11/97 6/00

V-3 STABILITY EVALUATION: COHESIVE SOILS

* Supplemental Handout: Ladd (1991) "Stability evaluation during staged construction: 22nd Terzaghi Lecture", JGE, ASCE, 117(4), 537-615

STABILITY EVALUATION: COHESIVE SOILS

1. CLASSES OF STABILITY PROBLEMS & TYPES OF ANALYSES

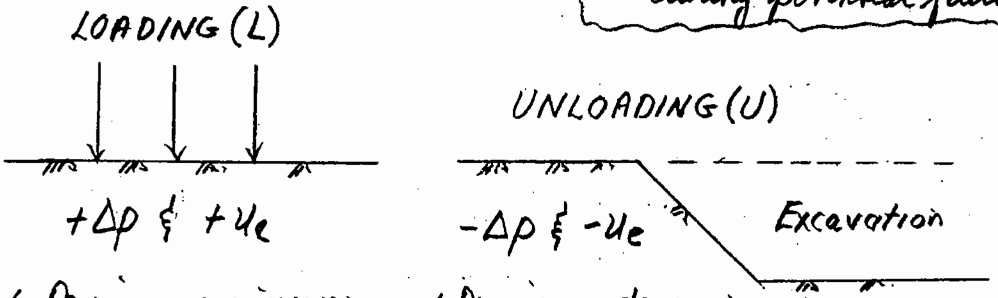
1.1 Problem Definition

Pore Pressure Notation

u_e = excess u due to construction

u_{sh} = excess u due to shearing during potential failure

1) Does construction involve Loading or Unloading?



(Drainage → increase in strength with Consolidation)

(Drainage → decrease in strength with Swelling)

2) For calculation of Factor of Safety, $FS = \dfrac{\text{Available Shear Strength } (s)}{\text{Mobilized Shear Stress } (\tau_m)}$

Should you use Drained Strength (s_d) or Undrained Strength (s_u)?

3) Does lowest FS (most critical condition) occur During Construction or After Construction, i.e. does FS go up or down with time?

(Conclusions from Section 3: During Construction critical for L → undrained analysis
After Construction critical for U → drained analysis)

1.2 Three Classes of Stability Analyses

Have 3 CASES directly analogous to the 3 types of (triaxial) shear tests depending upon the assumed Drainage Conditions in the field.

① Consolidated-Drained (CD CASE) = "Long term" = Fully Drained Condition

- Have steady state (equilibrium) pore pressures, i.e. $u_e = u_{sh} = 0$
- Therefore available strength = Drained Strength = $s_d = \tau_{ff} = c' + \sigma'_{ff} \tan\phi'$
- Hence conduct Drained Strength Analysis (DSA), where $FS = \dfrac{s_d}{\tau_m}$

NOTE: Also called Effective Stress Analysis (ESA) à la Section 2.1

1.2 Cont.

② Unconsolidated-Undrained (UU CASE) = "end of construction" = $\boxed{\text{No Drainage = Undrained}}$

- Have $\Delta w = 0 \rightarrow w_f = w_N$ (no drainage during construction or failure)
- Therefore available strength = Undrained Strength = in situ s_u that existed prior to construction
- Hence conduct Undrained Strength Analysis (USA), where $FS = \text{Initial } s_u / \tau_m$

NOTE: Also called Total Stress Analysis (TSA) à la Section 3.2.
(If $S = 100\%$, then "$\phi = 0$" & $c = s_u$)

③ Consolidated-Undrained (CU CASE) = "intermediate" = $\boxed{\text{Partial Drainage}}$

- Either during or after construction, have partial or full drainage
  - $u_e \geq 0$ for Loading problems
  - $u_e \leq 0$ for Unloading problems

  } In either case, σ'_{vc} profile has changed from preconstruction profile
- But assume No Drainage during potential (rapid) failure
- Therefore available strength = in situ $s_u = f($in situ σ'_{vc} & OCR that exists just prior to potential failure
- Hence conduct USA, where $FS = \text{New } s_u / \tau_m$

Comments: CD & UU Cases represent limiting conditions to more general CU Case. However, in practice, check most critical "extreme" condition of either fully drained or no drainage. See Section 5 for CU Case.

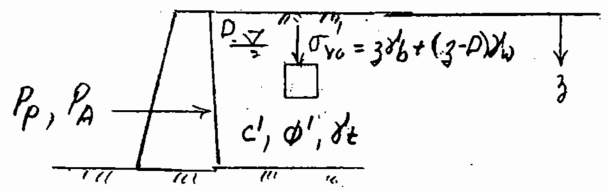
2. LONG TERM DRAINED STABILITY (CD CASE)

