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AT URBANA-CHAMPAIGN

Static and Seismic Strength Parameters for Stability Analyses

TIMOTHY D. STARK, Ph.D., P.E., D.GE
University of Illinois at Urbana-Champaign
tstark@illinois.edu

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illinois.edu

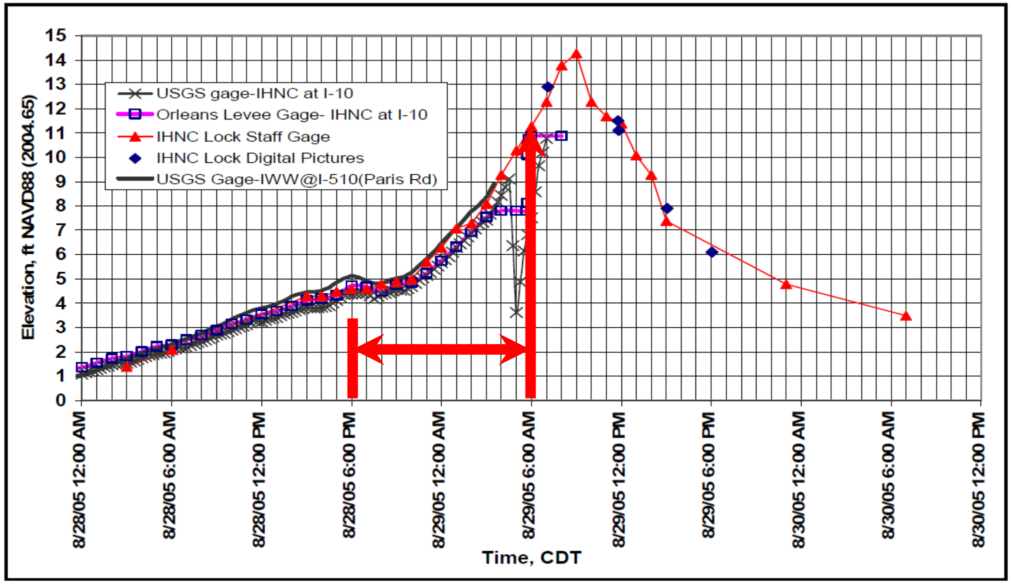
Outline

- Drained v. Undrained Analyses
- Static/Drained Shear Strengths
- Static Slope Stability Analyses
- Seismic/Undrained Shear Strengths
- Summary

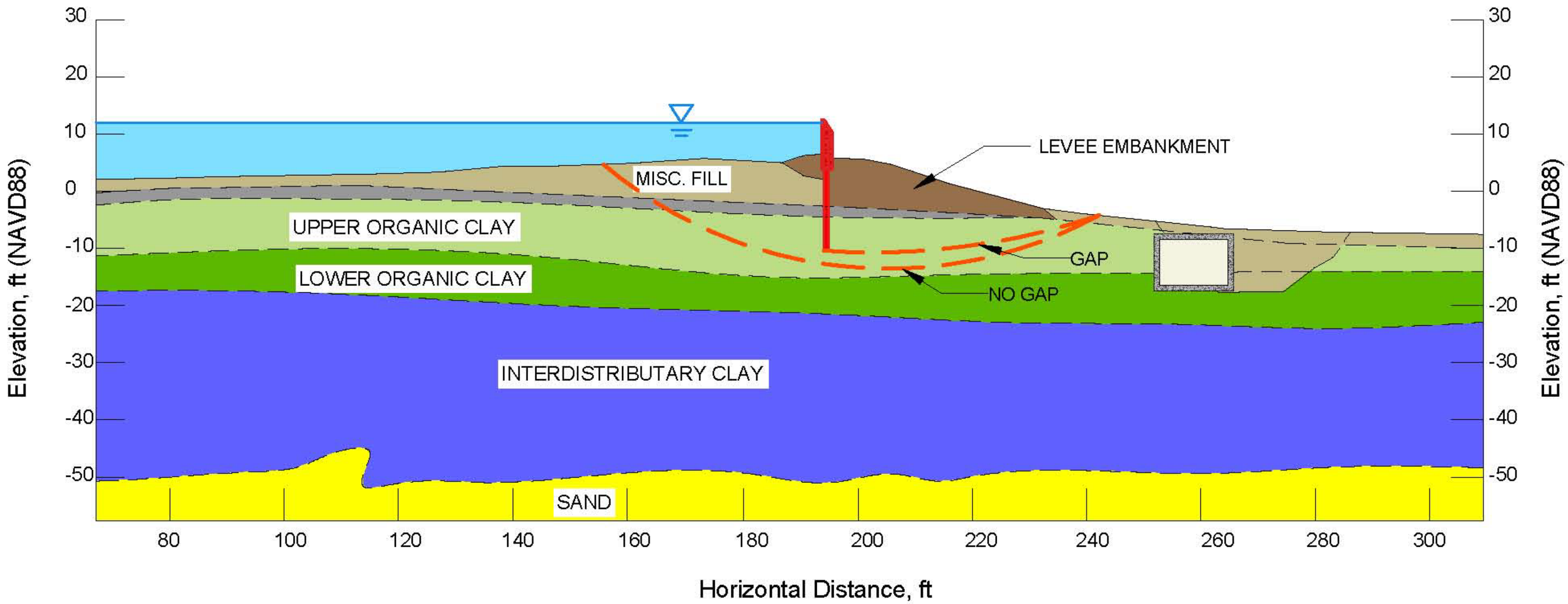
Drained vs. Undrained Behavior

USACE Photos

IPET (2006)



Hurricane Storm Surge



USACE Photo

Drained v. Undrained Factors of Safety

- Undrained/Total Stress

$$FS = \left[\frac{c + \sigma * \tan(\phi)}{W * Sin(\beta)} \right] * L = \left[\frac{S_u}{W * Sin(\beta)} \right] * L$$

- Drained/Effective Stress

$$FS = \left[\frac{c' + \sigma' * \tan(\phi')}{W * Sin(\beta)} \right] * L = \left[\frac{c' + (\sigma - u) * \tan(\phi')}{W * Sin(\beta)} \right] * L$$

Drained v. Undrained Analyses

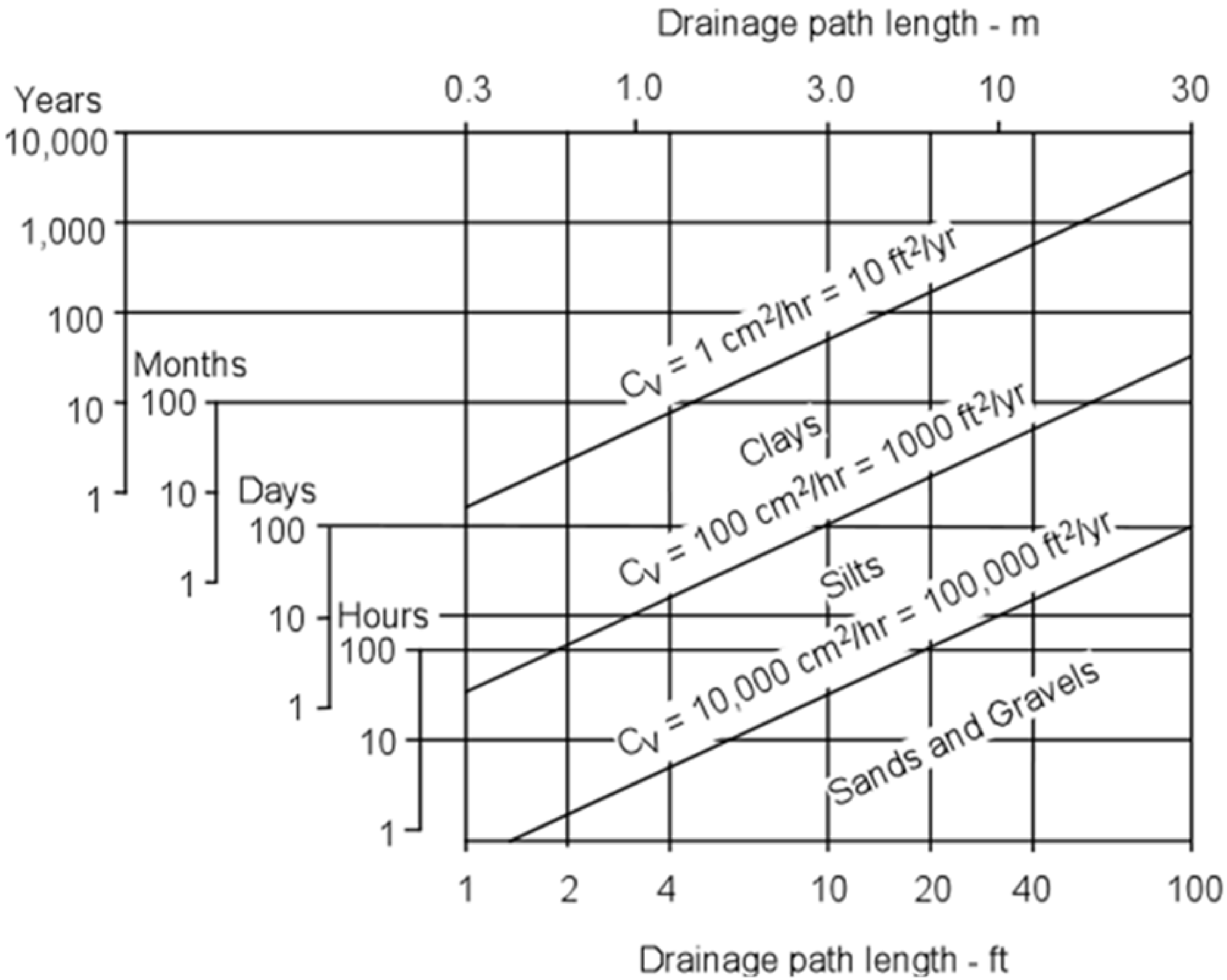


Figure from Duncan and Wright (2005)

- Time required for Drainage (99% dissipation of excess pore-water pressure)

Rainfill-Induced Landslide

LaConchita, California - 1995

Images from Jibson (2006)

Outline

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- Summary

Types of Drained Strengths

- **INTACT OVERCONSOLIDATED PEAK STRENGTH**
  Rare
- **JOINTED OVERCONSOLIDATED PEAK STRENGTH**
- **FULLY SOFTENED STRENGTH**
- **RESIDUAL STRENGTH**

Types of Drained Strengths

- **INTACT OVERCONSOLIDATED PEAK STRENGTH**
- **JOINTED OVERCONSOLIDATED PEAK STRENGTH**
  Brittle with Jointing or Fracturing & NO Softening
- **FULLY SOFTENED STRENGTH**
- **RESIDUAL STRENGTH**

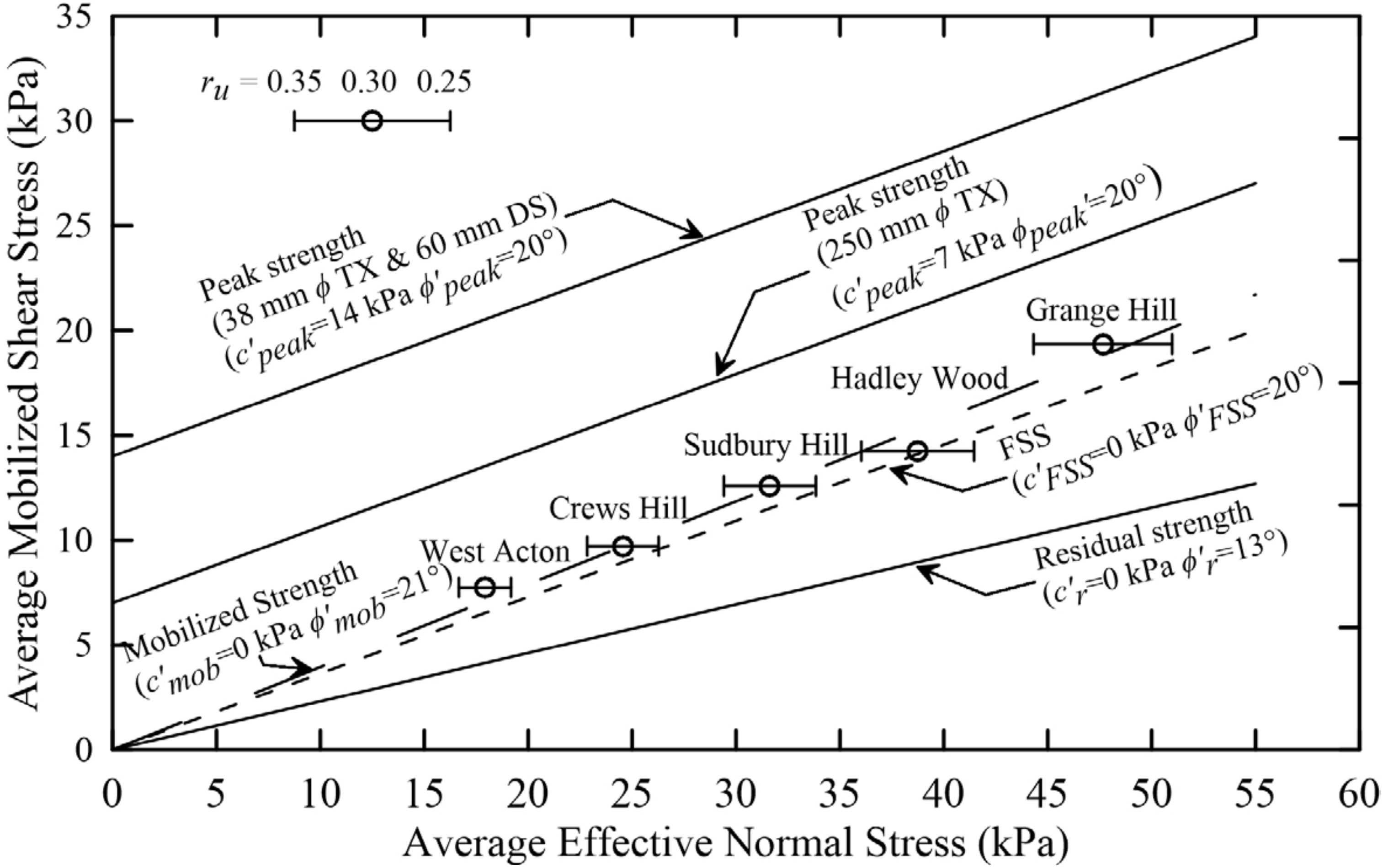
Types of Drained Strengths

- **INTACT OVERCONSOLIDATED PEAK STRENGTH**
- **JOINTED OVERCONSOLIDATED PEAK STRENGTH**
- **FULLY SOFTENED STRENGTH**
- **RESIDUAL STRENGTH**

