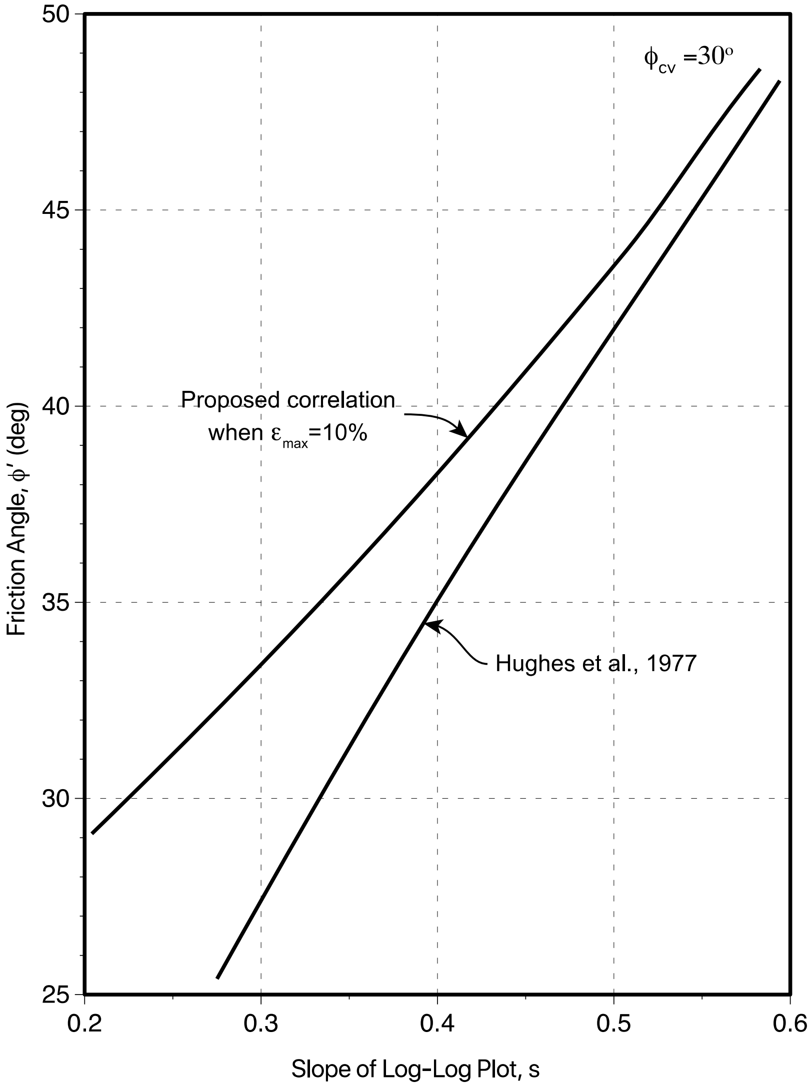




Liquefaction and Loose Sands

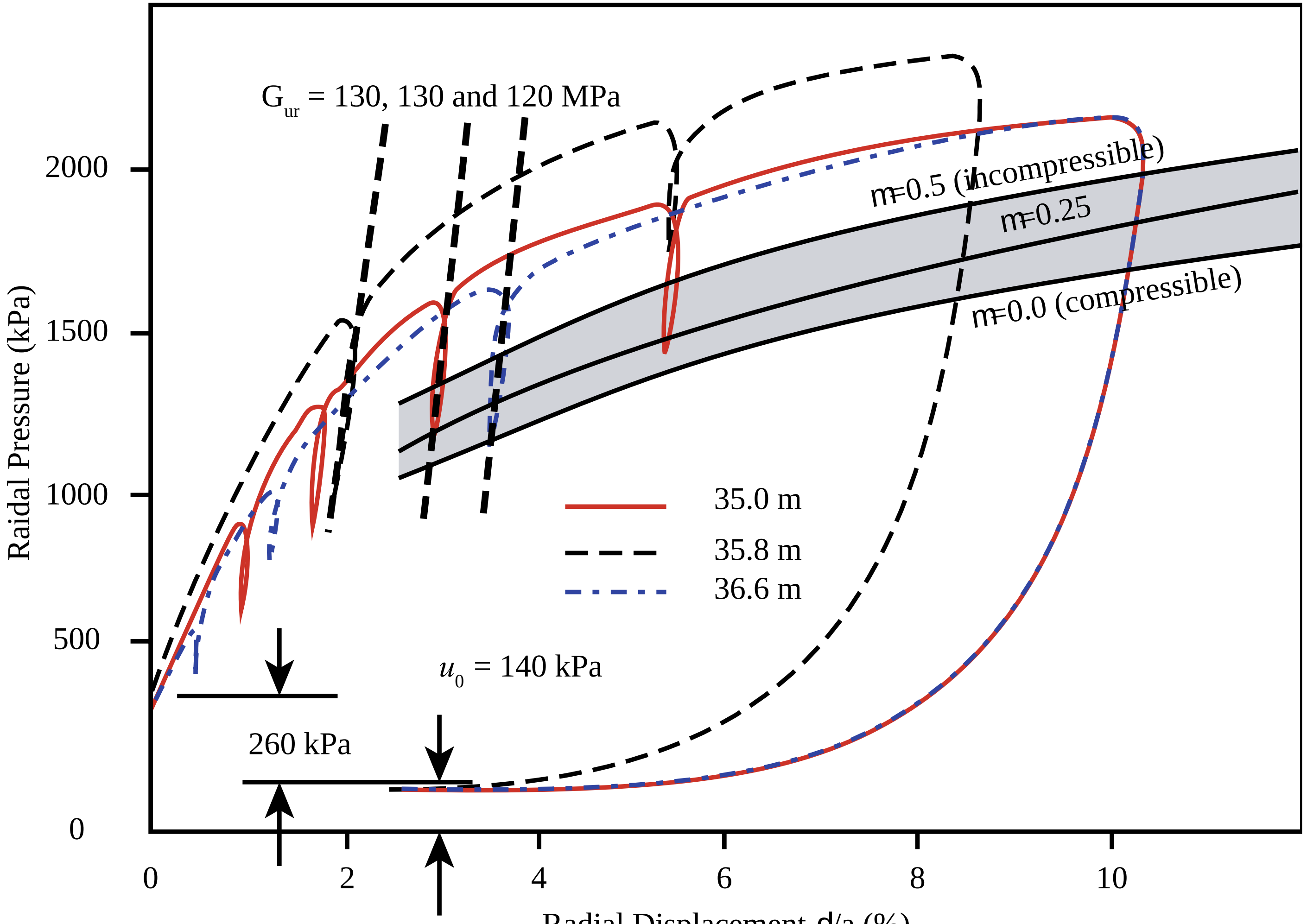






Liquefaction and Loose Sands

- SBPM testing at Syncrude's J-Pit were conducted prior to constructing an embankment
- The embankment was designed to result in static liquefaction upon completion
- Use of the Carter Model demonstrated that failure could not occur



Final Thoughts…

- The pressuremeter tests a large volume of material at representative loads.
- High resolution pressuremeters (HRPM) are not for the faint hearted. They are scientific instruments and skilled people are required to use and maintain them.
- The field curve they produce is unusual in the context of soil testing because it is solved analytically without introducing empiricism. The success of this depends on the match of the analytical solution to the particular material being investigated.
- They are extraordinarily good at determining the stiffness of the ground and describing the decay of stiffness with increasing strain. Nothing else comes close.
- Coupled with the SCPTu, a complete modulus curve can be developed.
- HRPM data are used to calibrate numerical models of geotechnical problems.
- Possibly not the tool of choice for building your house. Use it for the bridge going over the top of it or the tunnel going under it.