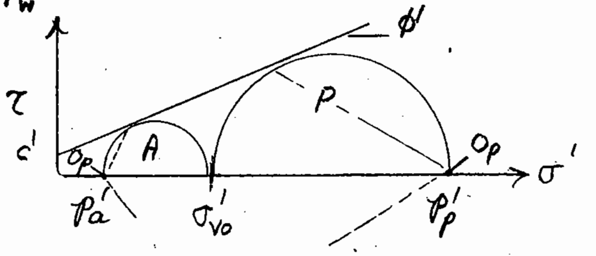
2.1 Assumptions and Approach

1) Inherent assumptions: $u_e = 0$ requires extremely slow construction or very long time after construction (full consolidation or swelling); $u_{sh} = 0$ requires extremely slow failure (Not possible for Loading Conditions à la Section 5)
2) Compute drained strength, $s_d = \tau_{ff} = c' + (\sigma'_{ff} = \sigma_{ff} - u_s) \tan\phi'$, where u_s = steady state condition (hydrostatic or steady state seepage).
3) Perform Drained Strength Analysis (DSA) → $FS = s_d / \tau_m$. However, usually called Effective Stress Analysis (ESA) since computing $s_d = f(\text{in situ } \sigma')$

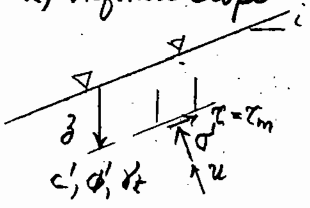
2.2 Examples (From prior Notes)

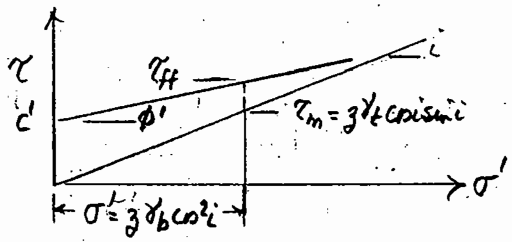
[Part IV-5] 1) Retaining Wall: Rankine: $P = \bar{P} + P_w$





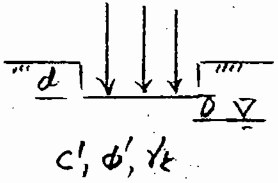
[Part IV-6] 2) Infinite Slope





$FS = \frac{s_d = \tau_{ff}}{\tau_m} = f(z)$ for $c' > 0$

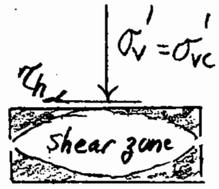
[Part IV-7] 3) Bearing Capacity Strip Footing



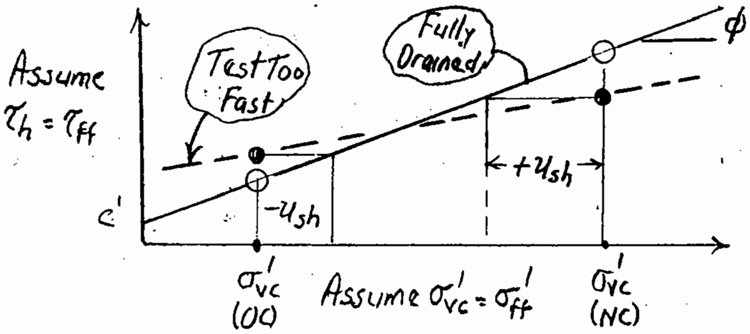
$$q_{ult} = c'N_c + \frac{1}{2}\underset{\uparrow \gamma_b \pm j}{\bar{\gamma}} B N_\gamma + \underset{\uparrow d \cdot \gamma_t}{q_s} N_q + \underbrace{D\gamma_w (N_q - 1)}_{\text{WT below footing w/ full capillarity}} = \Delta q_{ult}^{(c)}$$

2.3 Evaluation of c' & φ' In Practice

1) CD Testing: Must shear slowly so that $u_{sh} = 0$



a) Direct Shear: Test at varying σ'_{vc}

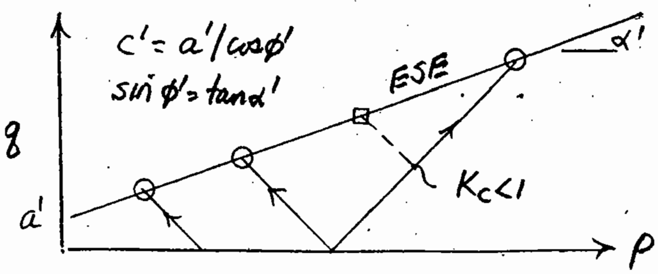


Low Cost & Quick, BUT

- ESE too low if $\tau_h > \tau_{ff}$
- No stress-strain curve
- LARGE ERROR WITH HAND CRANKED ($u_{sh} \neq 0$): c' too high, φ' too low

Most common CD Test

b) Triaxial: Usually CIDC(L/U)

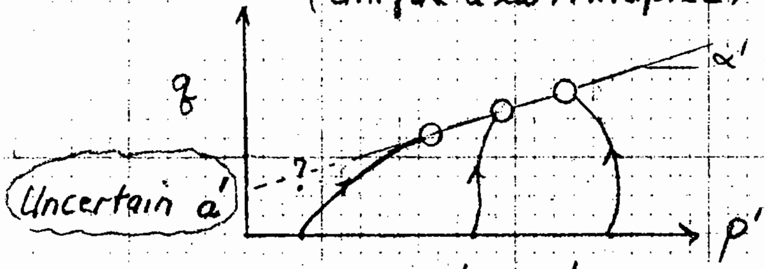


Most Accurate ESE (especially at low σ') & Obtain ε_a vs q & Δw

BUT
- Takes very long time
- Expensive
- Best if automated (Stress Path Triaxial)