Fully Softened Strength

- **No Shear Displacement (First-Time Slide) - Skempton, 1977**
- **Fissured or Fractured Overconsolidated Clays**
- **Compacted Fills**

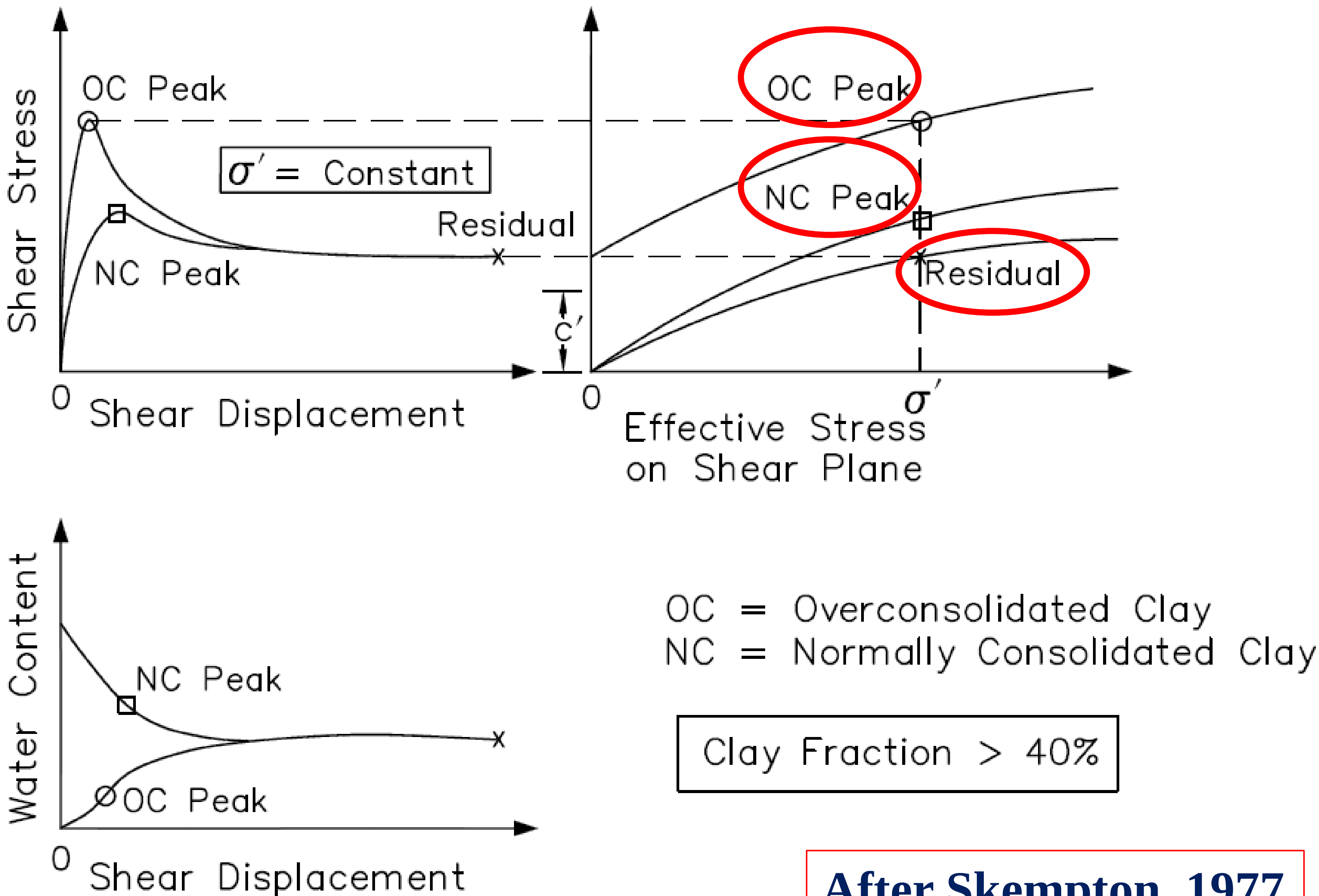
After Skempton (1977)



Types of Drained Strengths

- INTACT OVERCONSOLIDATED PEAK STRENGTH
- JOINTED OVERCONSOLIDATED PEAK STRENGTH
- FULLY SOFTENED STRENGTH
- RESIDUAL STRENGTH

Summary of Drained Strengths



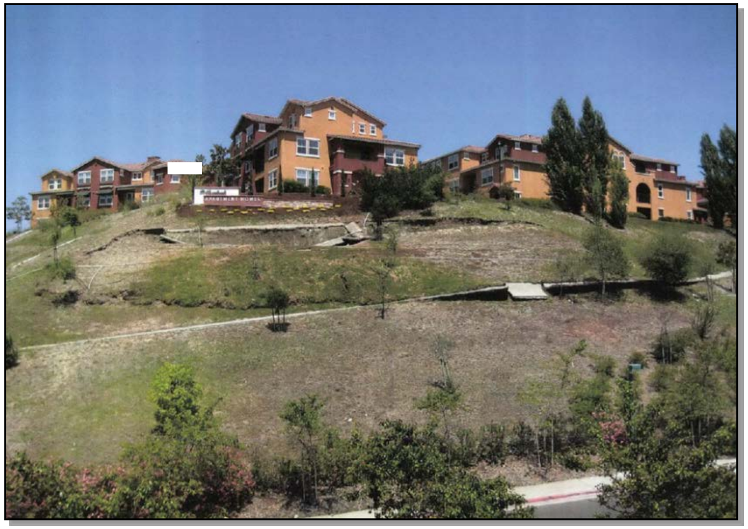
After Skempton, 1977

Fully Softened Strength Applications

- Overconsolidated Materials
  - Compaction
  - Mechanically Overconsolidated
  - Desiccation
- Subjected to Softening
  - Applied Shear Stress
  - Shallow Depth
  - Cycles of Wetting and Drying

Compaction

- Levees
- Highway Embankments
- Compacted Fill Slopes



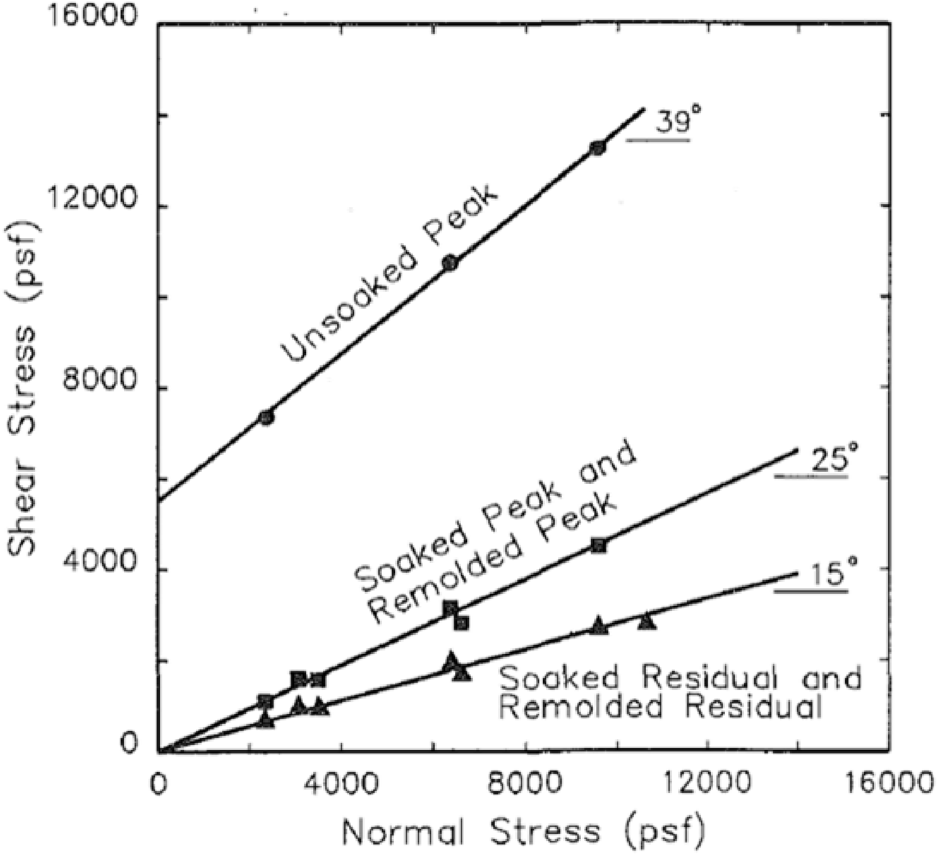
Photos from D. Steussey

Mechanically Overconsolidated

- Natural or Cut Slopes

Desiccation

California DWR Photos



- Stark and Duncan (1991)
- Stark (1987)

FSS Applications

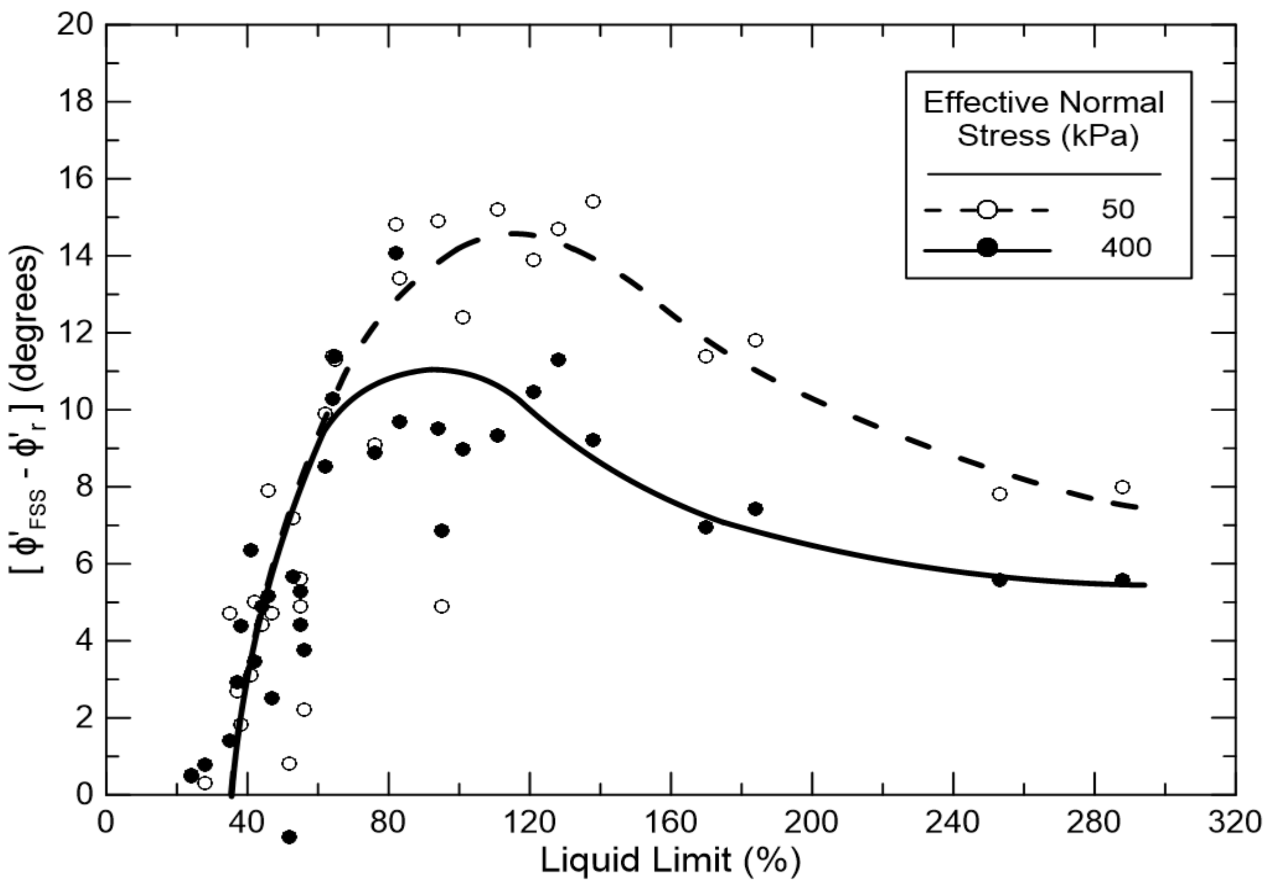
- “First-Time Slides”

