Shear Strength of Shallow Soils

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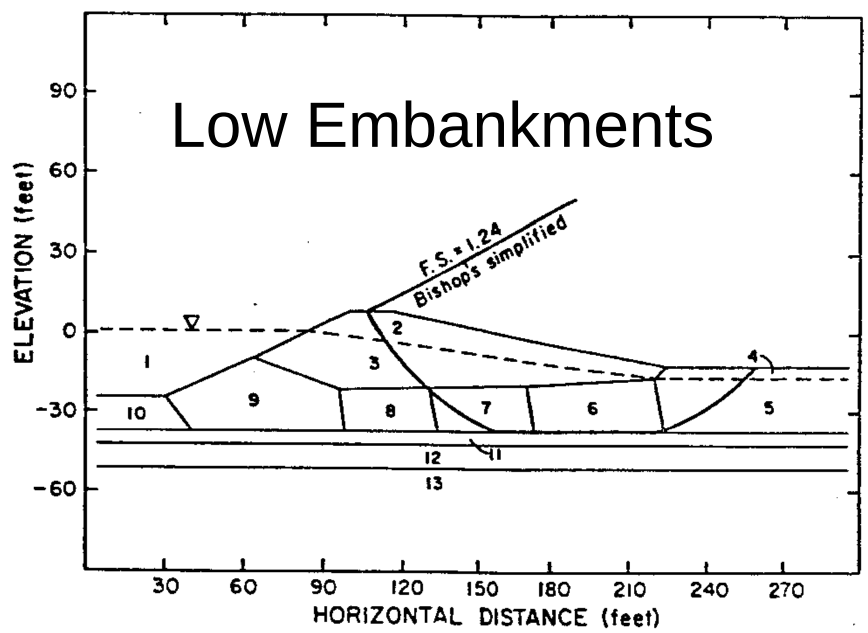
Issues

1. Relevant to practical problems
   - Shallow slopes
   - Organic soils
   - Pipeline embedment
2. Technical difficulties
   - Difficult to sample
   - Not amenable to conventional strength tests
3. Perspectives
   - Strength measurement
   - Soil suction

Relevant Situations



Difficulties in Measurement at Low Stress

1. Very soft (S_u ~ 100 psf) – difficult to sample

2. Limitations of testing equipment
   σ'_{vc} > 600 psf for many devices

Evaluating Strength: Extended Mohr-Coulomb Criterion

$$\tau_f = c' + p' \tan \phi' + h_m \tan \phi^b$$

Strength

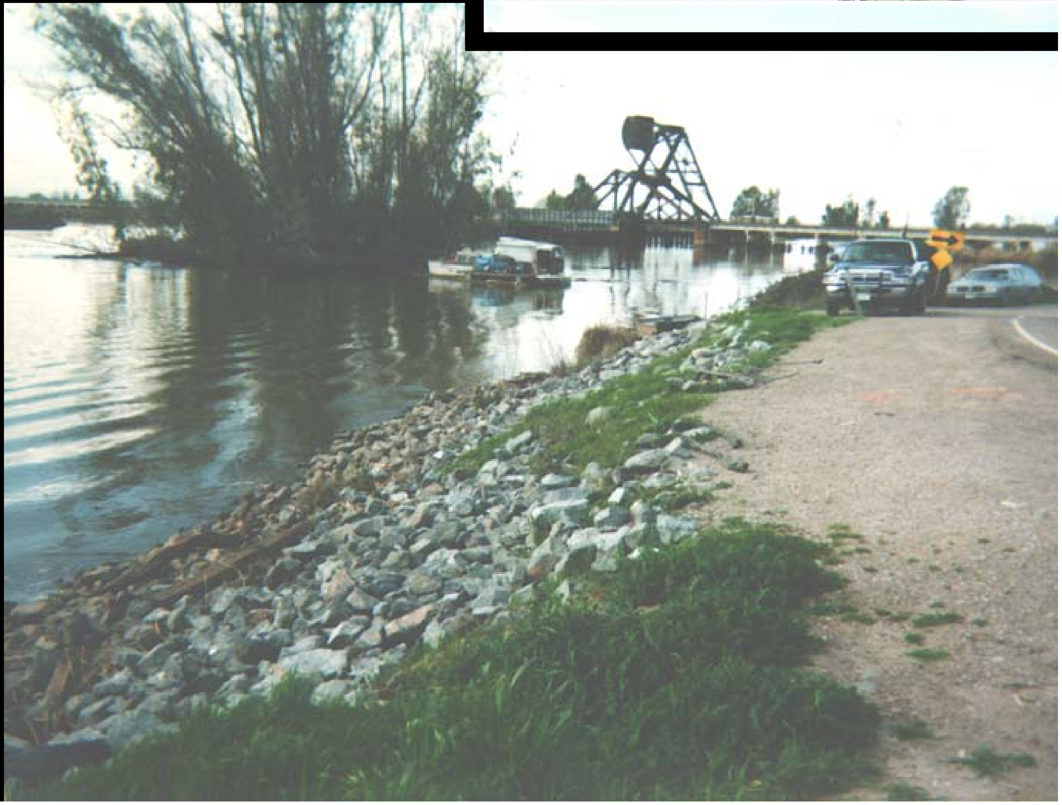
Suction

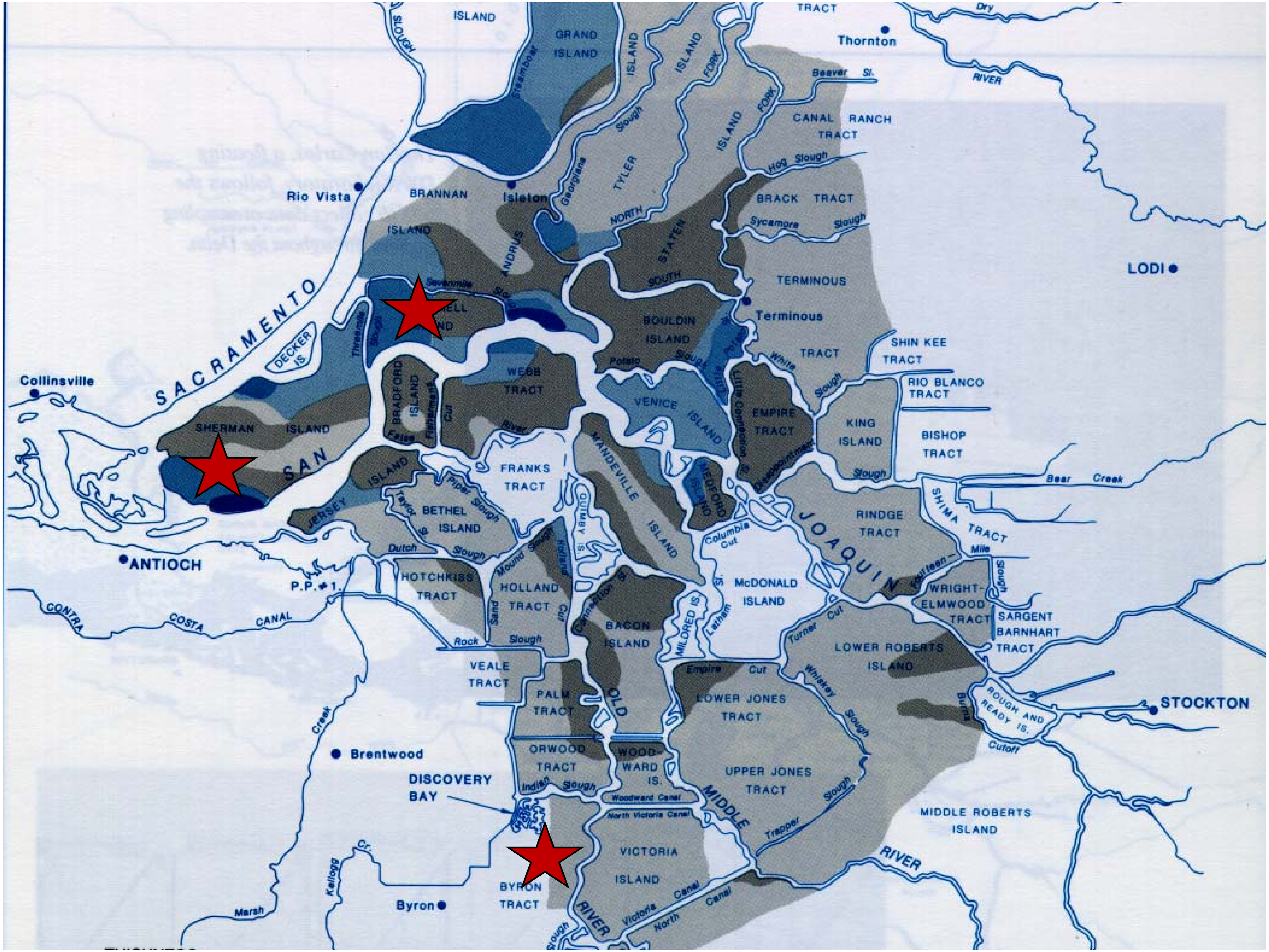
τ_f	=	shear strength
c'	=	effective cohesion
p'	=	net mechanical stress $(\sigma - u_a)$
ϕ'	=	mechanical stress friction angle
h_m	=	matric suction $(u_a - u_w)$
ϕ^b	=	suction friction angle