2.3 Continued

2) CU testing with u measurement - Usually CIUC
(Unique à la Principle I)



Above for $\sigma_c' << \sigma_p'$

Widely Used Since Cost Much Less Than CIDC, BUT
- Difficult to define c' at low σ'
- If run too fast (especially high OCR), LARGE error in ESE (c' too high & ϕ' too low)

3. END OF CONSTRUCTION = UNDRAINED STABILITY (UU CASE)

3.1 Basic Assumptions

- Rate of construction and potential failure so rapid compared to rate of consolidation that amount of drainage is negligible → undrained shear ($t << t_p$)
- For $\Delta w = 0$, $w_f = w_N$ - as in UU type testing

3.2 Basis for "$\phi = 0$" Total Stress Analysis (S=100%)

- Illustrated for plane strain condition & low OCR

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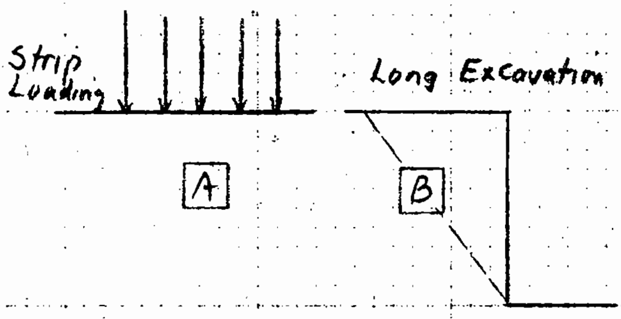
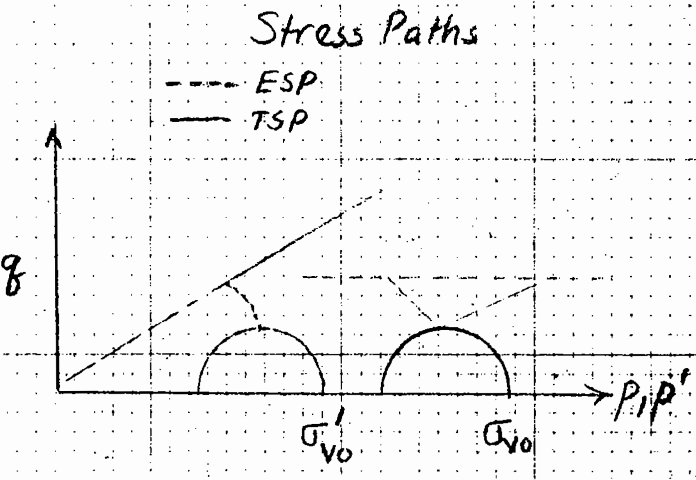


Footing Vertical Cut



Same ESP & s_u → TSA with $\phi = 0$, $c = s_u = q_f$ existing in situ prior to construction

3.2 Continued

Conclusion : For SAME mode of failure:

- $\alpha = \phi = 0$ & $c = q_f = s_u$ for Total Stress Analysis (TSA)
- s_u independent of TSP & equals insitu s_u existing prior to construction

3.3 Preliminary Discussion of s_u Evaluation

Covered in Part IV-4

1) Common assumption in CONVENTIONAL practice (S=100%)
   - Since s_u uniquely related to $w_f = w_N$ à la Principle II, can obtain s_u via any "UU" type shear test, e.g.
     In situ: Field vane (FV) Lab: Triaxial UUC or unconf. comp.
2) But in reality, s_u not uniquely related to $w_f = w_N$ due to:

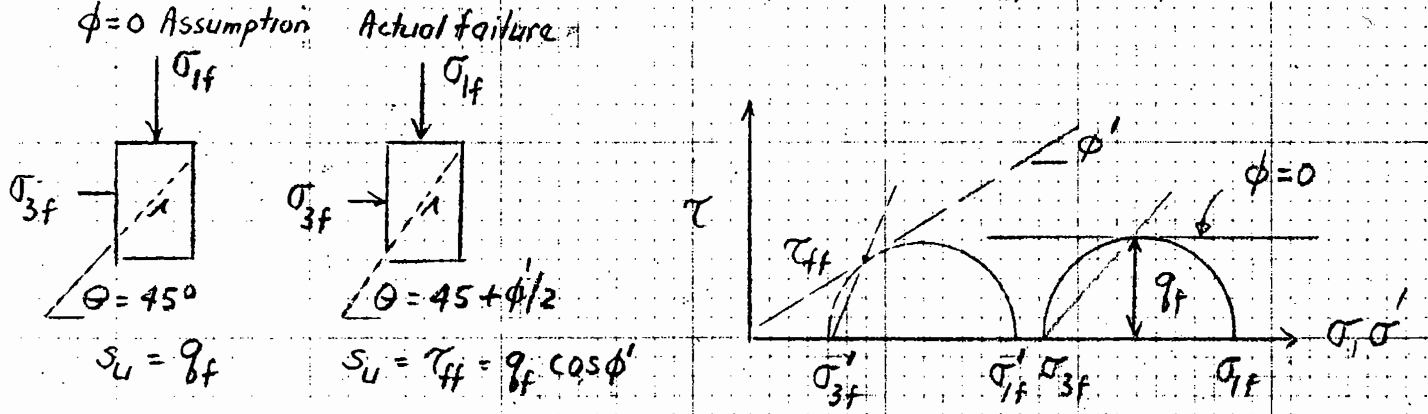
   Neglect for now
   - Sample disturbance (→ decrease in measured s_u via UU tests)
   - Strain rate (incr. $\dot{\varepsilon}$ = decr. t_f → incr. s_u)
   - Stress system = value of $\sigma_2 = f(b)$ & anisotropy = σ_{1f} direction (δ angle)