FSS v. Residual

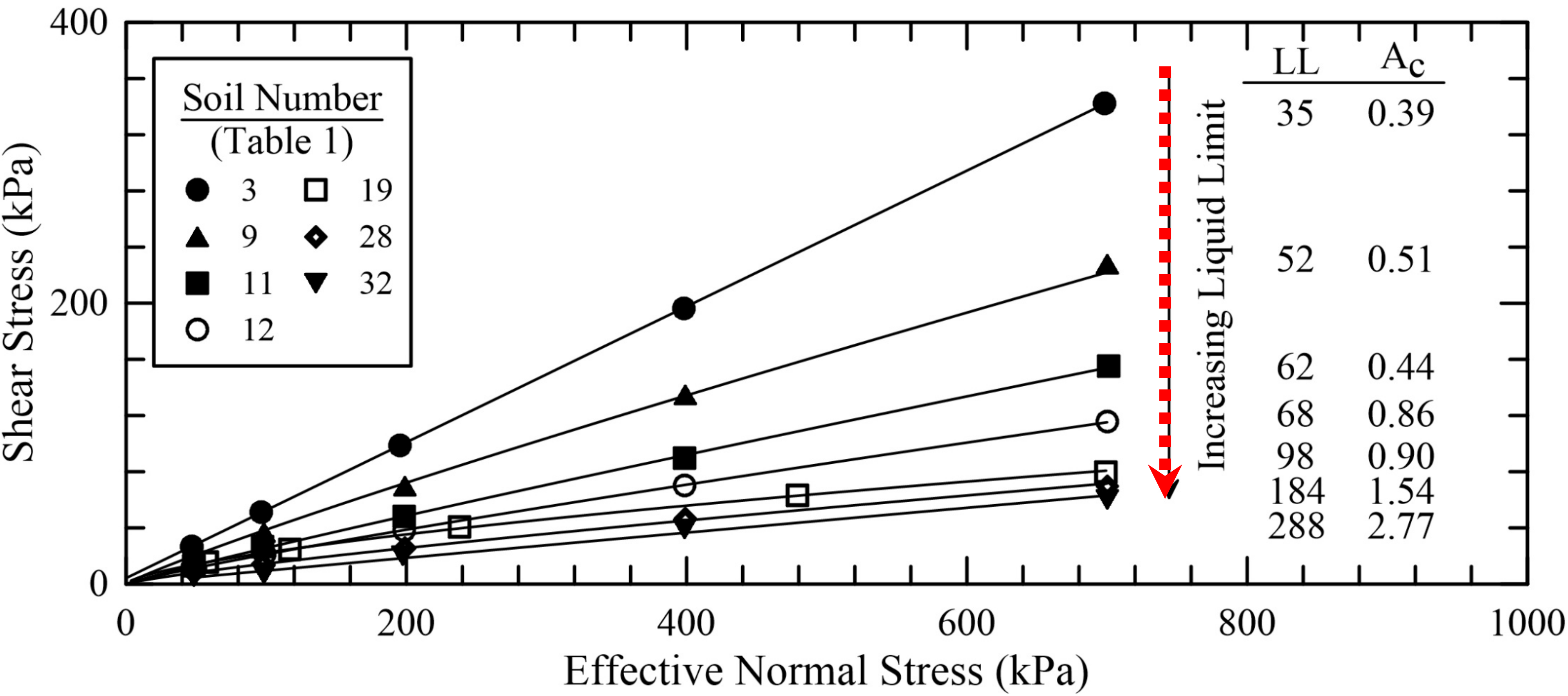
FSS v. Residual

- Prior shear displacement = ?
- Greater potential for progressive failure
- FS (FSS) >1.5
- FS (Residual) > 1.0

- Stark and Eid (1997)
- Stark et al. (2015)



Empirical Correlations

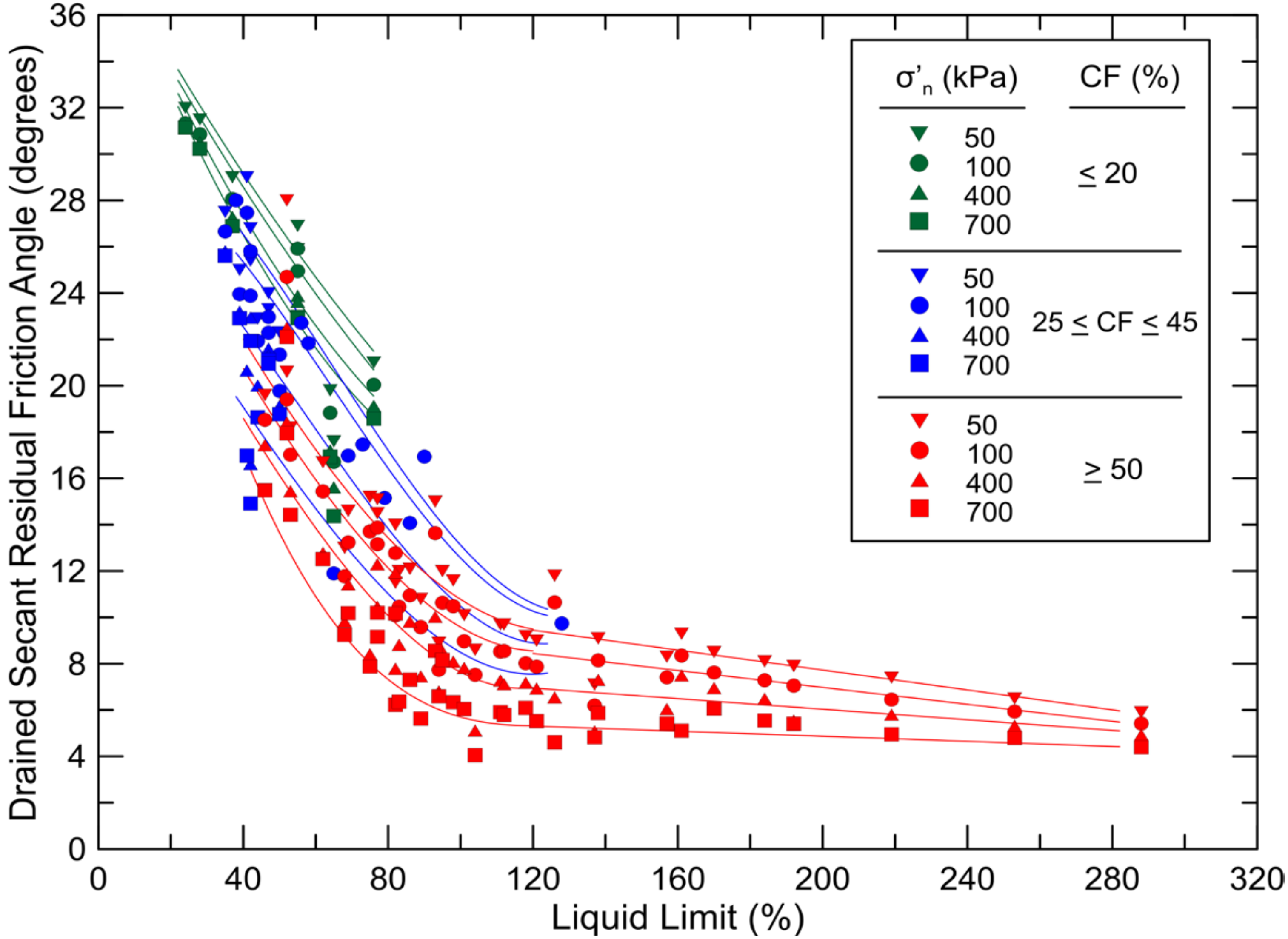


Stark and Eid (1994)

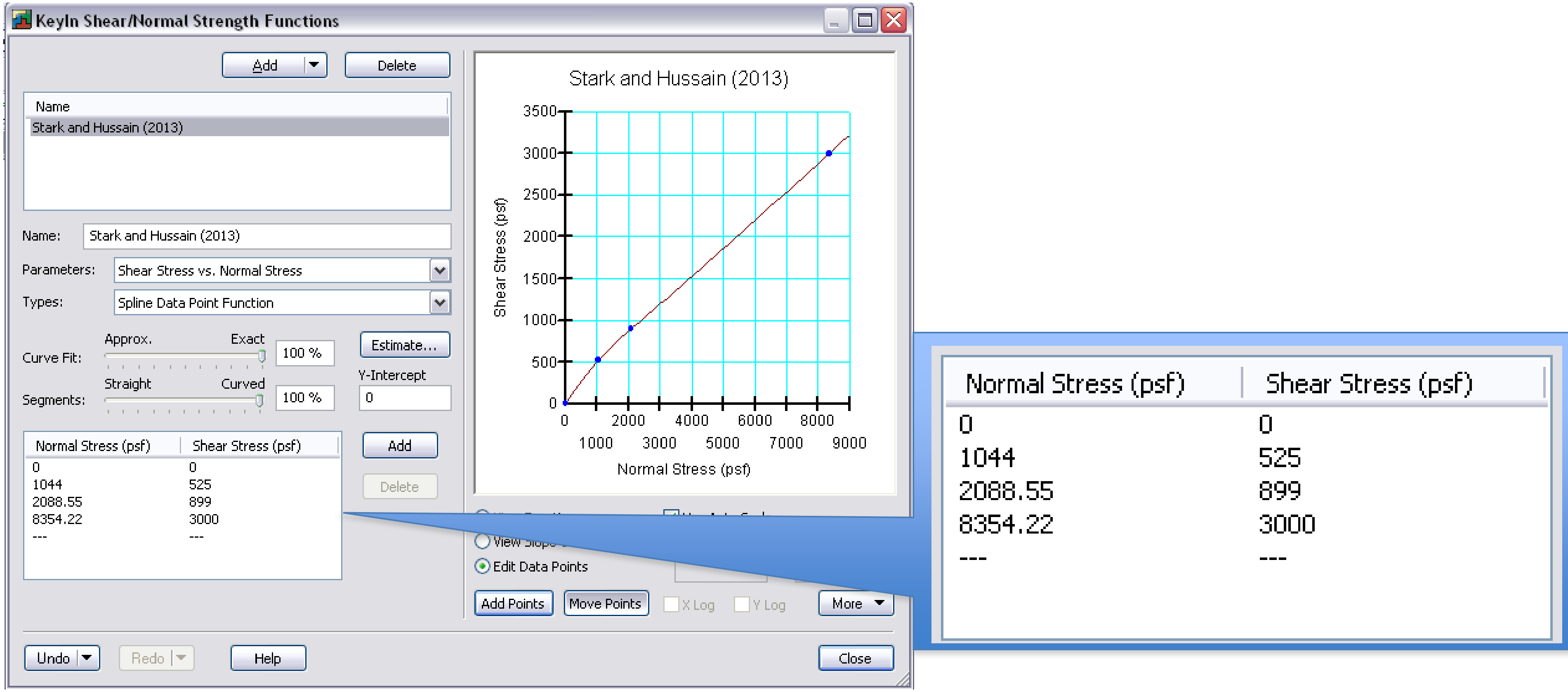
- **Liquid Limit**
- **Clay-Size Fraction**
- **Stress Dependent**

Residual Strength Correlation

- Stark et al. (2018)

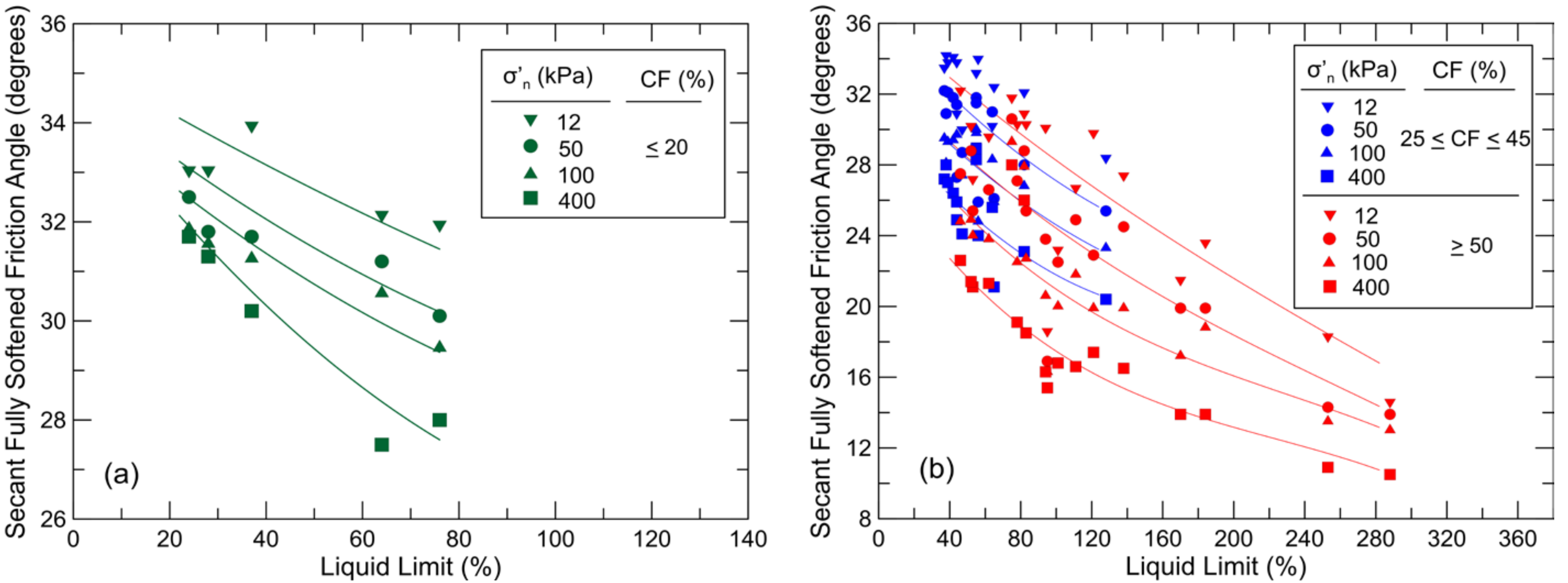


Stress Dependent Strength Envelope



FSS Correlation

- Stark et al. (2018)



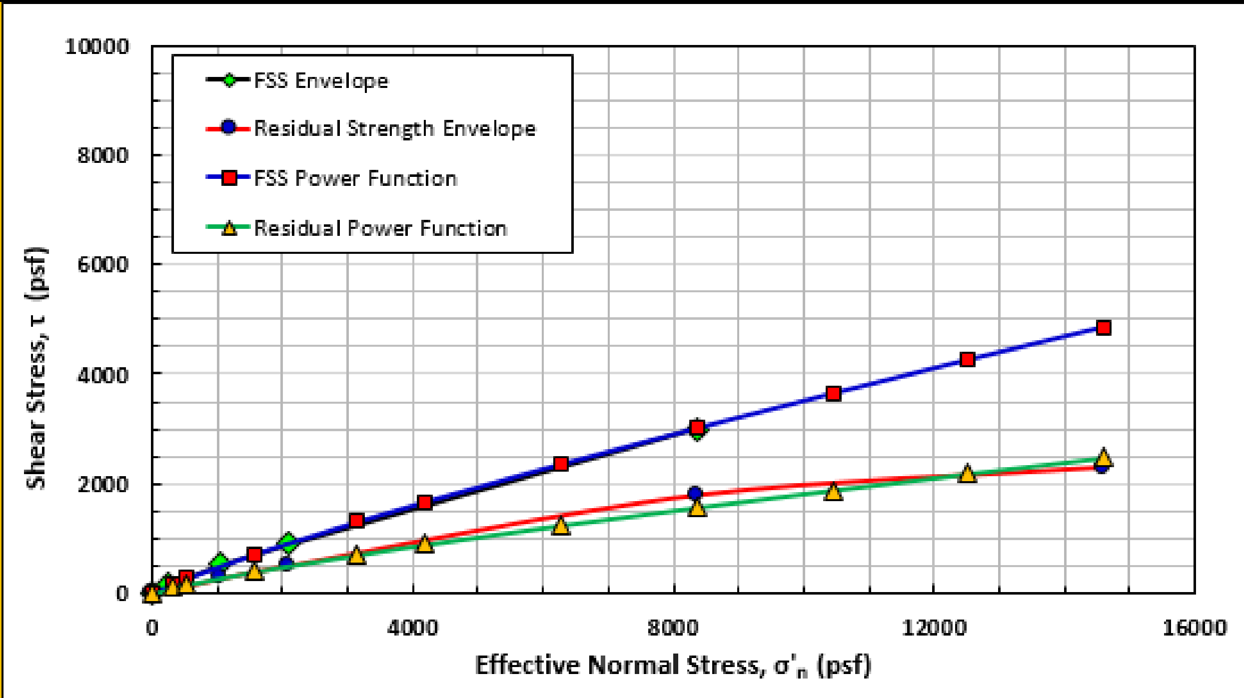
Empirical Correlation Spreadsheet

Drained Residual and Fully Softened Secant Friction Angles & Shear Stresses

Equations developed by Stark and Hussain (2013) and Stark et. al (2016)