Case Histories

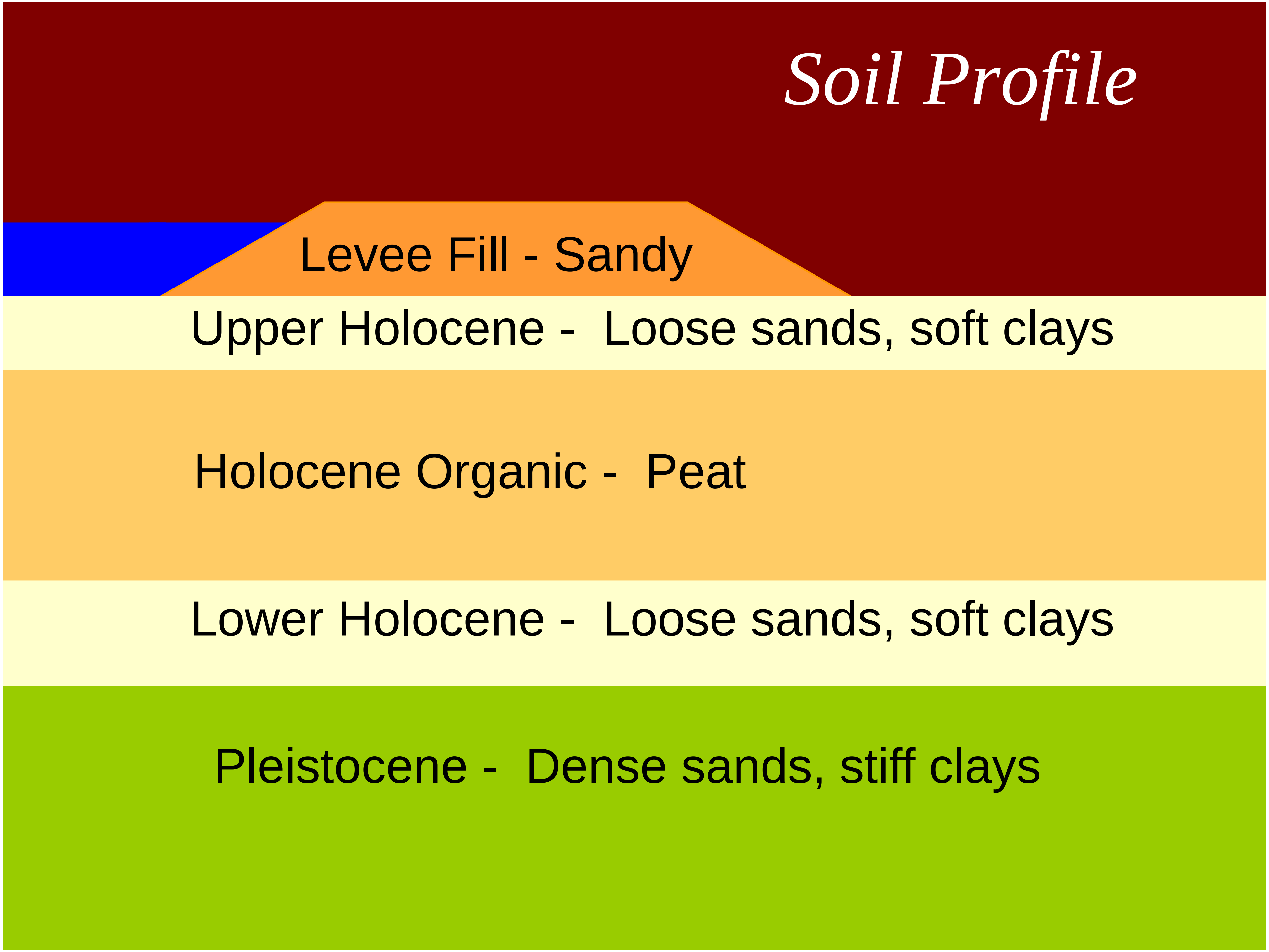
1. Organic soil deposits
2. Inorganic strength tests at low σ'
3. Shallow slope failures