Conventional practice methodology → s_u

3.4 Definition of s_u & TSA vs USA ← SHANSEP methodology → s_u

FYI: Not discussed in Class

Illustrate basics via lab UUC test ($\sigma_{3f} = \sigma_c$ = cell pressure)



$s_u = q_f$

$s_u = \tau_{ff} = q_f \cos\phi'$

- TSA "$\phi = 0$", $c = q_f$ — s_u usually obtained via FV, lab UUC, etc.
- Undrained Strength Analysis = USA — $s_u = \tau_{ff}$ (for actual failure surface) and estimated using SHANSEP (more rational & reliable)

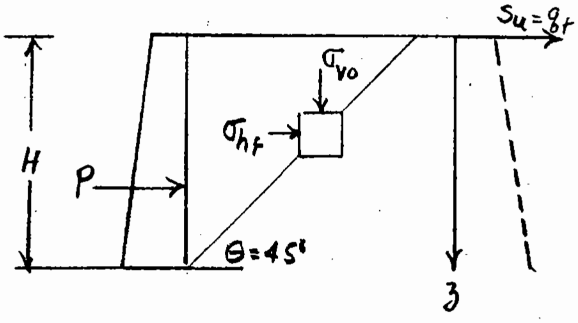
  e.g. $s_u / \sigma'_{vo} = S\,(OCR)^m$

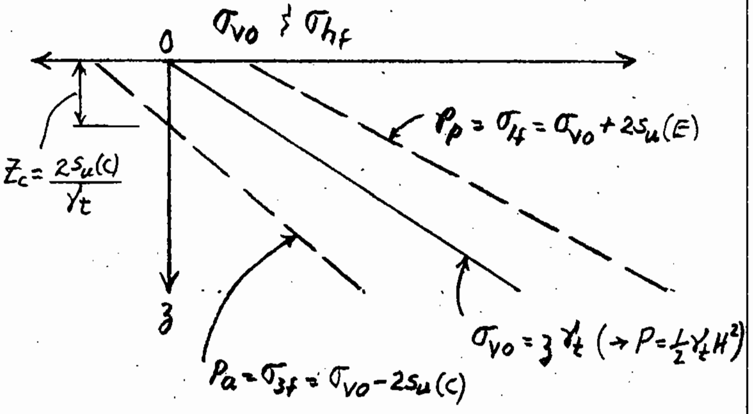
3.5 Examples of Applying Total Stress Analyses

1) Rankine Earth Pressures for Vertical Wall : $S = 100\%$

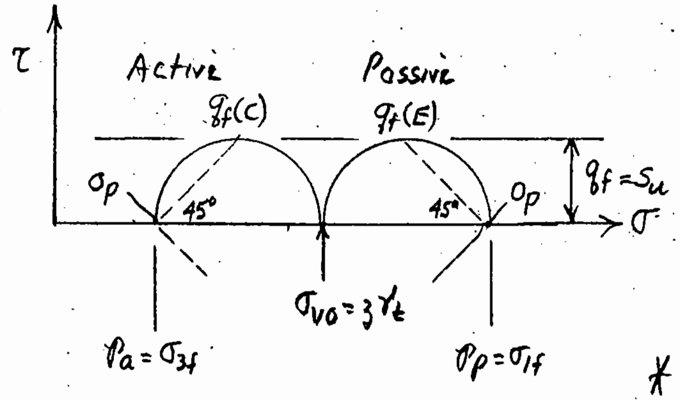
(NOTE: Plots assume $s_u(C) = s_u(E)$, i.e. they neglect s_u anisotropy)

Problem — Rankine Active & Passive (Fundamentals)





For $\phi = 0$ $(N_\phi = 1)$ & $c = s_u = q_f$, $\sigma_{1f} = \sigma_{3f} N_\phi + 2c\sqrt{N_\phi} \rightarrow \sigma_{1f} = \sigma_{3f} + 2c$



$$P_p = \frac{1}{2}\gamma_t H^2 + 2s_u(E)_{Ave} \cdot H$$

$$P_A = \frac{1}{2}\gamma_t H^2 - 2s_u(C)_{Ave} \cdot H$$

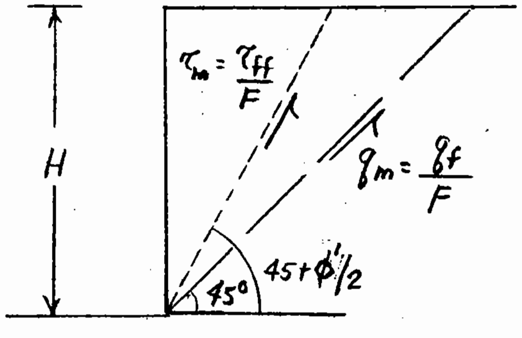
(P_A unsafe due to tension crack of depth Z_c)

