

11/97 6/00

V-3 STABILITY EVALUATION: COHESIVE SOILS

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

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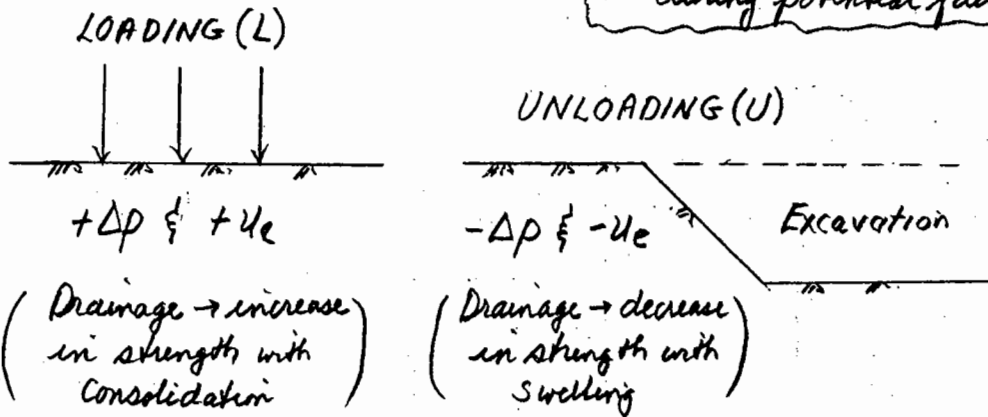
STABILITY EVALUATION: COHESIVE SOILS

1. CLASSES OF STABILITY PROBLEMS & TYPES OF ANALYSES

1.1 Problem Definition

1) Does construction involve Loading or Unloading?

Pore Pressure Notation  
 $u_e$  = excess  $u$  due to construction  
 $u_{sh}$  = excess  $u$  due to shearing during potential failure



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

(Conclusion 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  $FS = \frac{s_d}{\tau_m}$

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

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## 1.2 Cont.

② Unconsolidated-Undrained (UU CASE) = "end of construction" = 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  $FS = \text{in situ } s_u / \tau_m$

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" = 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,  $\sigma'_v$  profile has changed from preconstruction profile
- But assume No Drainage during potential (rapid) failure
- Therefore available strength = in situ  $s_u$  &  $f$  (in situ  $\sigma'_v$  & 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.

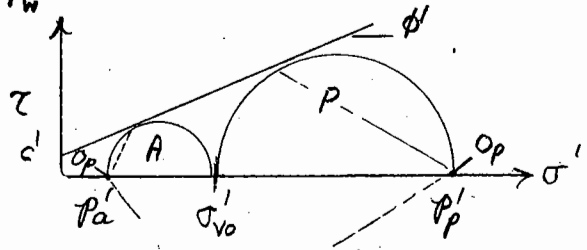
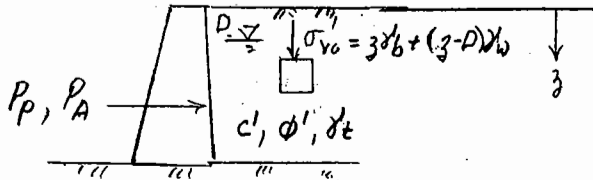
## 2. LONG TERM DRAINED STABILITY (CD CASE)

## 2.1 Assumptions and Approach

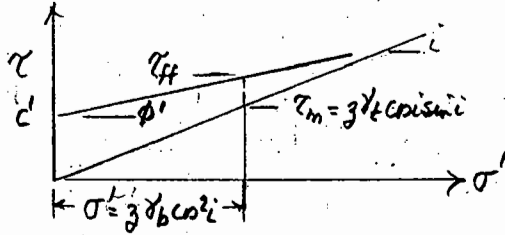
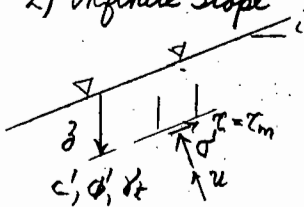
- 1) Inherent assumptions:  $u_e = 0$  requires extremely slow construction or very long time after construction (full consolidation or swelling);  $u_{sh} = 0$  requires extremely slow failure (Not possible for loading conditions à la Section 5)
- 2) Compute drained strength,  $s_d = \tau_{ff} = c' + (\sigma'_{ff} = \sigma'_{ff} - u_s) \tan \phi'$ , where  $u_s =$  steady state condition (hydrostatic or steady state seepage).
- 3) Perform Drained Strength Analysis (DSA)  $\rightarrow FS = s_d / \tau_m$ . 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  $P = \bar{P} + P_w$