Input	
LL (%)	CF (%)
70	60

Output	Secant Friction Angle, ϕ' (degrees)					Shear Stress, τ (psf)					
σ'$_n$ (kPa/psf)	12/250	50/1,044	100/2,088	400/8,354	700/14,620	0	250	1044	2088	8354	14620
Residual	NA	15.2	13.9	12.1	8.9	0.00	NA	284.0	515.6	1790.6	2296.7
Fully Softened	30.5	26.7	23.3	19.8	NA	0.00	147.4	525.5	898.8	3000.0	NA



FSS & Residual Power Functions

$$\tau_{FSS} = 0.44 * 2115.7\,\text{psf} * \left(\frac{\sigma(\text{psf})}{2115.7\ \text{psf}}\right)^{0.852}$$

$$\tau_{R} = 0.243 * 2115.7\,\text{psf} * \left(\frac{\sigma(\text{psf})}{2115.7\,\text{psf}}\right)^{0.81}$$

σ'$_n$(psf)	Φ'$_R$(deg)	τ$_R$(psf)	Φ'$_{FSS}$(deg)	τ$_{FSS}$(psf)
0	0	0	0	0
313	19.2	109	30.4	184
522	17.5	165	28.6	284
1566	14.4	403	24.8	725
3133	12.7	708	22.7	1308
4177	12.1	895	21.8	1672
6266	11.2	1244	20.7	2362
8354	10.7	1572	19.9	3018
10443	10.2	1885	19.3	3649
12531	9.9	2186	18.8	4263
14620	9.6	2478	18.4	4861

Aplicable Range	LL (%) Minimum	LL (%) Maximum
Group #1 (CF ≤20%)	30	80
Group #2 (25≤CF ≤45%)	30	130
Group #3 (CF ≥50%)	30	300

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Effect of Cohesion

$$FS = \frac{\tau_{\max}}{S_m} = \frac{\sum \{c' * \Delta l + \sigma' \tan\phi' * \Delta l\}}{\sum \{W \sin\alpha\}}$$

Moment Equilibrium

Cohesion

- **FULLY SOFTENED STRENGTH**
  - **- Normally Consolidated Clay (c'_{FSS} ~ 0)**
- **RESIDUAL STRENGTH**
  - **- Sheared**
  - **- Face-to-Face Orientation**
  - **- $c_R' \approx 0$**
- **Use stress dependent envelope**

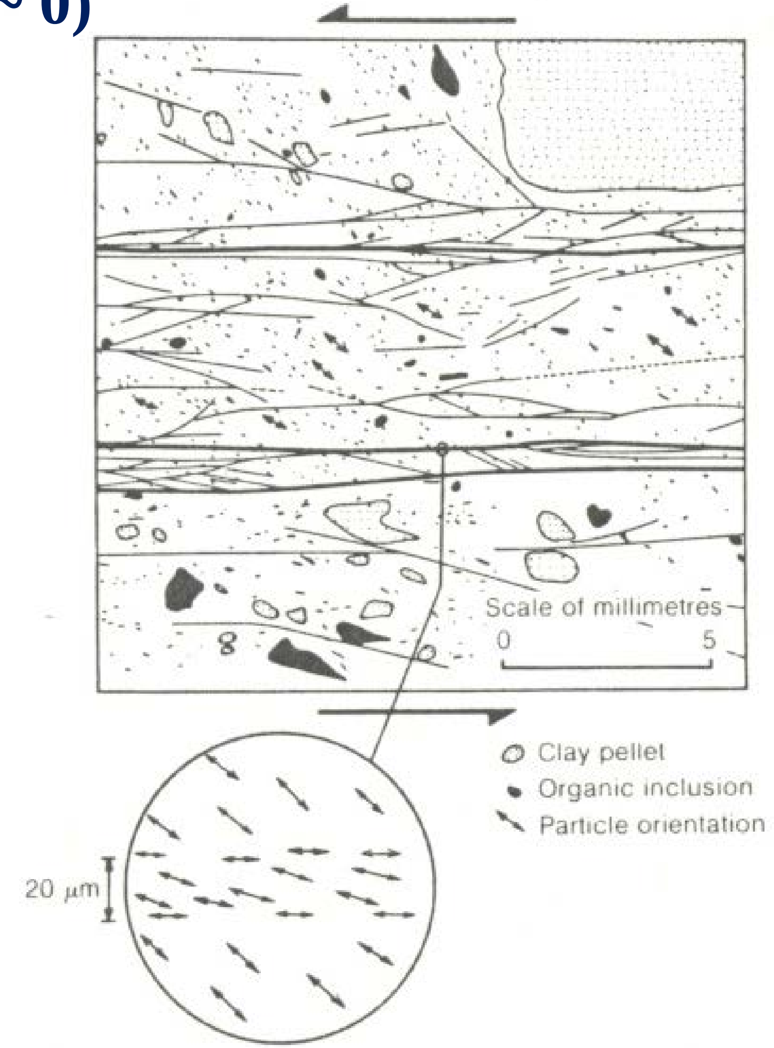

Figure from Skempton (1985)

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Seismic Shear Strengths

- Effect of Cyclic Loading
- Effect of Shear Displacement

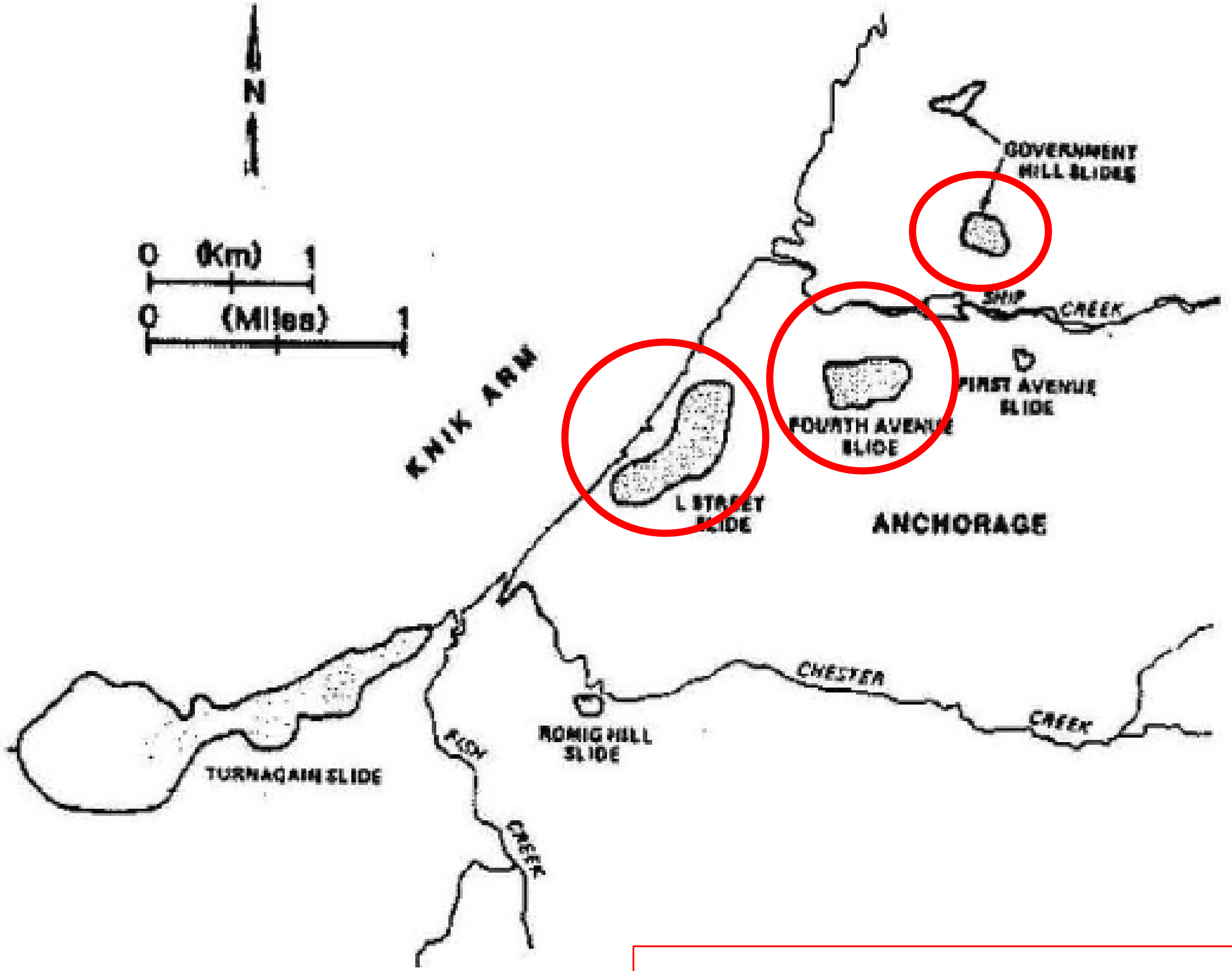
Effect of Cyclic Loading

- Makdisi and Seed (1978)
- Strength to estimate yield coefficient
- NO permanent deformation – elastic range
- Clayey soils ≥ 80% static undrained peak strength

Seismic Shear Strengths

- Effect of Cyclic Loading
- Effect of Shear Displacement

1964 Alaska Earthquake



(Mw= 9.2)