* For most clays, $s_u(E) < s_u(C)$

FYI: Not discussed in class

For case of vertical cut & neglecting tension cracks (upper bound solution):

$P_A = 0 \rightarrow \frac{1}{2}\gamma_t H^2 = 2s_u H$ at failure $\rightarrow H_{cr} = \frac{4s_u}{\gamma_t}$, where $s_u = q_f = q_f(C)$



For $H < H_{cr}$, $\phi = 0$ analysis →

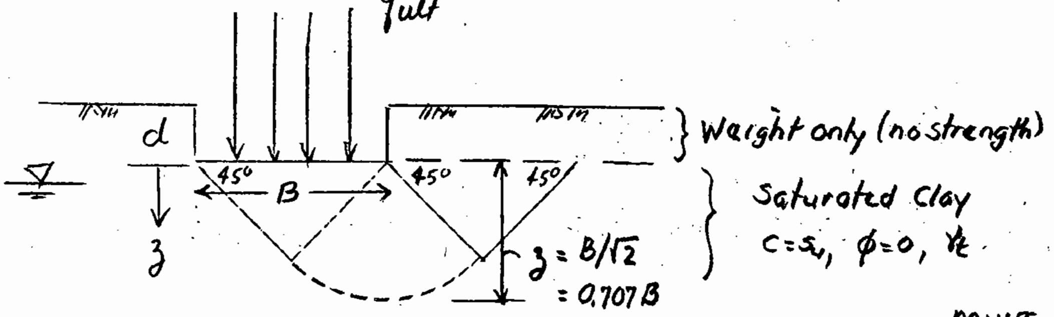
$$F = \frac{H_c}{H} = \frac{4q_f}{\gamma_t H} = \frac{q_f}{(\gamma_t H)/4} = \frac{q_f}{q_m}$$

And: for actual failure surface at $\theta = 45 + \phi'/2$

$$FS \cong F = \frac{\tau_{ff}}{\tau_m} = \frac{q_f \cos\phi'}{q_m \cos\phi'} = \frac{q_f}{q_m} = \text{same}$$

3.5 Continued

2) Footing on Saturated Clay



} Weight only (no strength)

} Saturated Clay $c = s_u$, $\phi = 0$, γ_t

MUST USE $\phi = 0$ ANALYSIS TO BE CONSISTENT WITH THEORY

$$\text{Strip: } q_{ult} = cN_c + \tfrac{1}{2}\gamma B \overset{\approx 0}{N_\gamma} + \gamma d \overset{\approx 1}{N_q}$$

$$= s_u N_c + \gamma_t d \quad \text{for } \phi = 0$$

where $s_u = q_f$

} $N_c = 5.14$ for strip ($L = \infty$)

$= 1.2 * 5.14 \approx 6.2$ for $B = L$

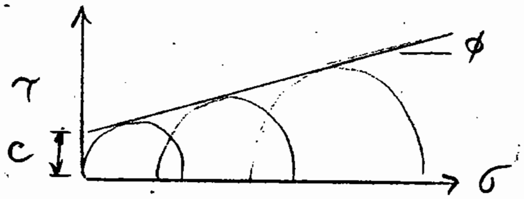
Since $S_c = \left(1 + \frac{B}{L}\frac{N_q}{N_c}\right)$

$= 1 + 0.2\frac{B}{L}$ for $\phi = 0$

$$* \boxed{\text{Practice: Use } c = \text{average } s_u \text{ within } z = \tfrac{2}{3}B}$$

3) Footing: Partially Saturated Clay

Since $B < 1 \rightarrow \phi > 0$ ∴ Run UUC tests (neglecting disturbance & anisotropy)

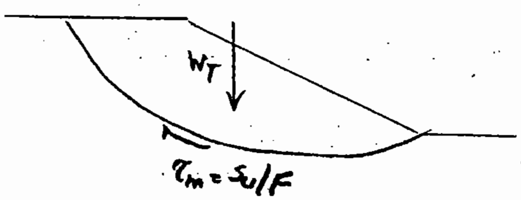


FYI: Not discussed in class even though v. important in practice

4) Slope Stability ($S = 100\%$)

$$FS \equiv F = \frac{s_u}{\tau_m} \left\{ = \frac{W_T \cdot d}{l_a \cdot r} \right\}$$

Circular Arc Analysis



"TRUTH": Actual failure surface probably closer to log spiral

How define s_u? Controversial

- Most practitioners & L & W ('69) use $s_u = q_f$ for Total Stress $\phi = 0$ analyses
- CCL: If arc approximates an actual failure surface, then should use