Sacramento-San Joaquin Delta Peat Deposits

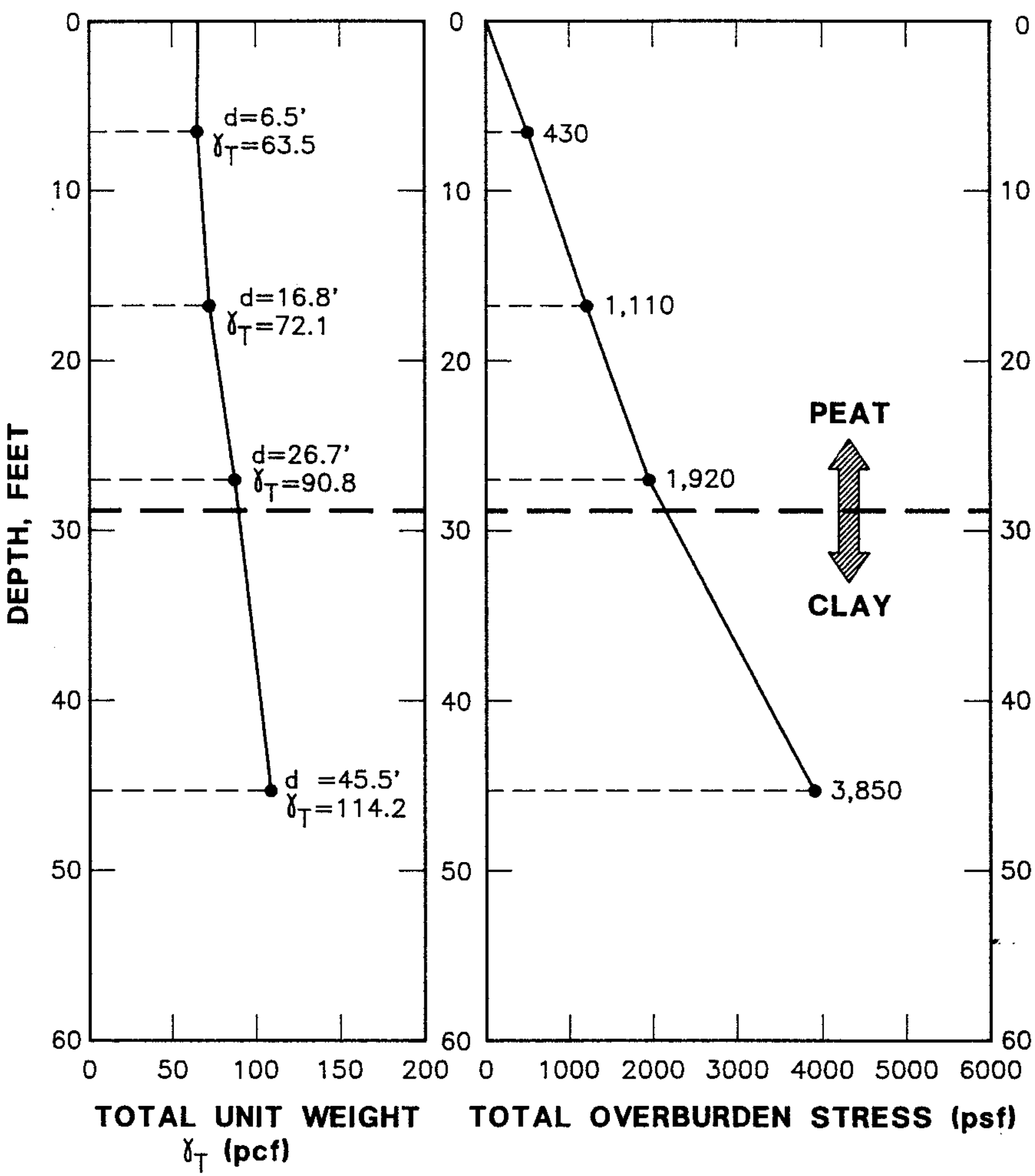




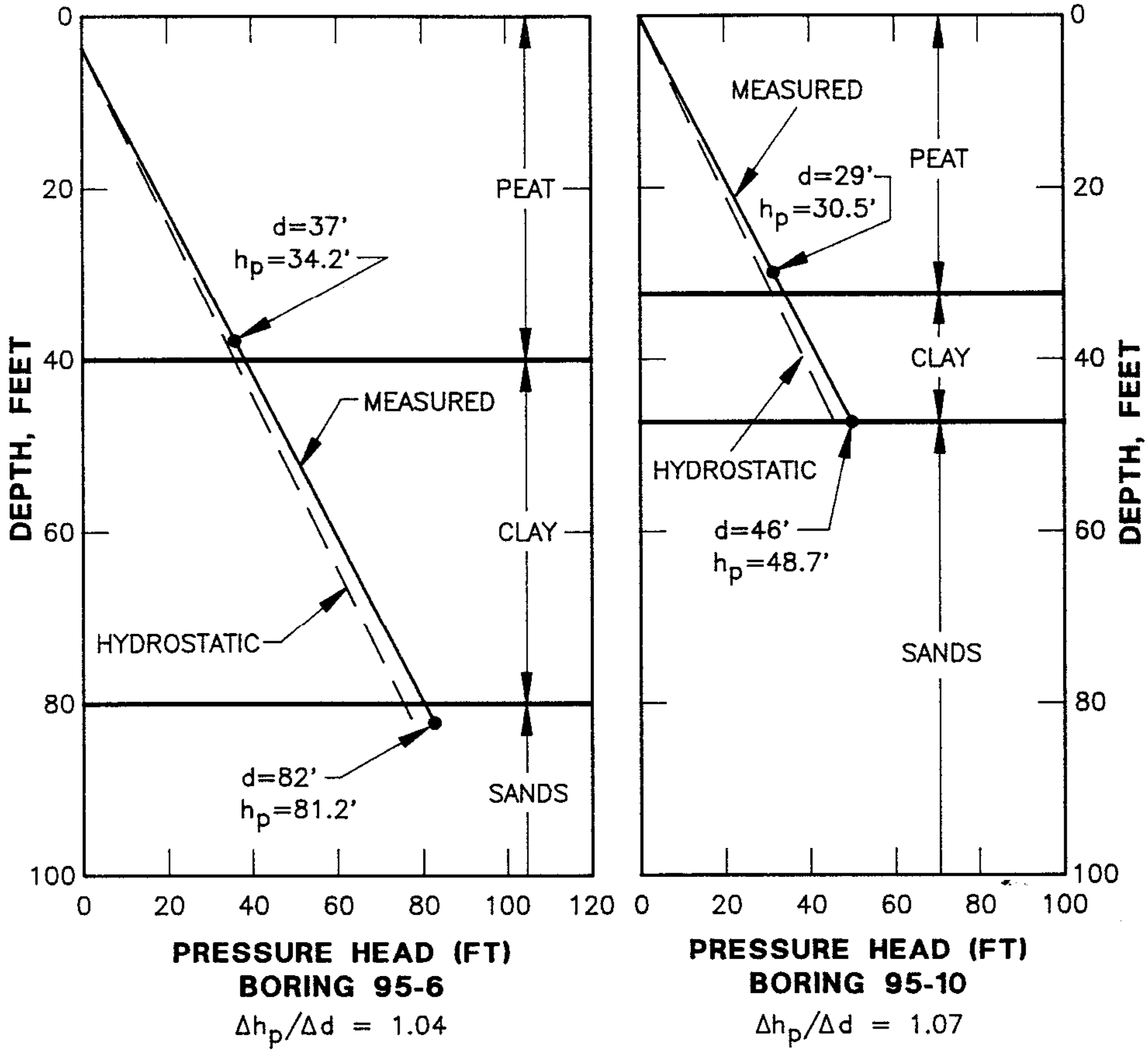
ISLAND
SLOUGH
GRAND ISLAND
Steamboat
ISLAND
TRACT
Dry
Thornton
ISLAND
FORK
Beaver Sl.
RIVER
Slough
ISLAND
FORK
CANAL RANCH TRACT
Georgiana
TYLER
Hog Slough
Rio Vista
BRANNAN
Isleton
NORTH
BRACK TRACT
Sycamore Slough
ISLAND
ANDRUS
STATEN
SOUTH
TERMINOUS
LODI
SACRAMENTO
Sevenmile Slough
BOULDIN ISLAND
Terminous
Threemile Slough
DECKER IS.
WEBB TRACT
Potato Slough
TRACT
SHIN KEE TRACT
White Slough
RIO BLANCO TRACT
Collinsville
BRADFORD ISLAND
Fisherman's Cut
VENICE ISLAND
Little Connection Sl.
EMPIRE TRACT
KING ISLAND
BISHOP TRACT
SHERMAN ISLAND
False River
SAN
FRANKS TRACT
MANDEVILLE
MEDFORD ISLAND
Disappointment
Slough
Bear Creek
ISLAND
Piper Slough
Taylor Sl.
BETHEL ISLAND
JERSEY
QUIMBY IS.
ISLAND
JOAQUIN
Columbia Cut
RINDGE TRACT
SHIMA TRACT
Dutch Slough
Mound Slough
Holland Cut
Mile Slough
ANTIOCH
HOTCHKISS TRACT
HOLLAND TRACT
McDONALD ISLAND
Fourteen-
WRIGHT-ELMWOOD TRACT
P.P.#1.
Connection Sl.
MILDRED IS.
Latham Sl.
Turner Cut
SARGENT BARNHART TRACT
CONTRA COSTA CANAL
Sand
BACON ISLAND
Rock Slough
LOWER ROBERTS ISLAND
VEALE TRACT
Empire Cut
Whiskey Slough
PALM TRACT
OLD
LOWER JONES TRACT
Burns
ROUGH AND READY IS.
STOCKTON
Creek
Brentwood
ORWOOD TRACT
WOOD-WARD IS.
UPPER JONES TRACT
Cutoff
DISCOVERY BAY
Indian Slough
Woodward Canal
MIDDLE
Slough
North Victoria Canal
MIDDLE ROBERTS ISLAND
Trapper
Cr.
VICTORIA ISLAND
RIVER
Kellogg
BYRON TRACT
Canal
Canal
Byron
Marsh
RIVER
Victoria
North
Slough