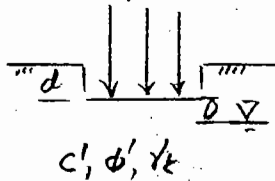


[Part IV-6] 2) Infinite Slope



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

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



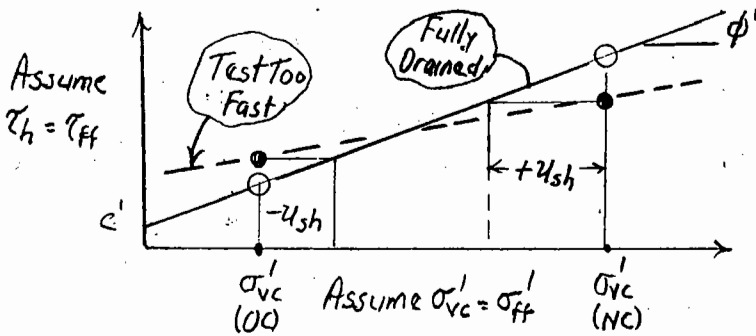
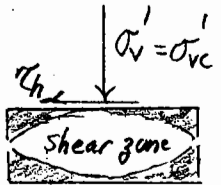
$$q_{ult} = c'N_c + \frac{1}{2} \bar{\gamma} B N_q + q_s N_q + D\gamma_w (N_q - 1)$$

$\bar{\gamma} \left[ \begin{matrix} \uparrow \\ \text{1/2 } \gamma \text{ } \end{matrix} \right] \leq \gamma$   $\left[ \begin{matrix} \uparrow \\ \text{D } \gamma_w \end{matrix} \right]$  }  $\Delta q_{ult}(c)$   
 w/ full capillarity }  
 w/ below footing }  
 w/ full capillarity }

2.3 Evaluation of  $c'$  &  $\phi'$  In Practice

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

a) Direct Shear: Test at varying  $\sigma'_{vc}$

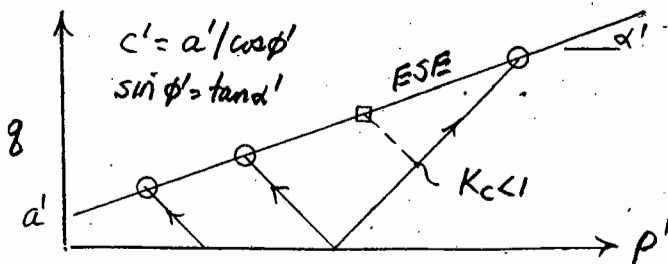


Low Cost & Quick, BUT

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

Most Common CD Test

b) Triaxial: Usually CIDC (L/U)



Most Accurate ESE (especially at low  $\sigma'$ ) + Obtain  $\epsilon_a$  &  $q$  &  $D_w$

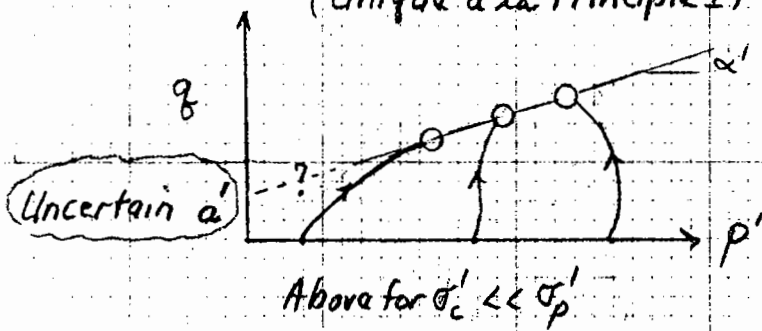
BUT: Takes very long time

- Expensive
- Best if automated (Stress Path Triaxial)

2.3 Continued

2) CU testing with  $u$  measurement - Usually CIUC

(Unique à la Principe I)



Widely Used Since Cost Much Less Than CIDC, BUT

- Difficult to define  $c'$  at low  $\sigma'$
- If run too fast (especially high OCR), LARGE error in ESE ( $c'$  too high &  $\phi'$  too low)

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

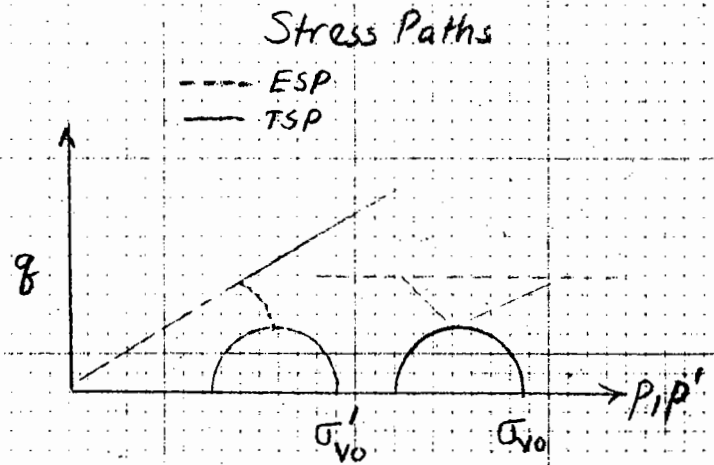
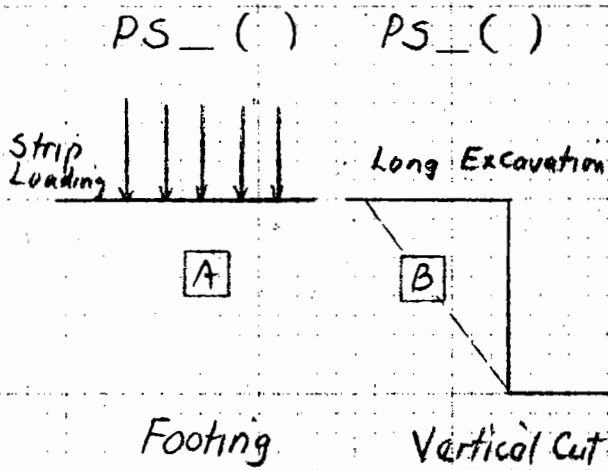
3.1 Basic Assumptions