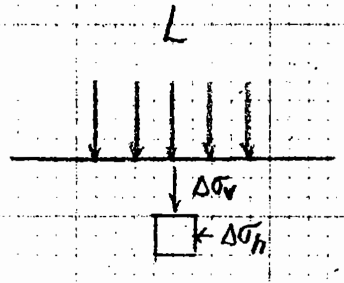
$$s_u = \tau_{ff} = q_f \cos\phi' = \underbrace{(0.85 - 0.9)}_{\phi' = 29 \pm 3°} q_f$$

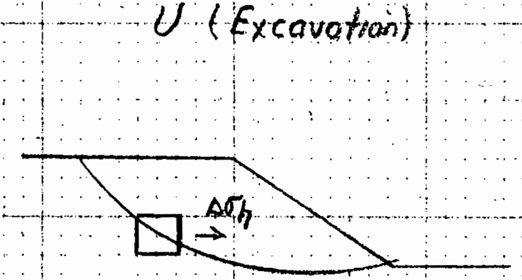
4. WHICH STABILITY CASE IS CRITICAL: UU OR CD?

(Undrained "end of construction" vs Drained "long term")

4.1 Introduction

1) Will compare Loading vs Unloading (plane strain) to illustrate





2) General Guidance: If during construction, for representative element

- $+\Delta p$ & $+u_e$: then drainage → $+\Delta\sigma'$ (consolidation) → incr. strength → incr. FS with time (always occurs for loading, esp. low OCR)

$\boxed{\text{UU CRITICAL}}$

- $-\Delta p$ & $-u_e$: then drainage → $-\Delta\sigma'$ (swelling) → decreased strength → decr. FS with time (usual case for unloading, esp. high OCR)

$\boxed{\text{CD CRITICAL}}$

4.2 Illustration for Loading Problem (Fig V3-1(L) p9; medium-low OCR)

1) TSP & ESP during undrained construction

2) " " " " consolidation

3) ESP if drained loading

4) Conclusions

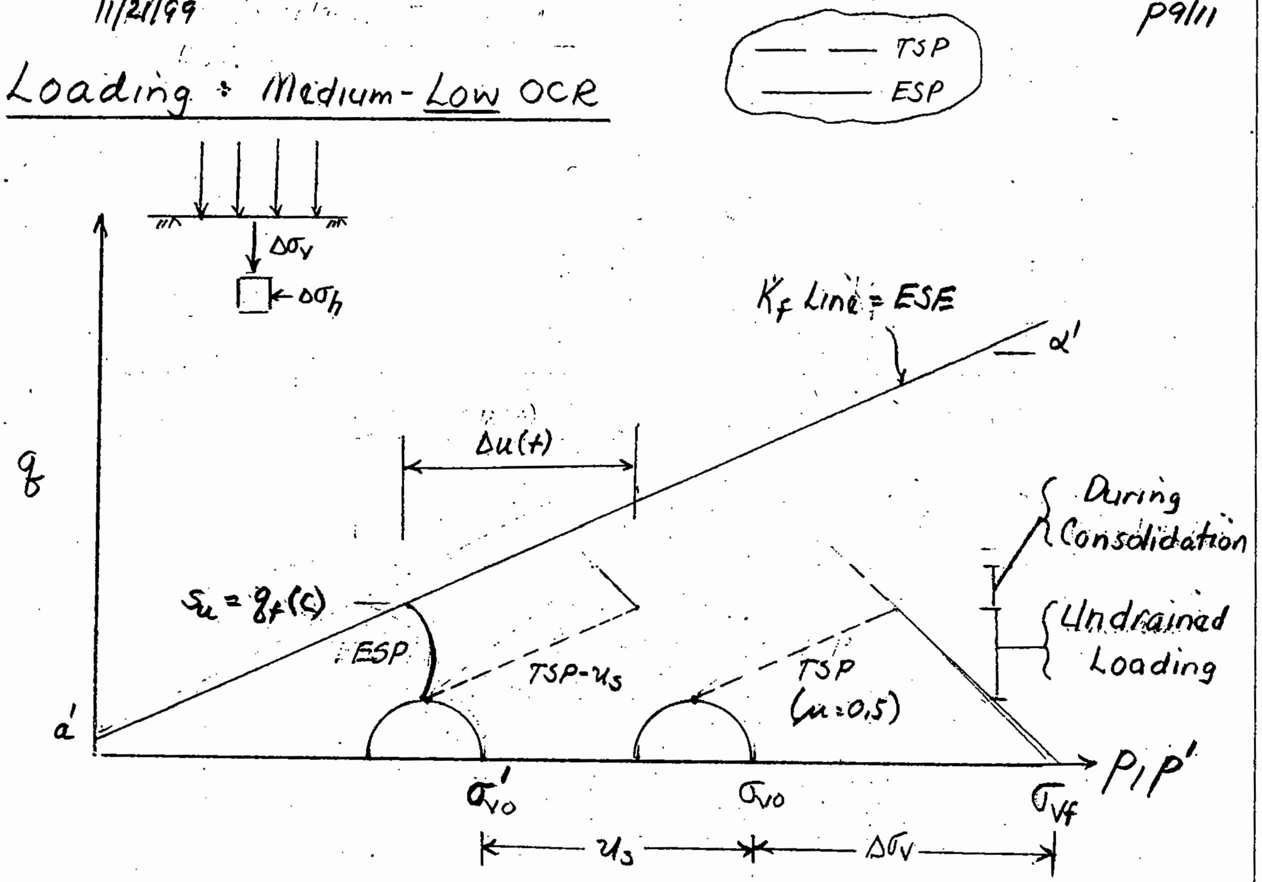
- Undrained (UU) always critical → failures during construction
- Discussion of why drained ESA (CD CASE) not applicable