Soil Profile
Levee Fill - Sandy
Upper Holocene - Loose sands, soft clays
Holocene Organic - Peat
Lower Holocene - Loose sands, soft clays
Pleistocene - Dense sands, stiff clays

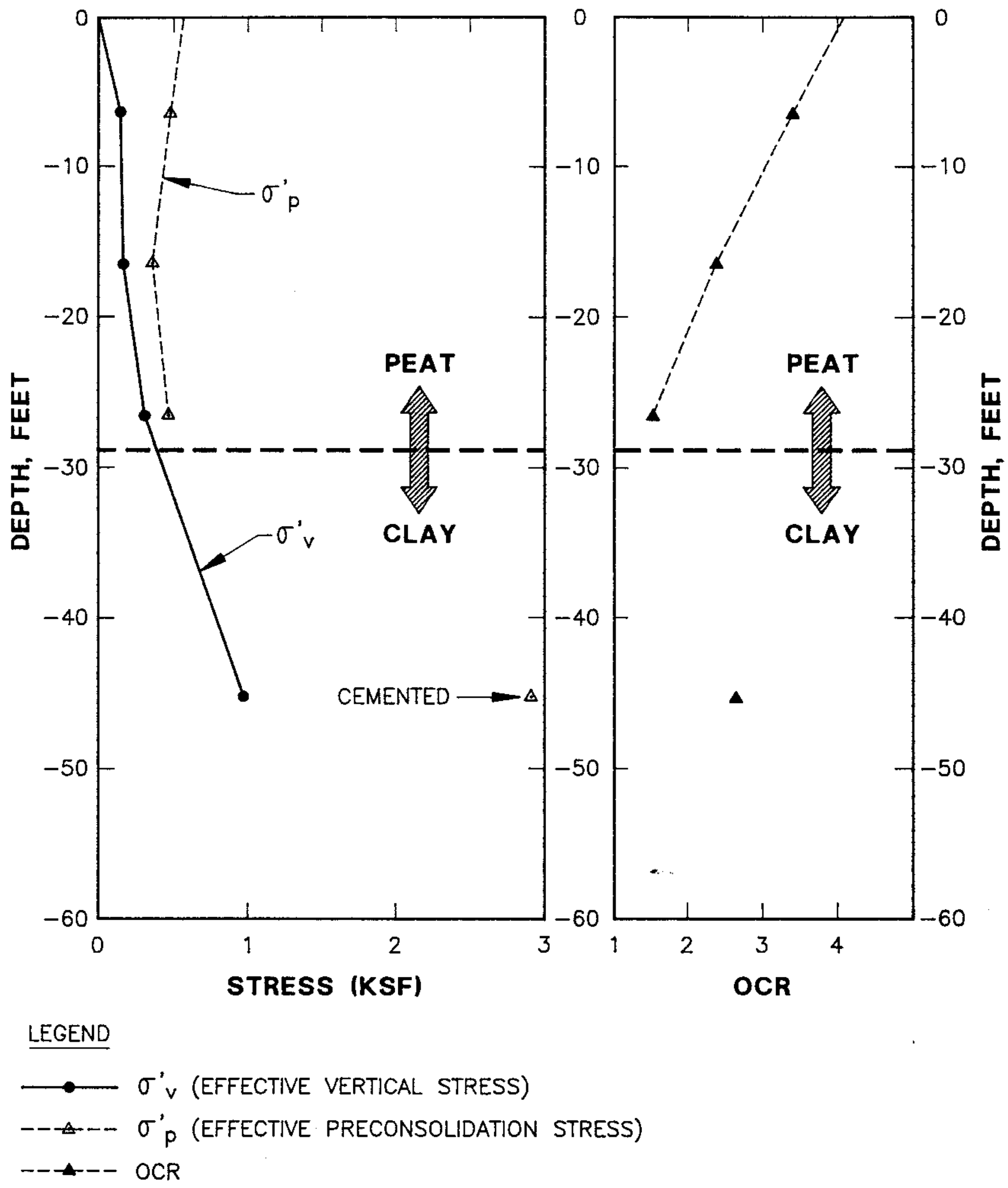
Sherman Island Soil Density



Sherman Island Pore Pressures



Sherman Island Effective Stress Profile



Undrained Strength Ratio, s_u/σ'_{v0}

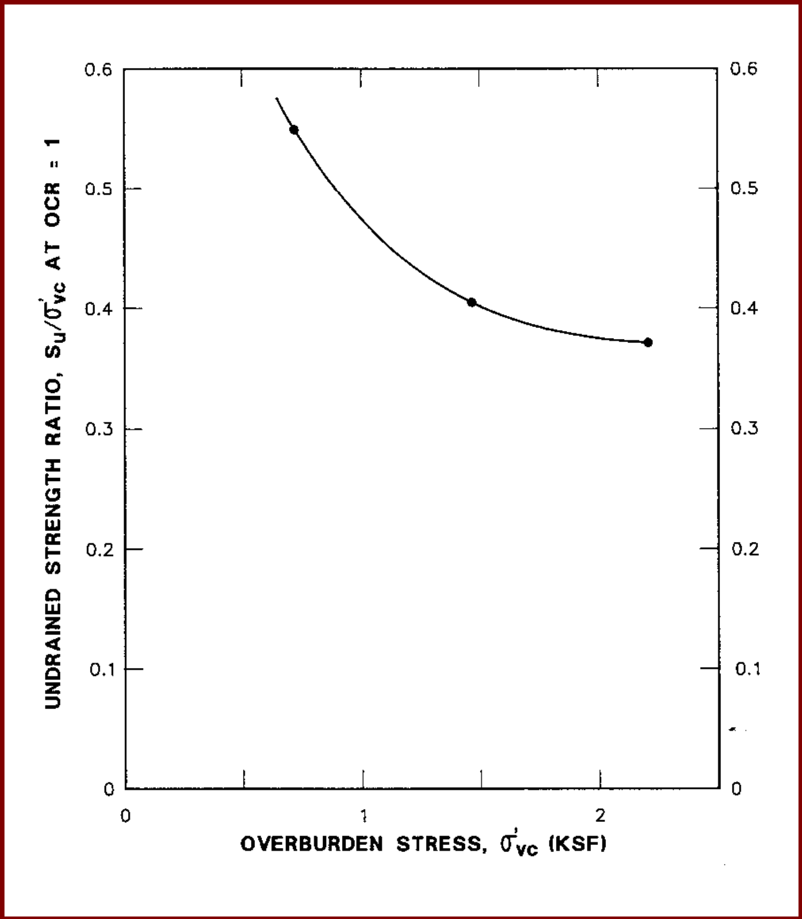
SHANSEP (Ladd, 1986)