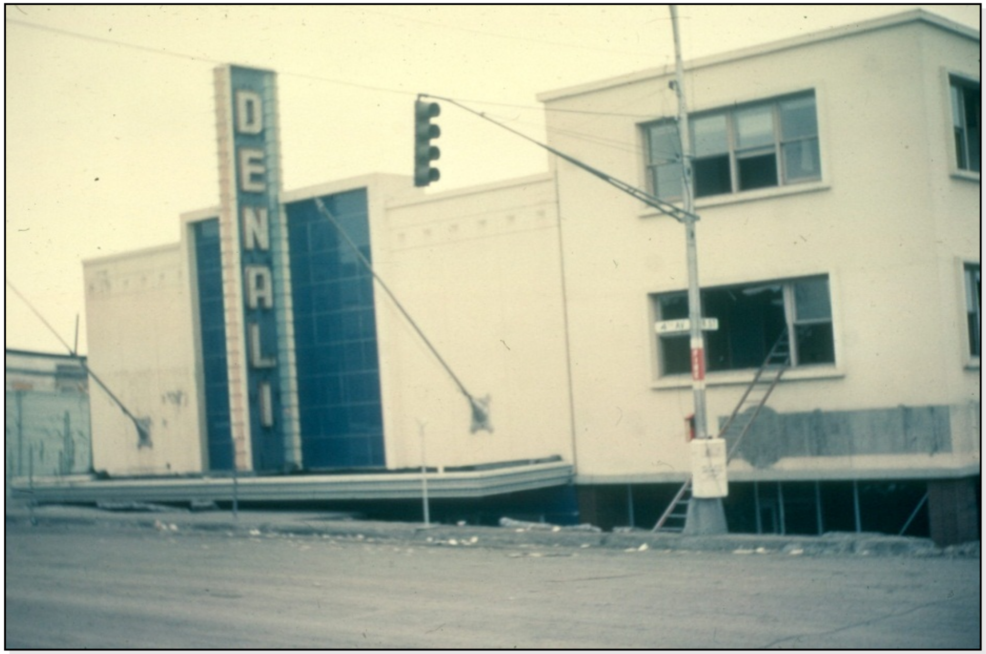
after Idriss, 1985

Government Hill Landslide

- **Movement of Slide Blocks**

Photos from R.B. Peck

Fourth Avenue Landslide



Photos from R.B. Peck

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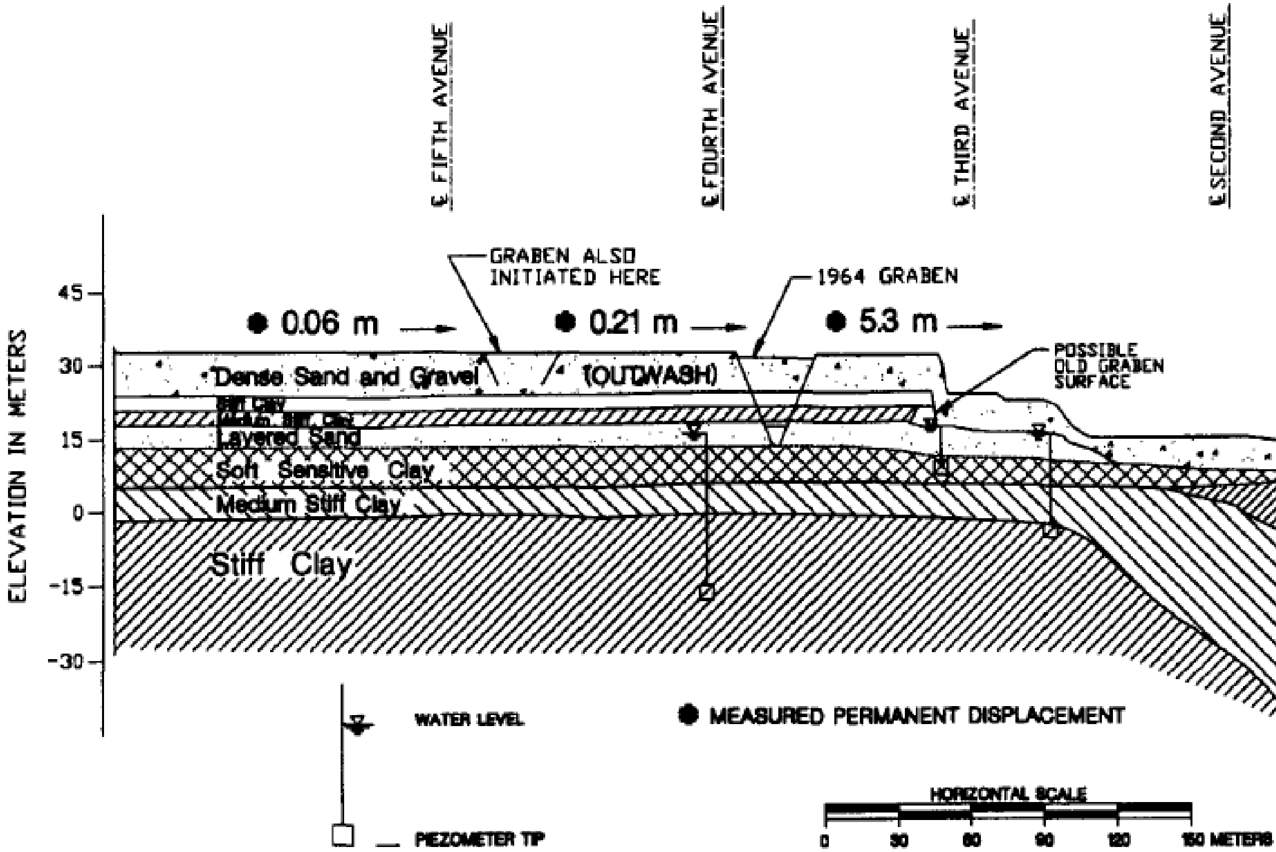


Stark and Contreras
(Feb., 1998, ASCE JGGE)

Fourth Avenue Landslide

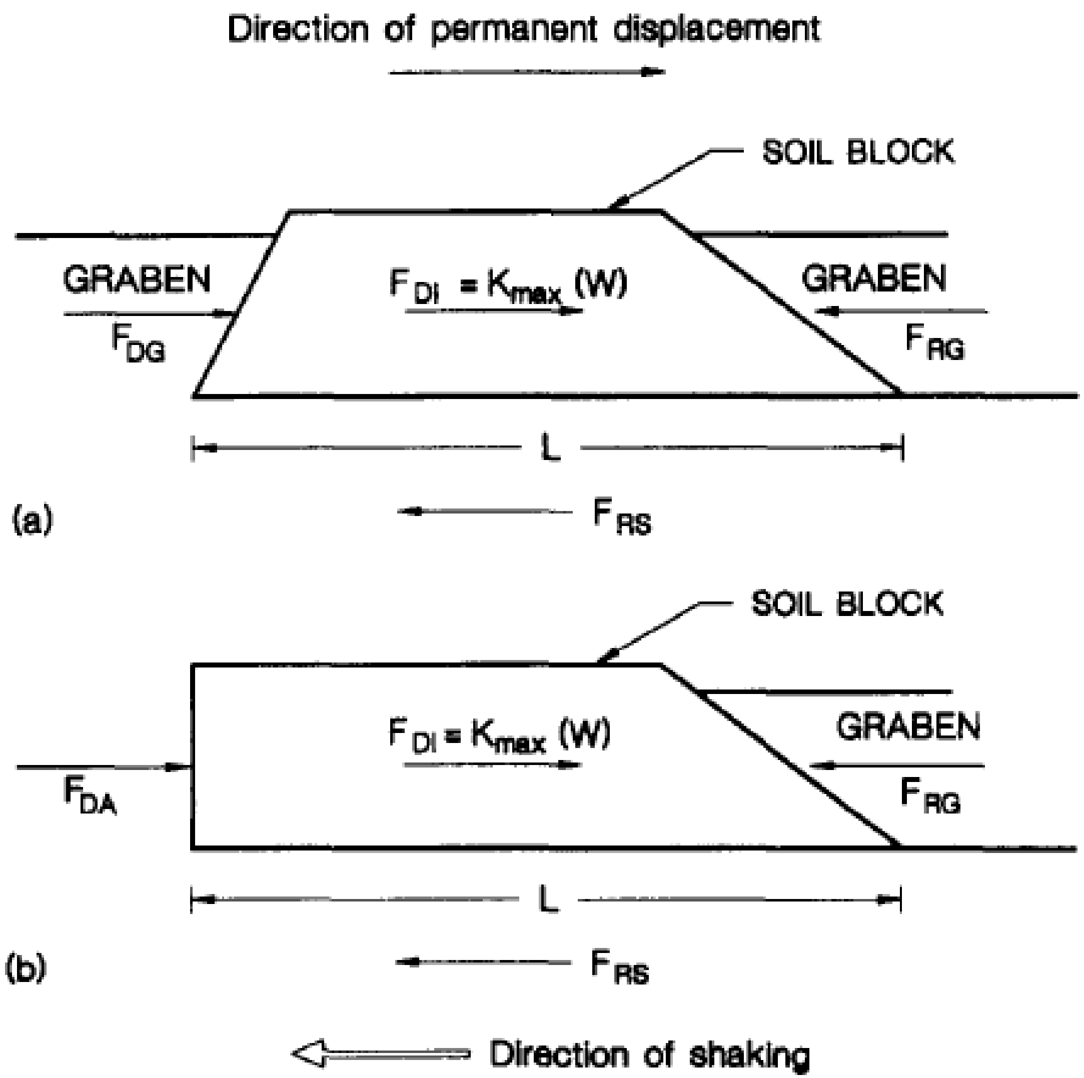
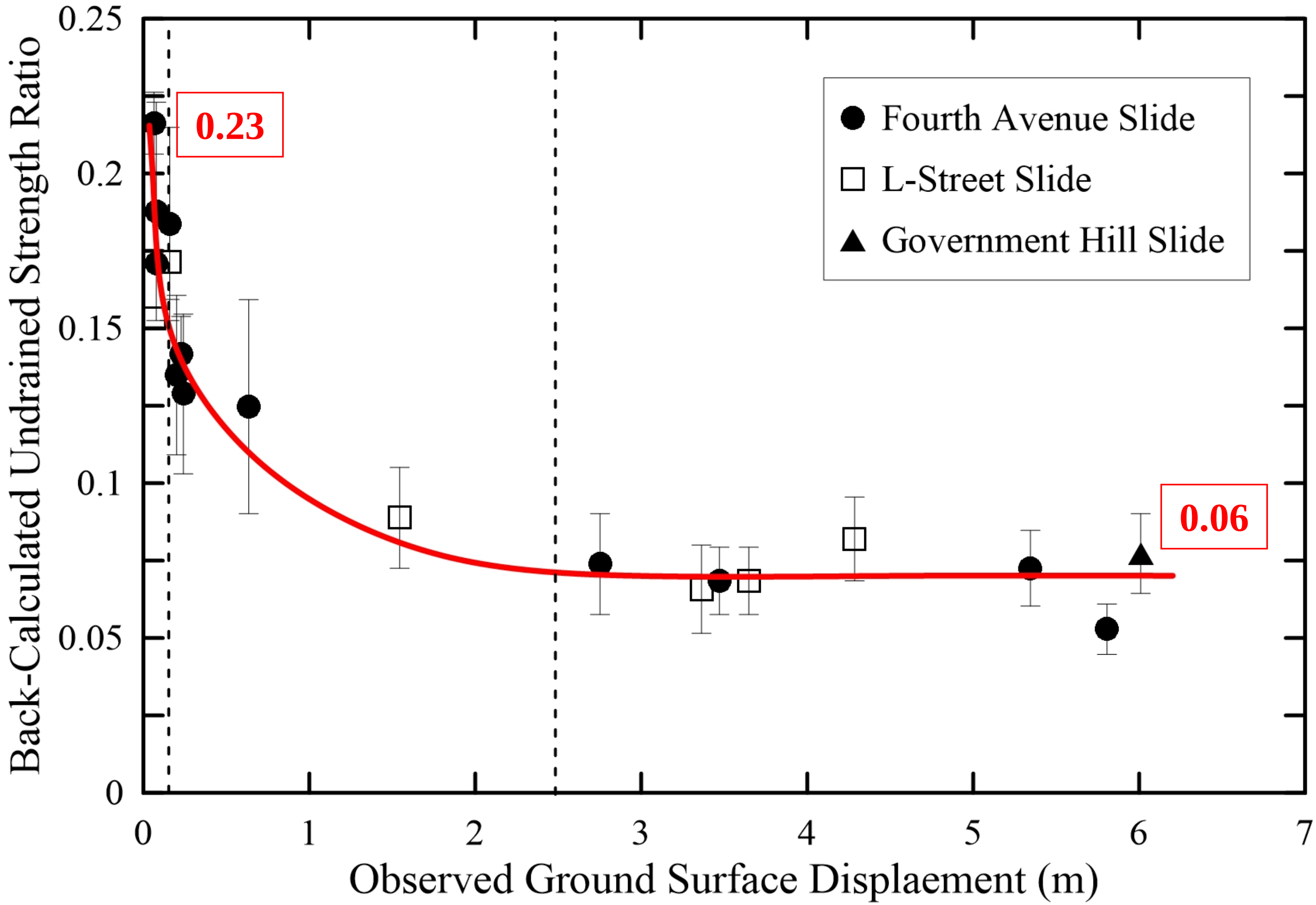


FIG. 7. Forces Used in Analysis for Calculating Permanent Lateral Displacement Due to Earthquake Ground Motions

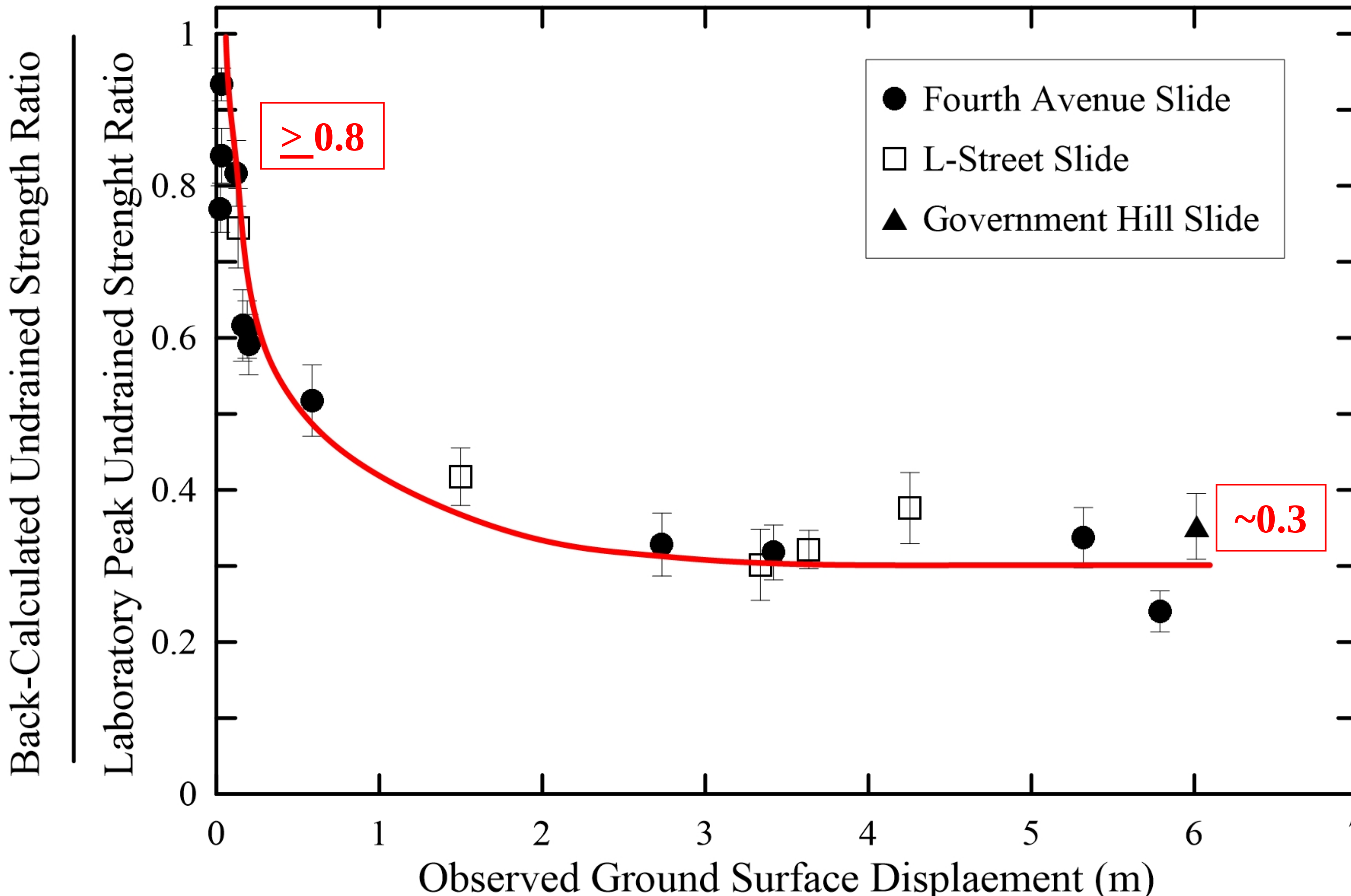
Stark and Contreras (Feb., 1998, ASCE JGGE)