For loading cases, actual failure will always be rapid (minutes → hours) → $u_{sh} > 0$ / decr. in σ'

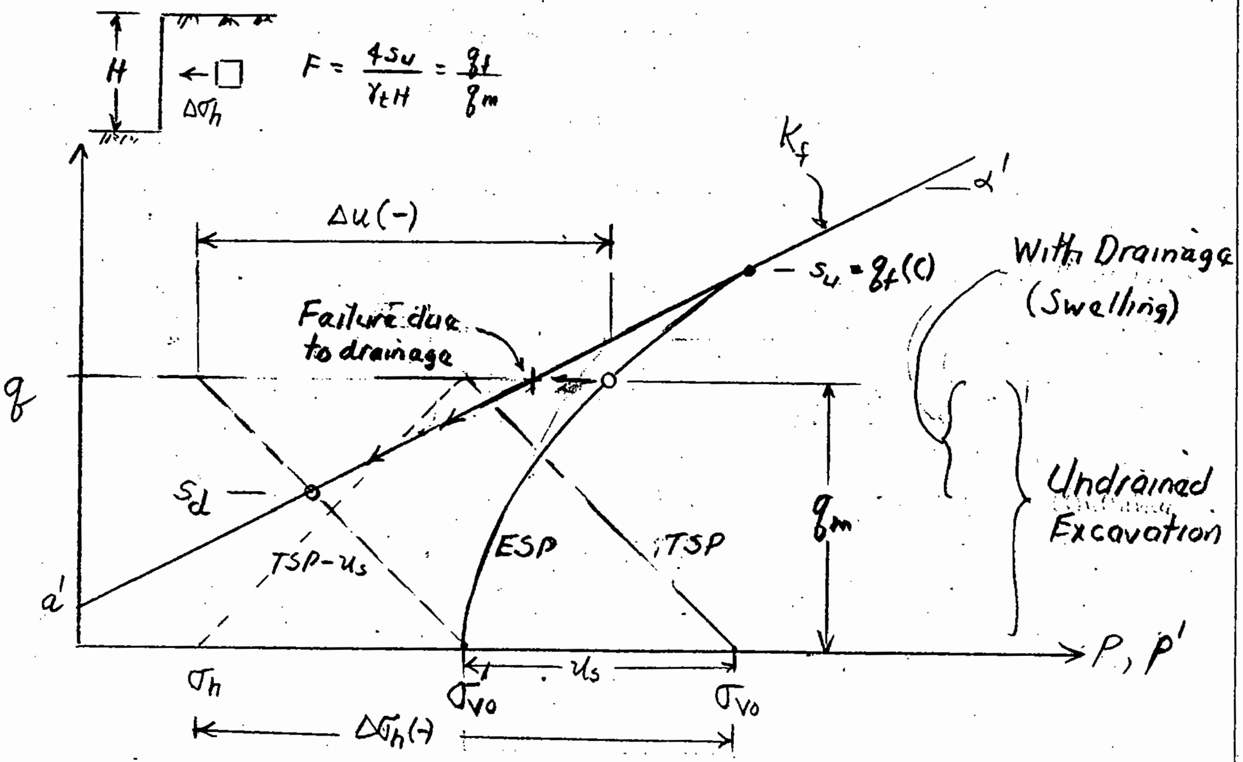
∴ CD analysis UNSAFE since actual σ'_{ff} < preshear value (not generally recognized in practice)

See Section 3.2 of TL

(L) Loading : Medium-Low OCR



(U) Unloading : Medium-High OCR (Take $K_o = 1$) & Vertical Cut)



$$F = \frac{4s_u}{\gamma_t H} = \frac{q_f}{q_m}$$

Fig V3-1 Stress Paths for Loading & Unloading : Undrained → Fully Drained

4.3 Illustration for Unloading Problem (Fig V 3-1(U), p9: med.-high OCR)

1) TSP & ESP during undrained construction

2) " " " " drainage (swelling)

3) Conclusions

- Drained (CD) always critical (except for low OCR → $A_f \geq 1$)
- FS decreases with time → failures after construction
- Time to failure generally increases with increasing OCR and can occur many years after construction
- NOTE: If stiff FISSURED clay, use $c'=0$ & ϕ' for NC clay,
  If PRIOR failure at site, use $c'=0$ & residual $\phi' = \phi'_r$ } 1.322

4.4 Summary

1) Loading Problems (increase in ave. total stress Δp & $u_e > 0$)

$Min\ FS = \frac{s_u}{\tau_m}$
- Undrained (UU) most critical since FS increases with time
- Failures occur during construction
- Do Undrained Strength Analysis, i.e. input $c = s_u$ ($S = 100\%$)