$$USR = s_u/\sigma'_{v0} = S\,(OCR)^m$$

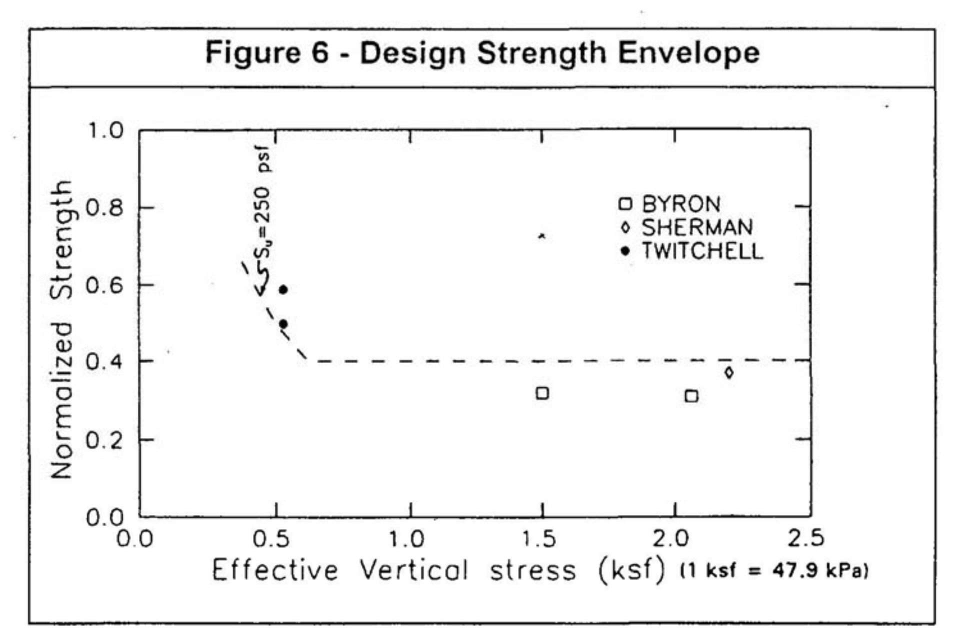
- OCR = over-consolidation ratio = σ'_p/σ'_{v0}
- S = 0.22 Inorganic Soils (excl. high S_t)
  0.25 +/- 0.05 Organic Soils (excl. peat)
- m = 0.8

Parameters independent of stress level

Measured Undrained Strength Ratio, DSS

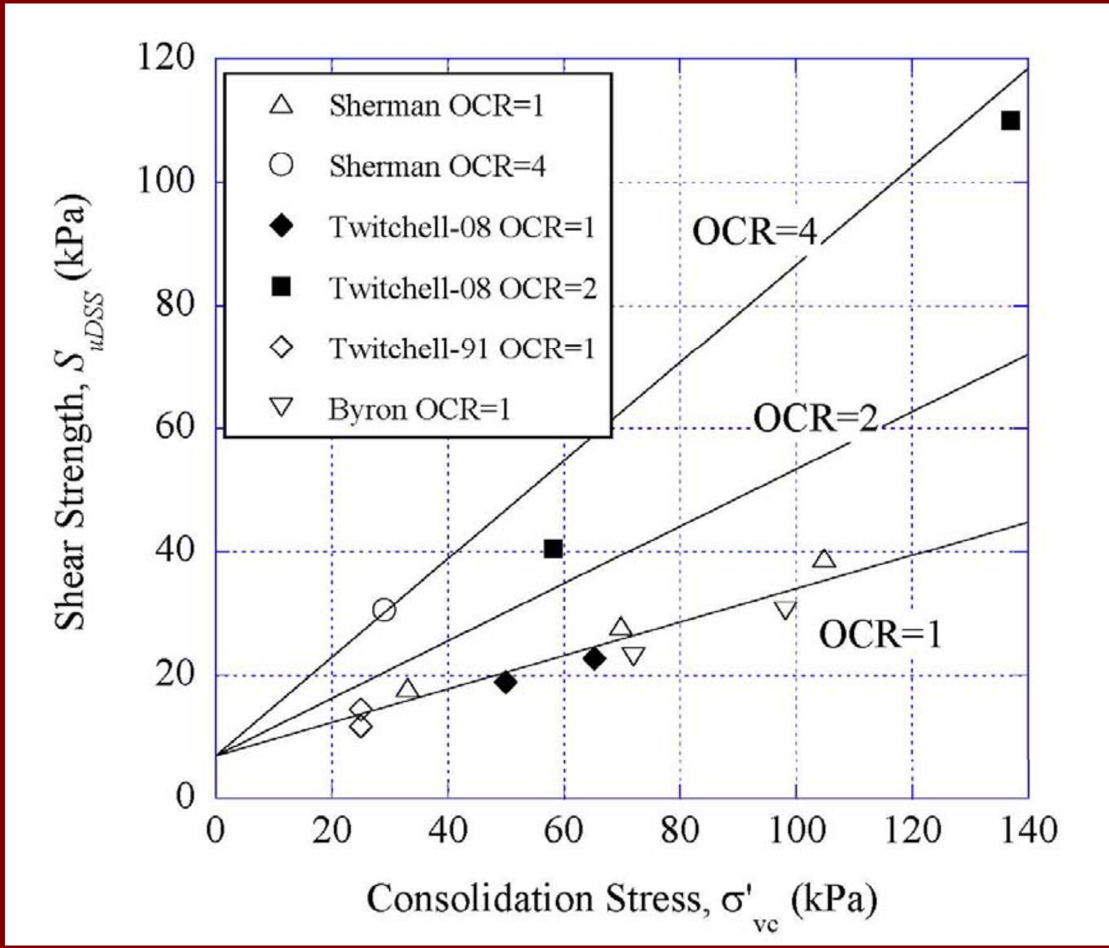


Sherman Island
Cross Levee Study



Brovold & Sisson (1995)
Byron Tract
Sherman Island
Twitchell Island

Direct Correlation, s_u vs. σ'_{v0}



Previous data supplemented by new tests in 2008

Conclusions from Peat Data

- Strength behavior linear
- Not normalizable due to intercept
- Undrained strength ratio tends to infinity
- Trend lines converge to a point (limited data for OC soil)
- Consistent w/previous data if strength intercept considered
- Physical source of intercept: fibers (?)