Fourth Avenue Landslide



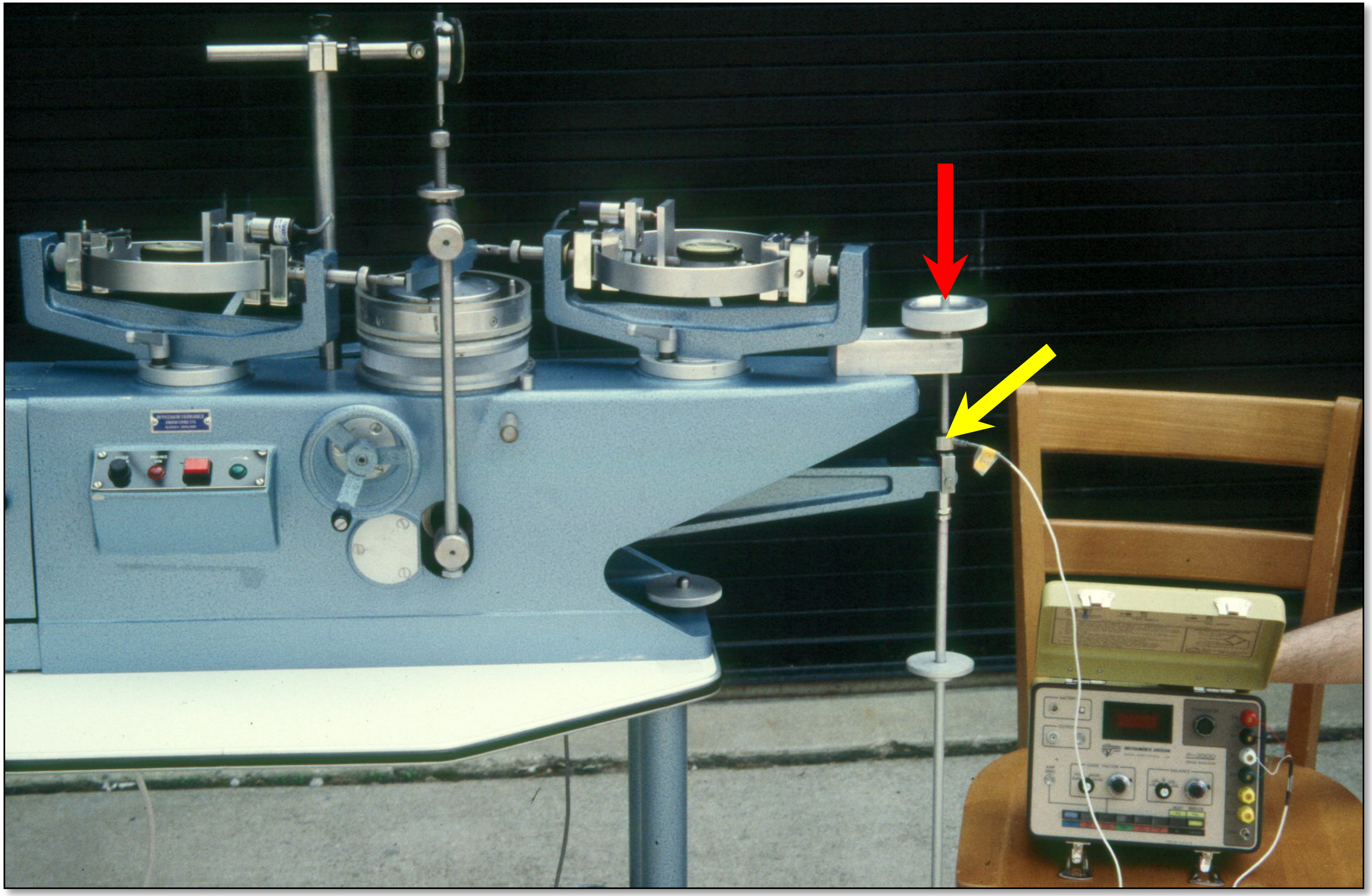
Stark and Contreras (Feb., 1998, ASCE JGGE)

Fourth Avenue Landslide

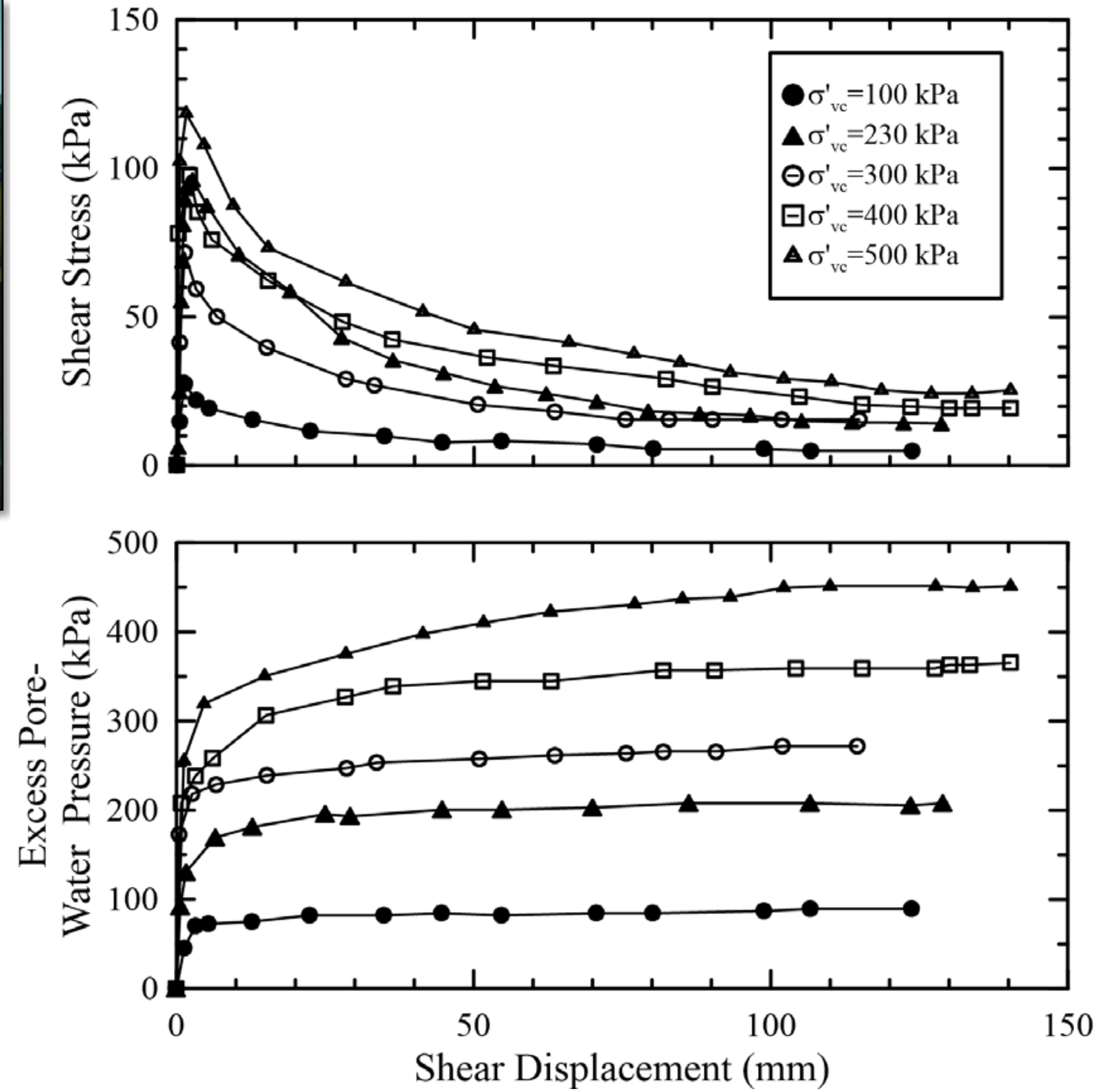


Stark and Contreras (Feb., 1998, ASCE JGGE)

Constant Volume Ring Shear Test

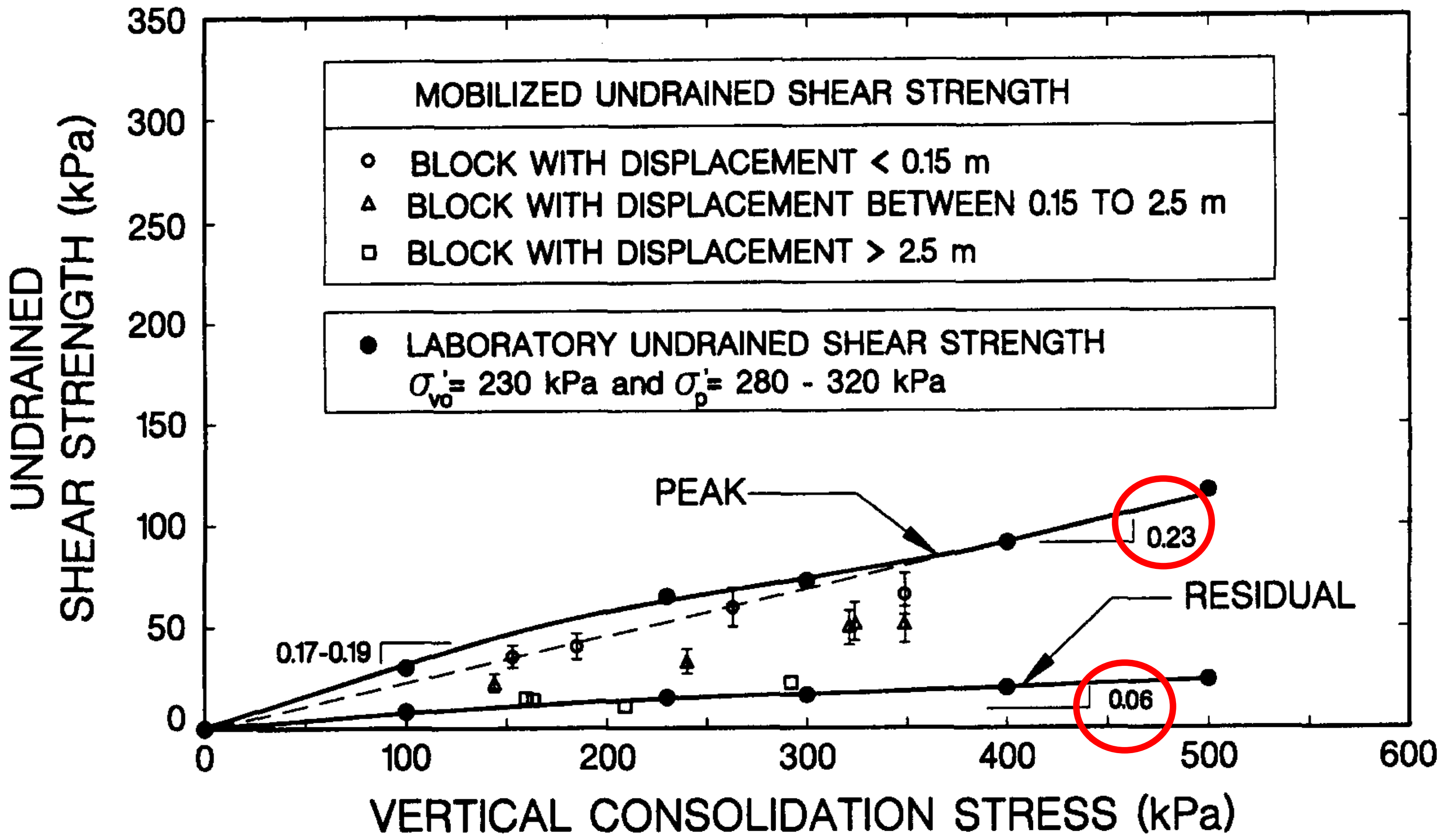


Bootlegger Cove Clay



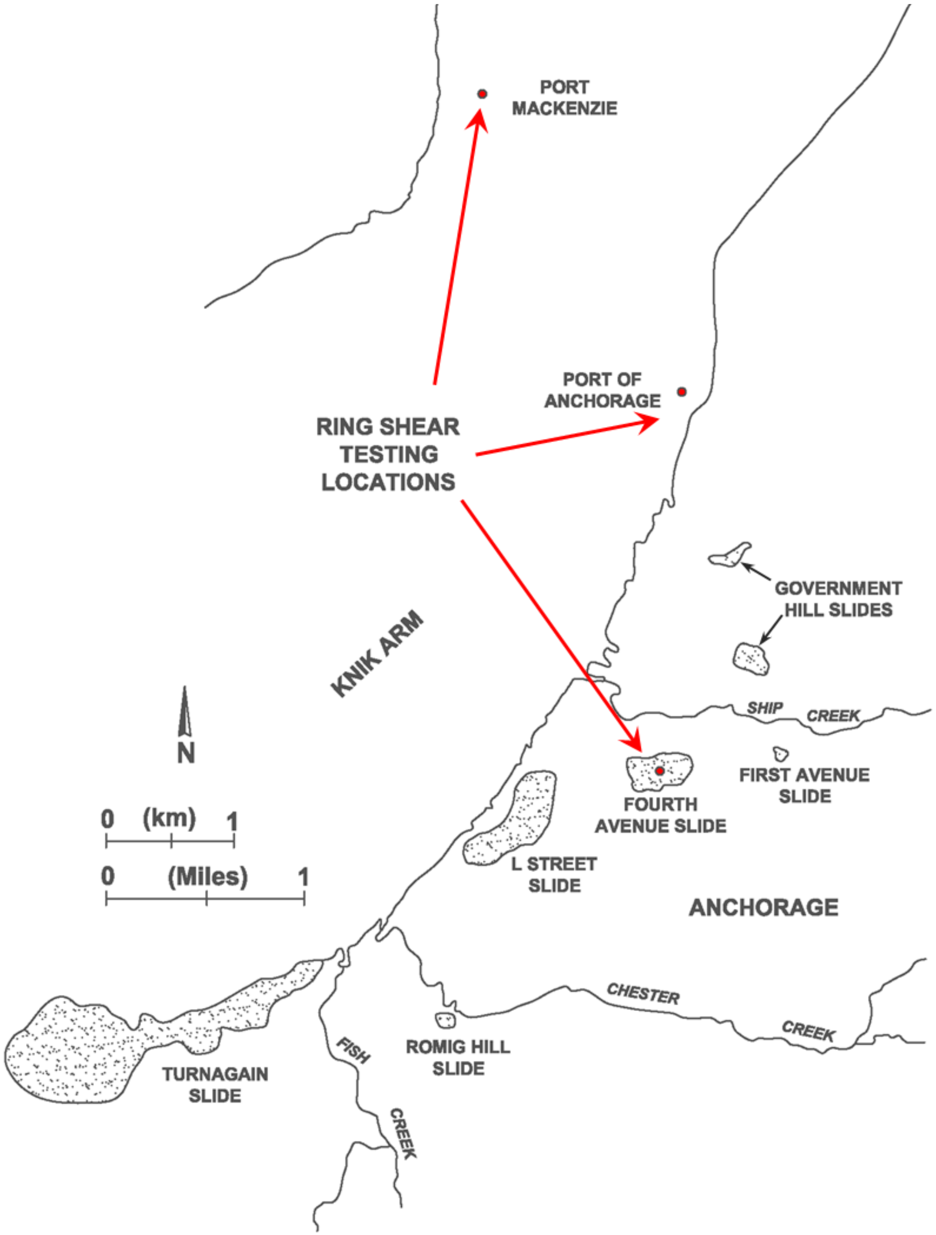
Stark and Contreras (Feb., 1998, ASCE JGGE)