$\Delta\sigma_v > (\sigma'_p - \sigma'_{vo})$ • "Soft Ground" condition : $\sigma_{vf} > \sigma_p$ - must check FS carefully

$\Delta\sigma_v < (\sigma'_p - \sigma'_{vo})$ "Stiff Ground" : $\sigma_{vf} < \sigma_p$ - FS should be OK

2) Unloading Problems (decrease in ave. total stress Δp & $u_e < 0$)

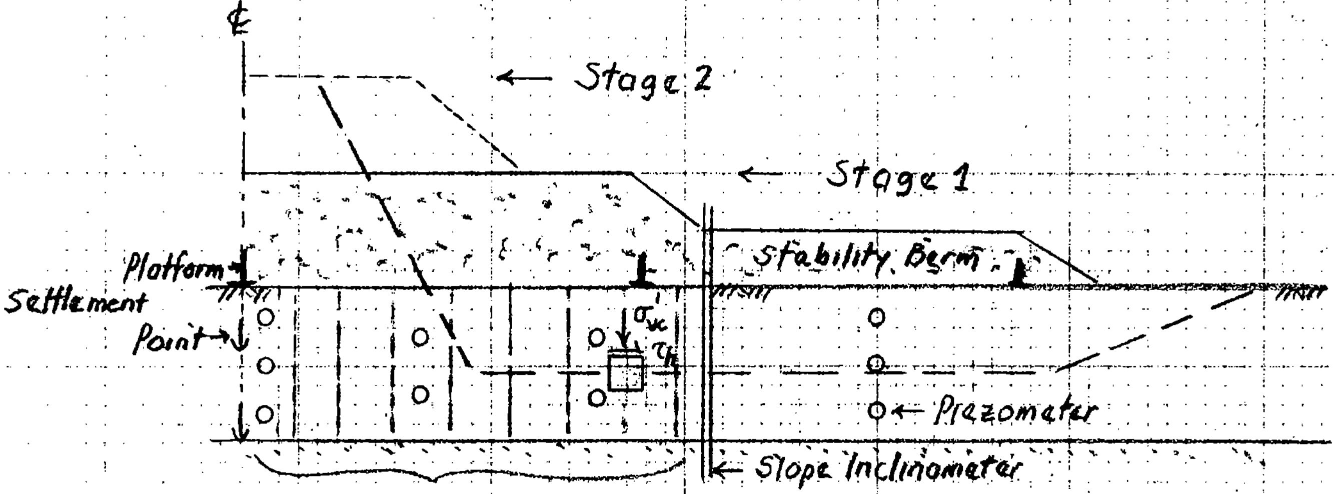
- Drained (CD) most critical since FS decreases with time
- Failures usually occur after construction (esp. at high OCR)
- Do Drained Strength Analysis, i.e. input c', ϕ' and equilibrium u (also called ESA)

$Min.\ FS = \frac{s_d = \tau_{ff}}{\tau_m} = \frac{\tan\phi'}{\tan\phi'_m}$

- NOTE: Still must conduct USA to guard against failure during construction. BUT very high undrained FS does not imply adequate long term stability

5. STAGED CONSTRUCTION FOR LOADING PROBLEM

5.1 Example of "Intermediate" = Partially Drained CASE

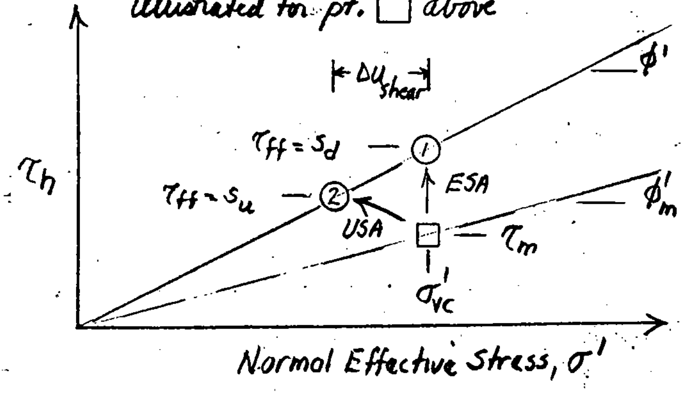


Vertical sand / wick drains to accelerate rate of consolidation

- Use when initial insitu s_u not adequate to safely support final geometry
- Construction sequence
  1) Vertical drains (if needed)
  2) Stage 1 to safe height
  3) Waiting period for consolidation → increase in fdn. s_u
  4) Stage 2

5.2 Comments on Stability Evaluation (after Fig. 3 of CCL (1991) = TL)

Illustrated for pt. □ above



NOTE: σ'_{vc} = computed σ_v - measured u

1) ESA = Drained Strength Analysis

- $FS = \frac{s_d}{\tau_m} = \frac{\tan\phi'}{\tan\phi'_m}$
  - UNSAFE since neglects + Δu shear

2) USA = Undrained Strength Analysis

- $FS = \frac{s_u}{\tau_m}$; $s_u = (s_u/\sigma'_{vc}) \times \sigma'_{vc}$
  - Correct approach for rapid, undrained failure