Best fit equation: $s_u = s_{u0} + \sigma'_{v0} S (OCR)^m$

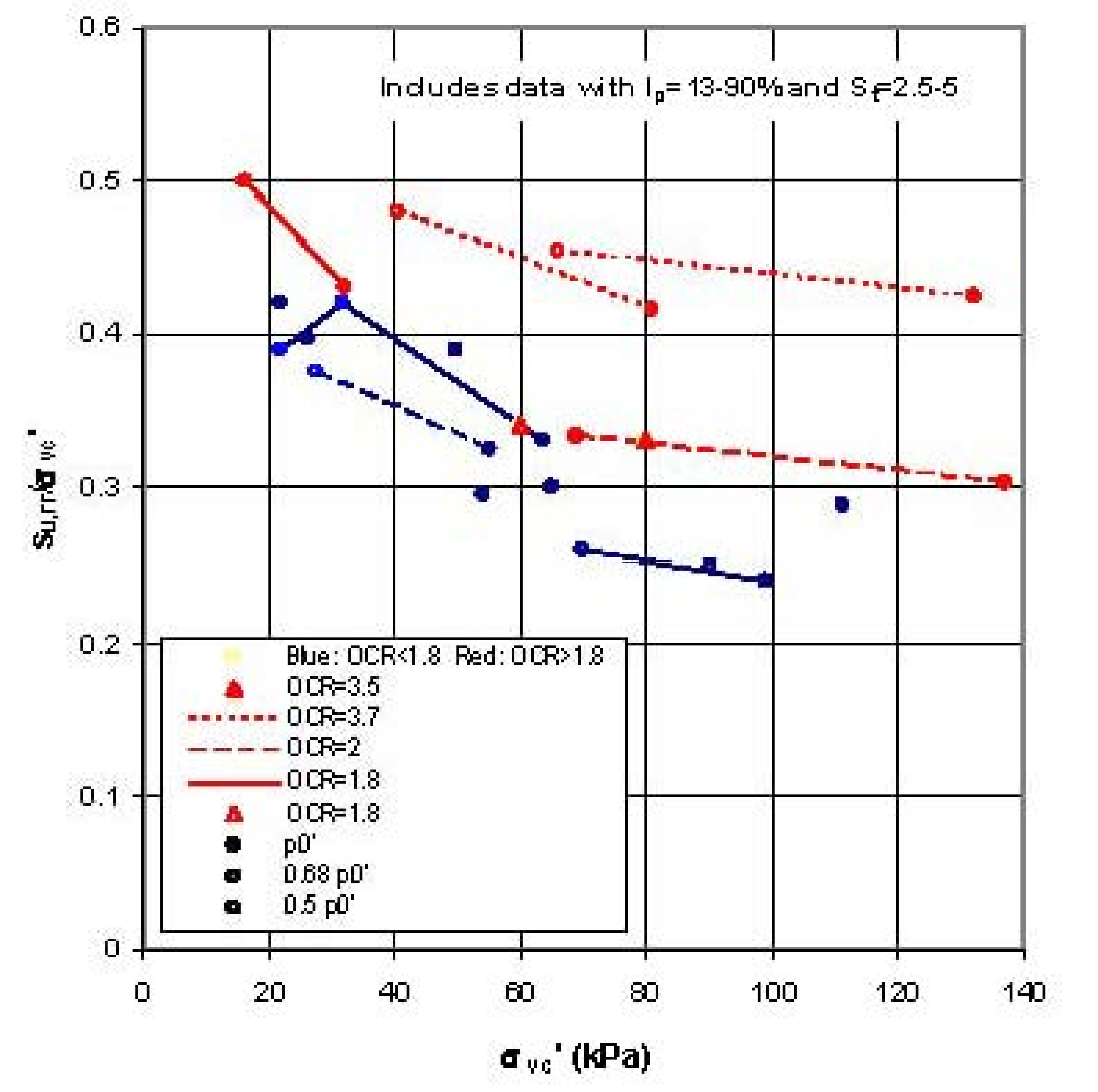
- s_{u0} = strength intercept ~ 5.5 kPa
- S = 0.27
- m = 0.8

Norwegian Geotechnical Institute (NGI) Investigations

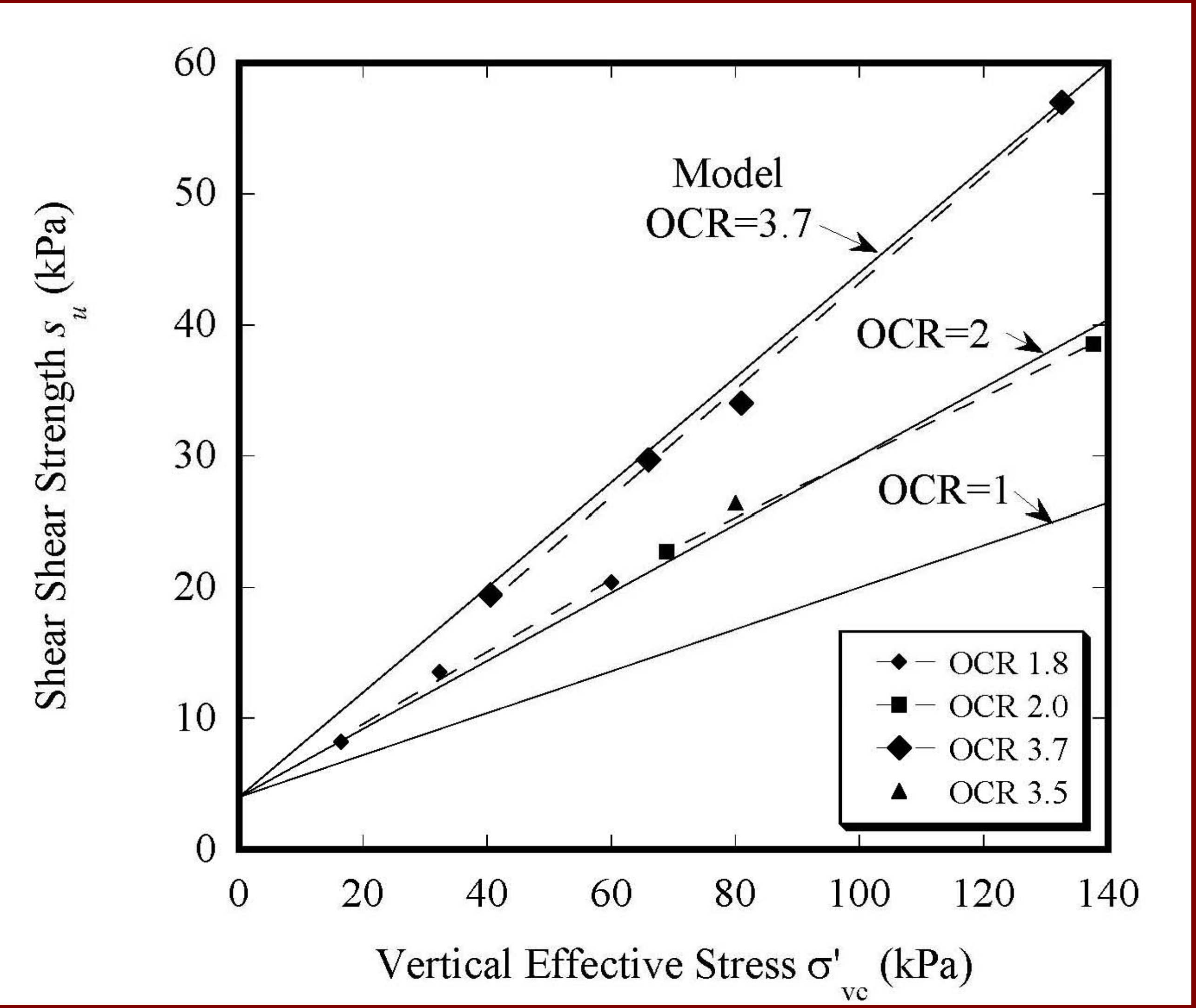
Lunne & Andersen (2008)

- Direct simple shear tests
- Inorganic soils
- Saturated
- Remolded (no cementation)

NGI Undrained Strength Ratio Data



Direct Correlation, s_u vs. σ'_{v0}



Comments on NGI Data

- Strength behavior linear
- Not normalizable due to intercept
- Undrained strength ratio tends to infinity
- Trend lines converge to a point
- Consistent w/previous data if strength intercept considered
- Physical source of intercept: (?)