Field v. Lab Strengths

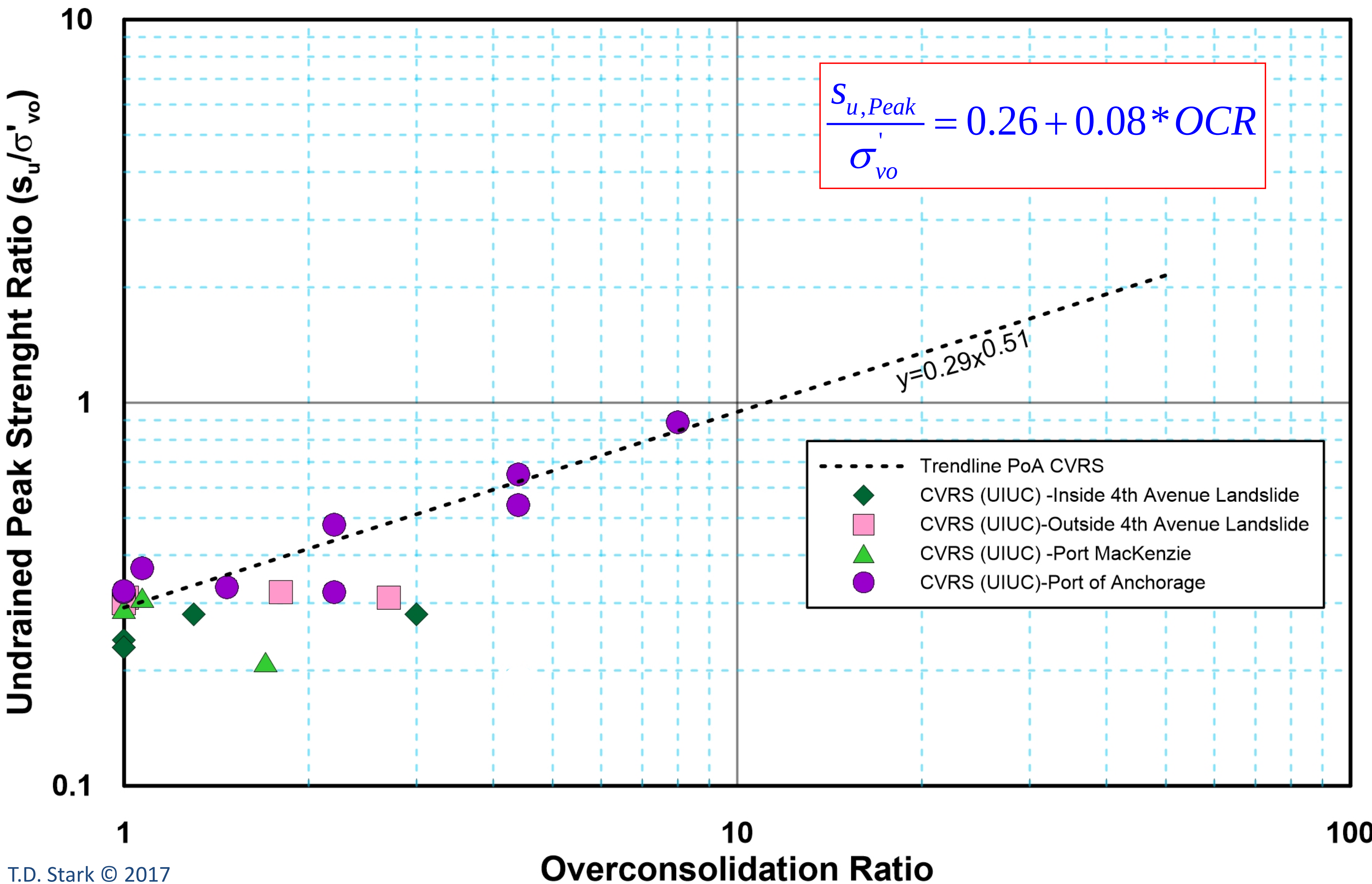


Stark and Contreras (Feb., 1998, ASCE JGGE)

Other Bootlegger Cove Clay



Undrained Peak Strength



Different CVRS Devices

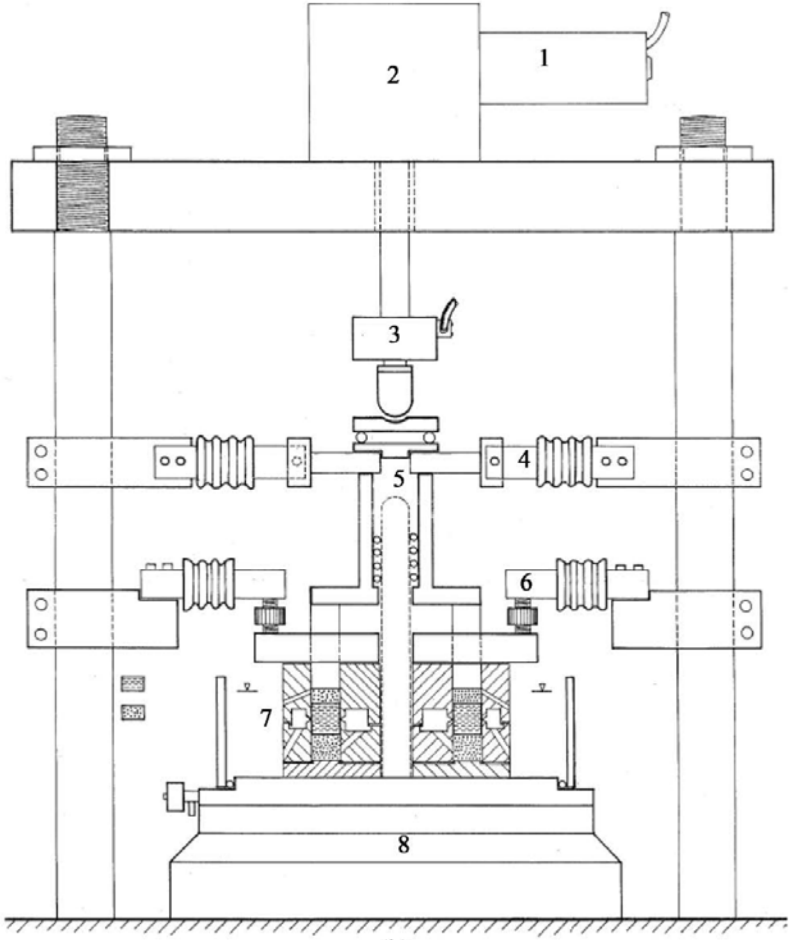
Wille Geotechnik

GDS Instruments

Different CVRS Test

1. Motor
2. Linear Gear-Box
3. Load Transducer
4. Point-Load Transducer
5. Shear Head
6. Wall friction transducer
7. Specimen Box
8. Torsion gear-box

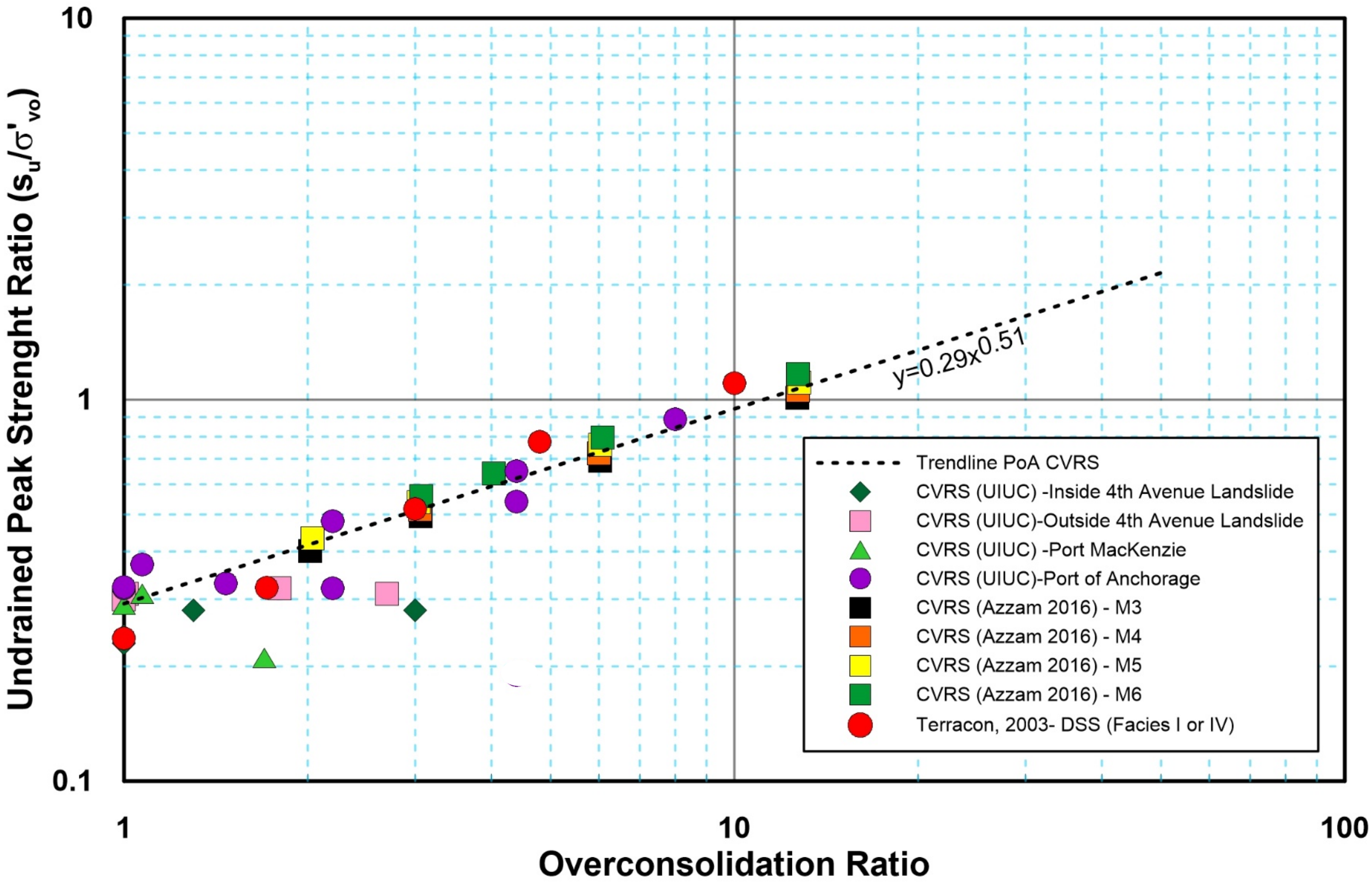
(a)



(b)