Best fit equation: $s_u = s_{u0} + \sigma'_{v0}\, S\, (OCR)^m$

- s_{u0} = strength intercept ~ 4.5 kPa
- S = 0.15
- m = 0.8

Shallow Slope Failures

Beaumont Clay Slope Failures

Kayyal and Wright (1991)

- Compacted fill, $c'=0$
- Age of Slopes 12-31 years
- Slope Angles β = 16-26^o from horizontal
- Depth of Slide Mass 0.6-1.5 meters
- 18 Failures
- Estimated Friction Angle ϕ' = 25^o

Paris Clay Slope Failures

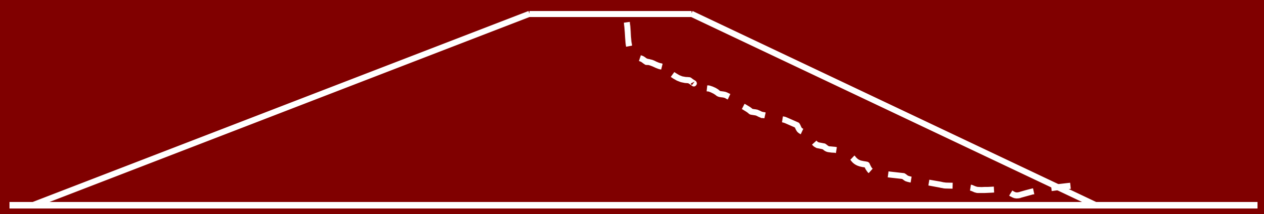
Kayyal and Wright (1991)

- Compacted fill, c'=0
- Age of Slopes 14-19 years
- Slope Angles β = 18-23^{o} from horizontal
- Depth of Slide Mass 0.6-3 meters
- 16 Failures
- Estimated Friction Angle ϕ' = 25^{o}

Back- Analysis from Infinite Slope Analysis
Aubeny & Lytton (2004)

Critical elements of analysis:

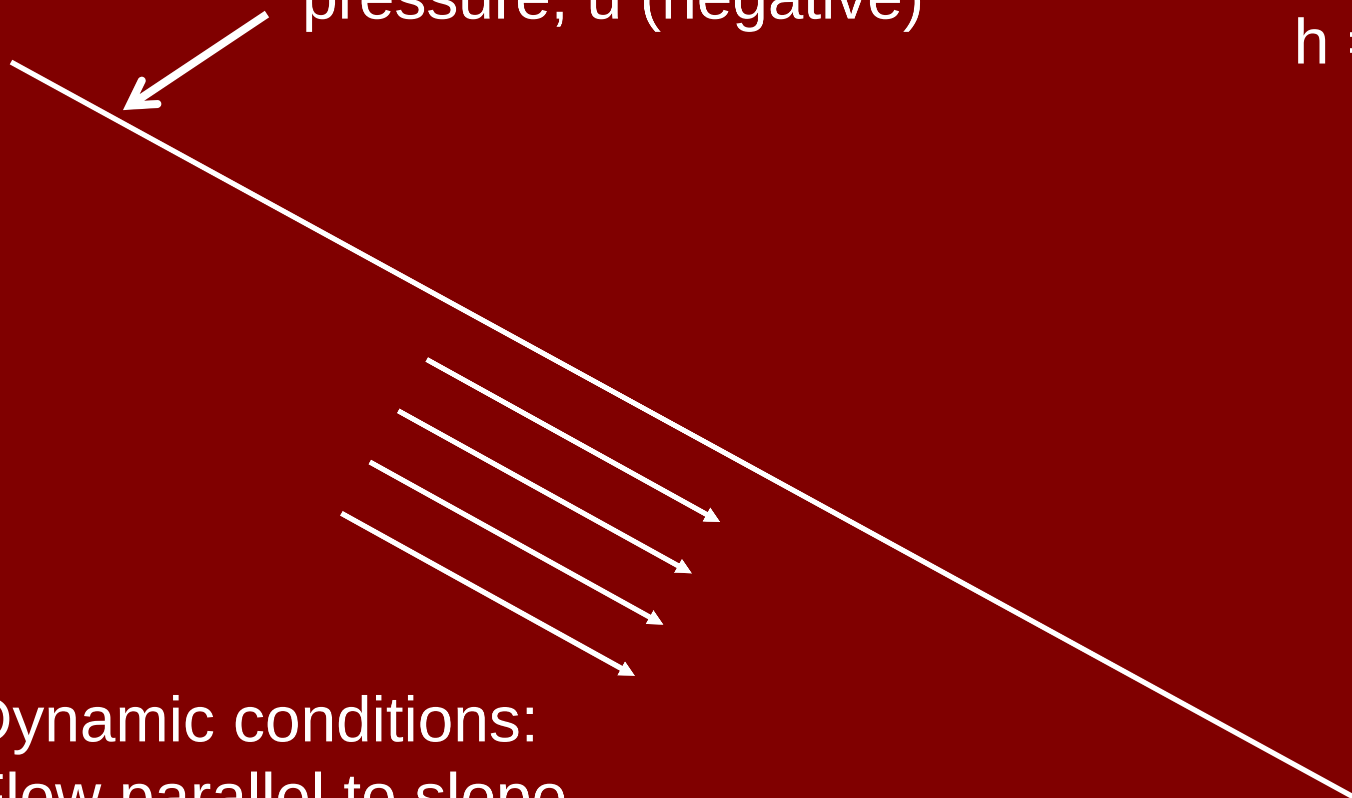
1. Characterization of flow state
2. Pore pressure distribution
3. Shear-induced pore pressures



Infinite Slope Analysis: Flow State

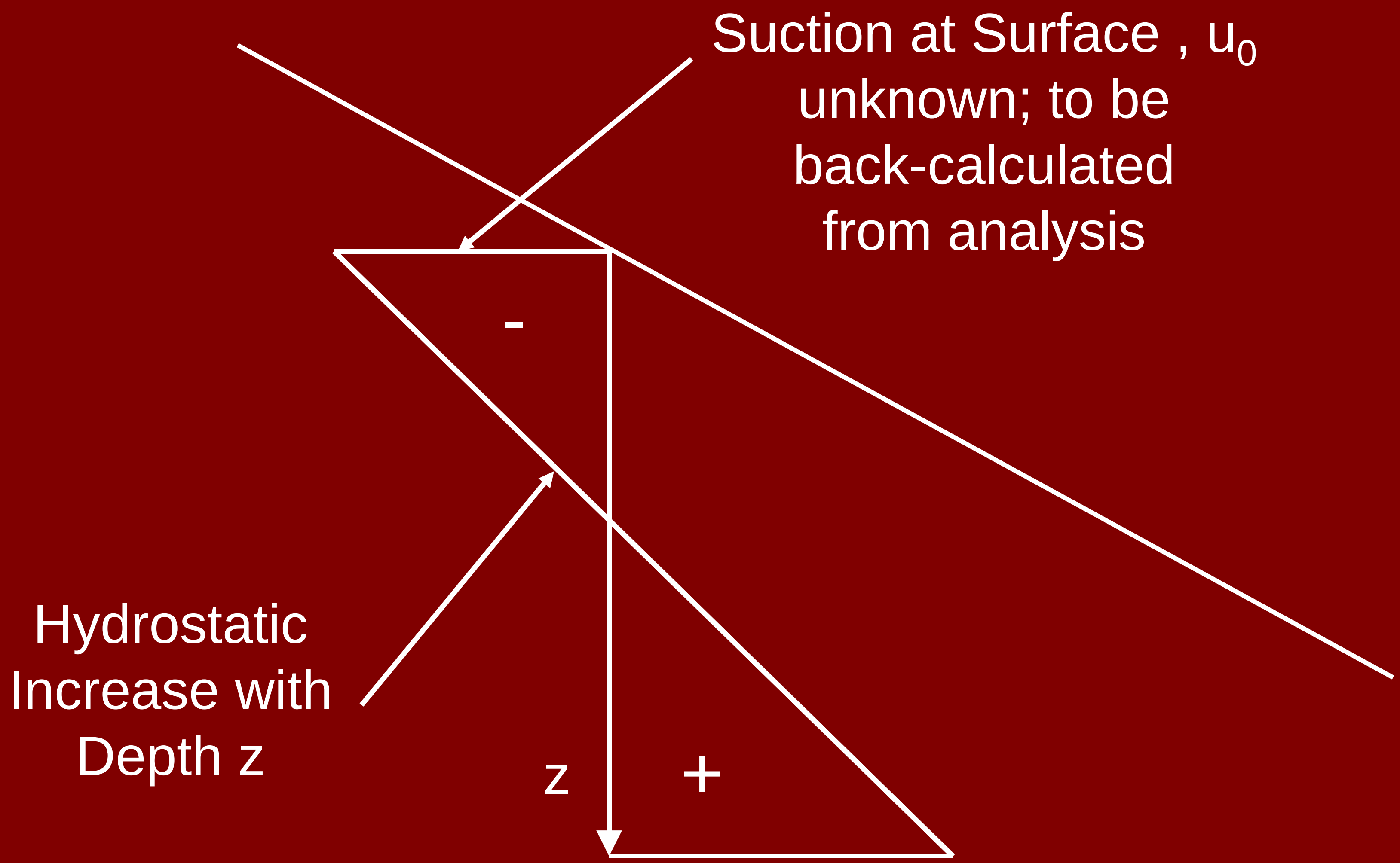
Uniform pore fluid pressure, u (negative)

Non-uniform total head
$h = z + u/\gamma_w$



Dynamic conditions:
Flow parallel to slope
$\Rightarrow$ Major destabilizing effect
(failures observed on very flat slopes

Pore Pressure Distribution



Stability Equation for Infinite Slope

$$FS = \left(\frac{\gamma_b}{\gamma} \right) \frac{\tan \varphi'}{\tan \beta} - \frac{u_0 \tan \varphi'}{\gamma H \sin \beta \cos \beta} - \sqrt{2/3}\, a_f \tan \varphi'$$

Mechanical Stress Contribution

Suction Contribution ($u_0 < 0$)

Shear-Induced Pore Pressure Effect

Back-Calculated Suction and Dimensionless Time Factors at Failure for Shallow Slides in Beaumont Clays

Case	Back-Calculated Surface Suction, $a_f = 0$		Back-Calculated Surface Suction, $a_f = 0.7$		Time Factor at Failure, T_f	
	u_{w0} (kPa)	u_{w0} (pF)	u_{w0} (kPa)	u_{w0} (pF)	$\alpha = 0.044$ m^2/yr	$\alpha = 0.126$ m^2/yr
1	-6.5	1.8	-14.7	2.2	0.76	2.25
2	-5.1	1.7	-13.3	2.1	0.88	2.61
3	-2.6	1.4	-7.1	1.9	2.79	8.32
4	-2.6	1.4	-8.7	1.9	1.29	3.85
5	-6.8	1.8	-15.5	2.2	0.67	2.01
6	-3.2	1.5	-8.8	2.0	1.15	3.44
7	-10.1	2.0	-21.7	2.3	0.44	1.31
8	-2.7	1.4	-7.4	1.9	1.66	4.95
9	-7.7	1.9	-15.4	2.2	1.09	3.25
10	-3.1	1.5	-7.3	1.9	2.54	7.56
11	-7.8	1.9	-18.4	2.3	0.38	1.15
12	-8.5	1.9	-19.4	2.3	0.54	1.61
13	-3.5	1.6	-9.3	2.0	0.81	2.42
14	-3.8	1.6	-10.3	2.0	0.59	1.77
15	-4.7	1.7	-10.3	2.0	1.05	3.12
16	-2.4	1.4	-6.2	1.8	2.35	7.00
17	-6.1	1.8	-13.0	2.1	1.47	4.38
18	-3.8	1.6	-10.3	2.0	0.93	2.78
Average	-5.0	1.7	-12.0	2.1	1.23	3.67
Std. Dev.	2.5	0.2	4.8	0.2	0.75	2.25

Best estimate of suction at surface:

$$u_0 = 7.8 \text{ kPa}$$

Back-Calculated Suction and Dimensionless Time Factors at Failure for Shallow Slides in Paris Clays

Case	Back-Calculated Surface Suction, a_f =0		Back-Calculated Surface Suction, a_f =0.7		Time Factor at Failure, T_f	
	u_{w0} (kPa)	u_{w0} (pF)	u_{w0} (kPa)	u_{w0} (pF)	α = 0.044 m^2/yr	α = 0.126 m^2/yr
1	-4.9	1.7	-12.7	2.1	0.62	1.85
2	-7.5	1.9	-16.5	2.2	0.48	1.42
3	-10.8	2.0	-26.9	2.4	0.15	0.44
4	-8.9	2.0	-21.3	2.3	0.27	0.79
5	-16.0	2.2	-37.2	2.6	0.10	0.29
6	-8.8	2.0	-18.3	2.3	0.66	1.98
7	-8.9	2.0	-21.3	2.3	0.27	0.79
8	-13.2	2.1	-27.5	2.4	0.28	0.83
9	-6.2	1.8	-15.9	2.2	0.38	1.12
10	-6.4	1.8	-14.9	2.2	0.60	1.79
11	-2.1	1.3	-5.8	1.8	2.32*	6.92*
12	-6.4	1.8	-14.9	2.2	0.62	1.89
13	-13.2	2.1	-27.5	2.4	0.29	0.88
14	-13.2	2.1	-27.5	2.4	0.29	0.88
15	-4.9	1.7	-12.7	2.1	0.62	1.85
16	-6.4	1.8	-14.9	2.2	0.63	1.89
Average	-8.6	1.9	-19.8	2.3	0.42	1.25
Std. Dev.	3.8	0.2	7.9	0.2	0.20	0.59

*Excluded from average.

Best estimate of suction at surface:

u_0 = 12 kPa

Estimated Strength: Wetted Soils for Zero Applied Stress

- Beaumont Clays:

  s_{u0} = 7.8 kPa x tan 25^0 = 3.6 kPa

- Paris Clays:

  s_{u0} = 12 kPa x tan 25^0 = 5.6 kPa

Note: NGI data showed s_{u0} = 4.5 kPa

Implications of Shallow Slope Studies

- Wetting of slope triggers failures
- Suction decreases as wetting occurs
- Suction does not trend to zero
- Lower limit of suction on order of 7-12 kPa
- Lower suction limit consistent with totally independent assessment of strength at low stress levels measured by DSS

Conclusions

- Non-zero strength intercept in peat – expected
- Non-zero intercept in inorganic soils also
- Lower bound strength & suction consistent
- USR approach not applicable at low stress
- SHANSEP still applicable if modified

Thank You!