Rafig Azzam (2016) - Germany

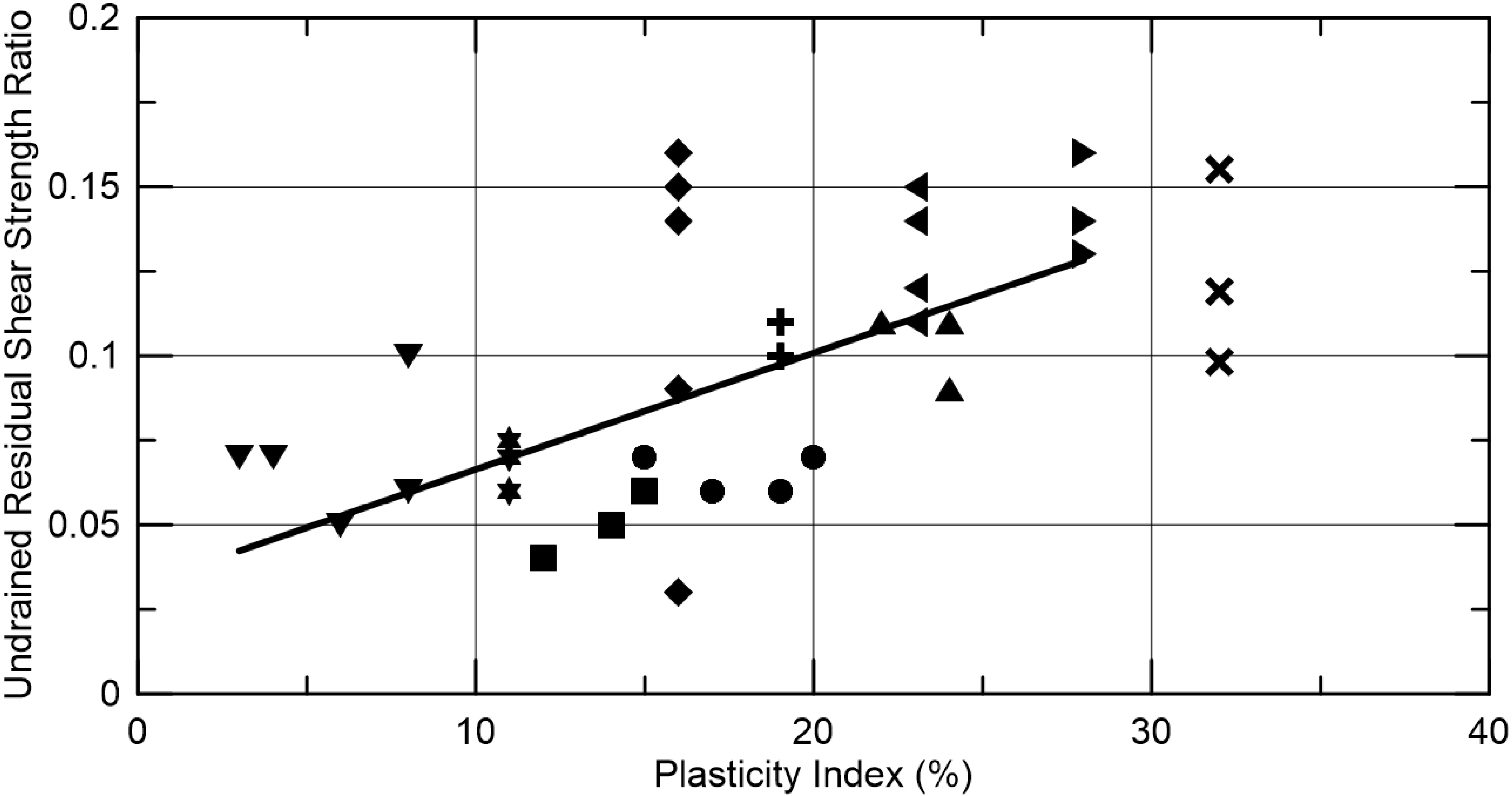
Tuffitic Sediments



- Tuffitic Sediments Rafig Azzam (2016) - Germany

$$\frac{s_{u,Peak}}{\sigma'_{vo}} = 0.30 + 0.07 * OCR$$

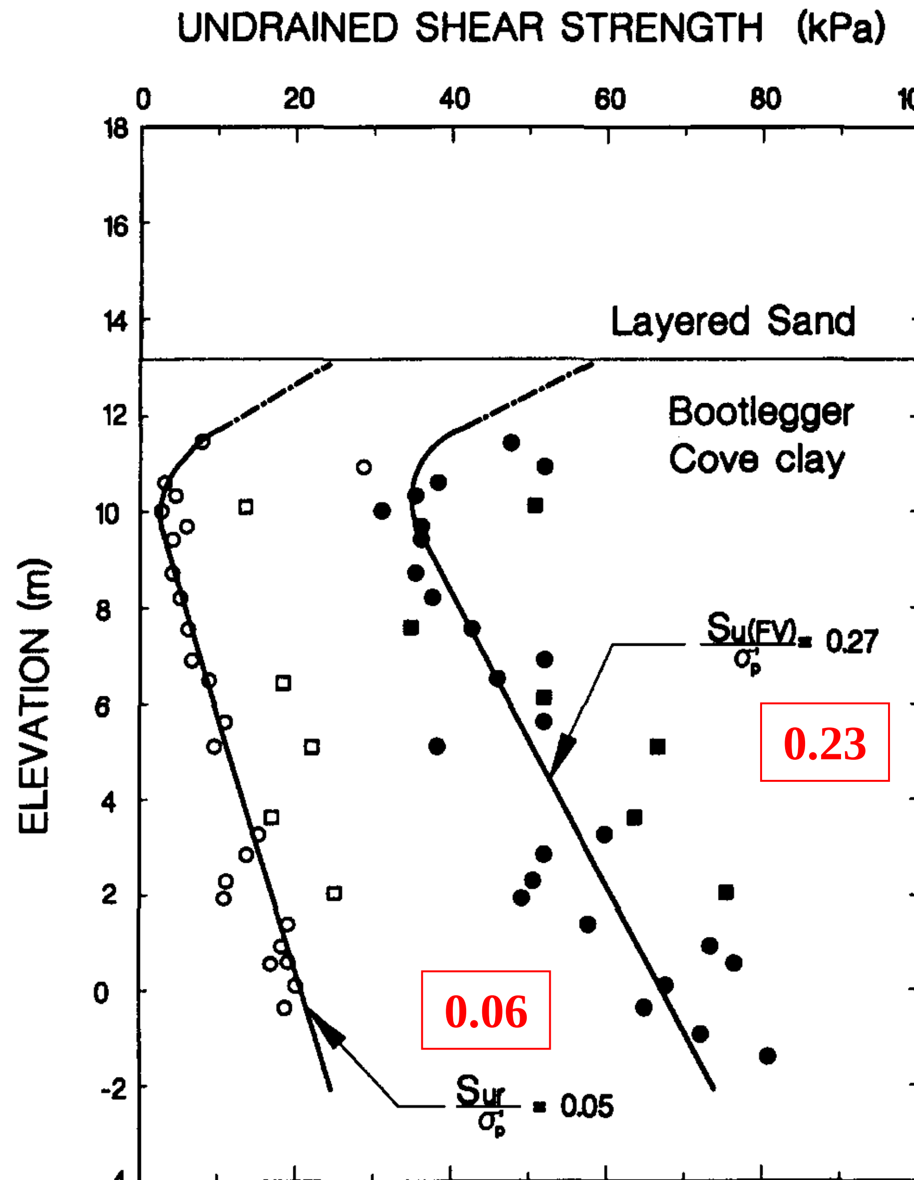
Undrained Residual Strength



$$\frac{S_{u,\mathrm{Residual}}}{\sigma'_{vo}} = 0.03 + 0.0035 * PI$$

Stark and Fernandez (2018)

Field Vane Shear Test



Stark and Contreras (Feb., 1998, ASCE JGGE)

Field Vane Shear Test

Stark and Contreras (Feb., 1998, ASCE JGGE)

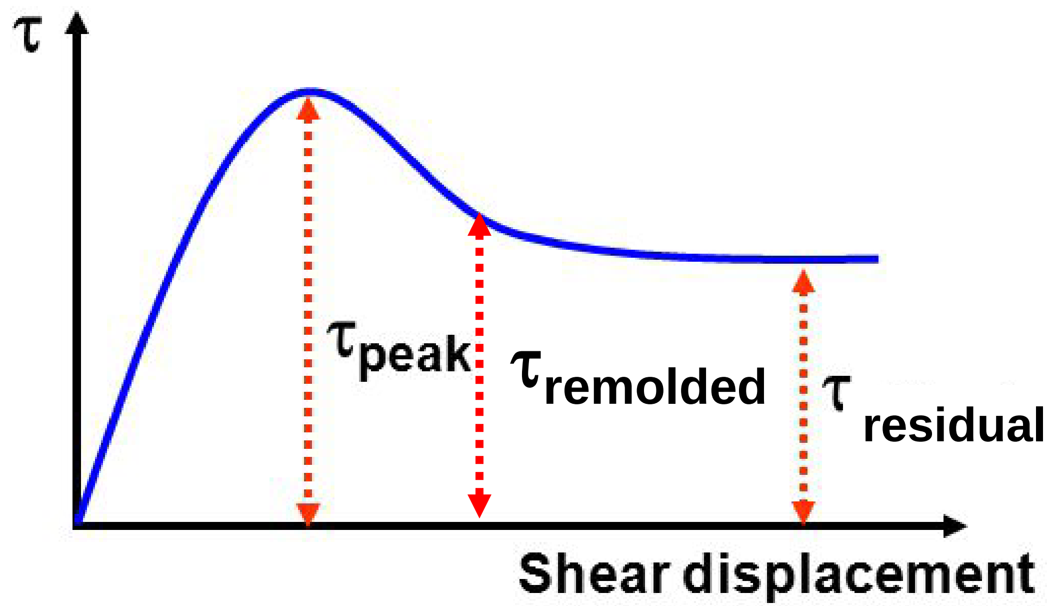
Conversion: kPa to kip/sq. ft. (ksf): 0.0209
Depth from Deck to MLLW (ft): 35.0
Depth from Deck to ML (ft): 71.0

Depth (From Deck)		Depth (From MLLW)		Vane*	Torque**			Undrained Shear Strength, Su***			Undrained Shear Strength, Su***		
From (ft)	To (ft)	From (ft)	To (ft)	Diameter (m)	Peak (N-m)	Residual (N-m)	Remolded (N-m)	Peak (kPa)	Residual (kPa)	Remolded (kPa)	Peak (ksf)	Residual (ksf)	Remolded (ksf)
97.0	98.0	62.0	63.0	0.0518	20	20	5	38.4	38.4	9.6	0.80	0.80	0.20
106.0	107.0	71.0	72.0	0.0518	48	35	8	92.2	67.2	15.4	1.92	1.40	0.32
111.0	112.0	76.0	77.0	0.0518	38	38	20	73.0	73.0	38.4	1.52	1.52	0.80
117.0	118.0	82.0	83.0	0.0518	52	35	10	99.9	67.2	19.2	2.09	1.40	0.40
124.0	125.0	89.0	90.0	0.0518	53	48	37	101.8	92.2	71.1	2.13	1.92	1.48
129.0	130.0	94.0	95.0	0.0518	68	58	32	130.6	111.4	61.5	2.73	2.33	1.28
138.0	139.0	103.0	104.0	0.0518	45	40	30	86.4	76.8	57.6	1.80	1.60	1.20
143.0	144.0	108.0	109.0	0.0518	55	40	20	105.6	76.8	38.4	2.21	1.60	0.80
148.0	149.0	113.0	114.0	0.0518	45	30	15	86.4	57.6	28.8	1.80	1.20	0.60
167.0	168.0	132.0	133.0	0.0518	60	39	17.5	115.2	74.9	33.6	2.41	1.56	0.70

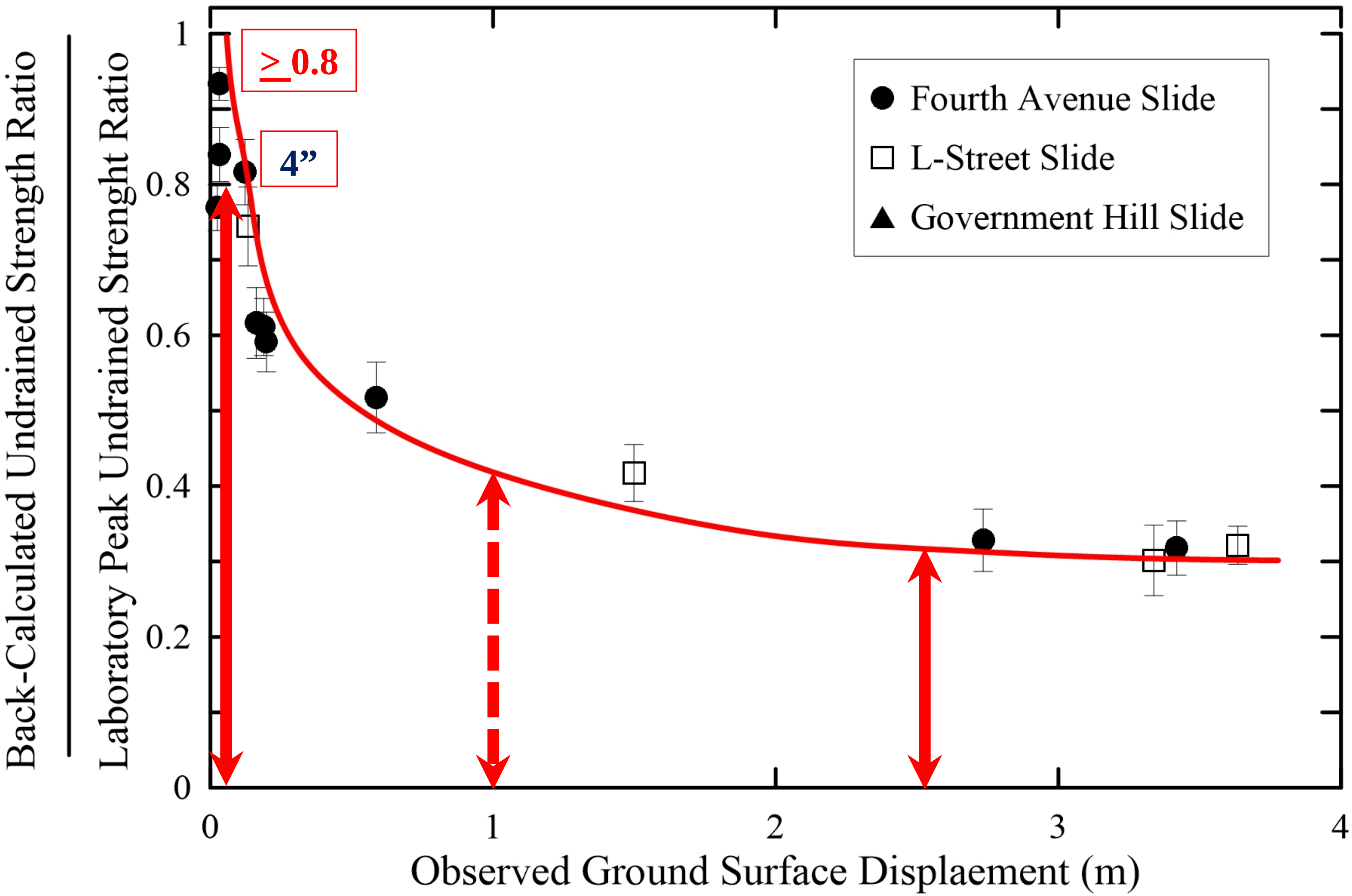
* Vane H/D =2 with 30 degree tapered ends (H bei
Vane 1 D=0.17' (2.04)", H=0.34' (4.08)", taper
Vane 2 D=0.25' (3.00"), H=0.50' (6.00)", taper

** Torque recorded using a torque wrench with a p

*** Su = 0.84 * T / (PI * D^3) (any units)



Design Recommendations



Stark and Contreras (Feb., 1998, ASCE JGGE)

SUMMARY

- **STATIC/DRAINED STRENGTHS**
  - Jointed Peak, FSS, or Residual
  - look for shear displacement
  - check difference of ϕ'_{FSS} and ϕ'_{R}
  - use ϕ'_{r} if small difference

- **DRAINED STABILITY ANALYSES -**
  - model stress-dependent strength envelope
  - $c'_{FSS} \sim 0$
  - $c'_{R} = 0$

- **SEISMIC/UNDRAINED STRENGTHS**
  - Cyclic Loading - 80% of static undrained peak strength or DSS testing
  - Permanent Displacements – residual strength
    - CVRS or FV

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University of Illinois at Urbana-Champaign
tstark@illinois.edu

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