and potential failure

- Rate of construction so rapid compared to rate of consolidation that amount of drainage is negligible  $\rightarrow$  undrained shear ( $t \ll t_p$ )
- 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



Some ESP  $\neq s_u \rightarrow$  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 in situ  $s_u$  existing prior to construction

3.3 Preliminary Discussion of  $s_u$  Evaluation

1) Common assumption in CONVENTIONAL practice ( $S=100\%$ )

- Since  $s_u$  uniquely related to  $w_f = w_{cr}$  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  $w_f = w_{cr}$  due to:

- Sample disturbance ( $\rightarrow$  decrease in measured  $s_u$  via UU tests)
- Strain rate (incr.  $\dot{\epsilon}$  = decr.  $f_f \rightarrow$  incr.  $s_u$ )
- Stress system = value of  $\sigma_2 = f(b)$  & anisotropy =  $\sigma_{1f}$  direction (Sample)

Covered in Part IV-4

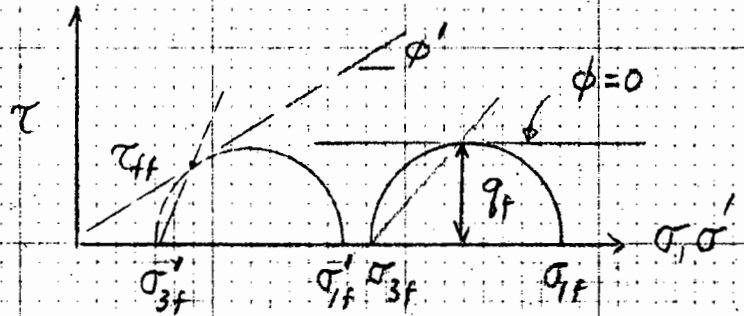
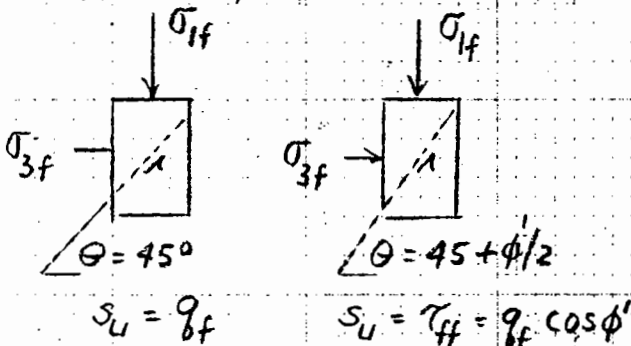
Neglect for now

Conventional practice methodology  $\rightarrow s_u$

3.4 Definition of  $s_u$  & TSA VS USA  $\leftarrow$  SHANSEP methodology  $\rightarrow s_u$

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

$\phi=0$  Assumption Actual failure



FYI: Not discussed in class

- TSA " $\phi=0$ ",  $c = q_f$
- Undrained strength Analysis = USA

$s_u$  usually obtained via FV, Lab UUC, etc (for actual failure surface)  
 $s_u = \tau_{ff}$  and estimated using SHANSEP (more rational & reliable)  
 e.g.  $s_u / \sigma'_{v0} = S (OCR)^m$

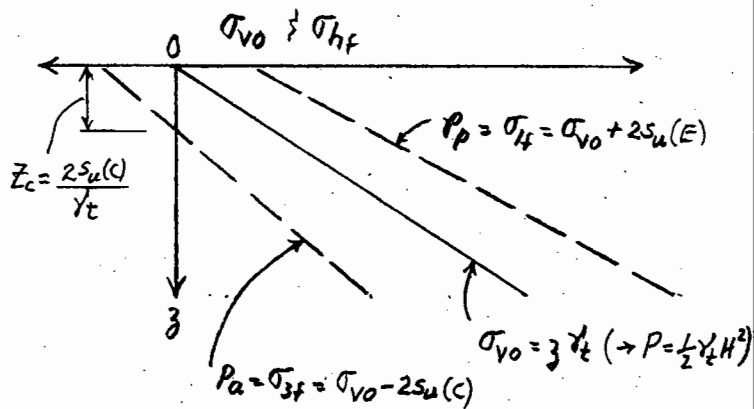
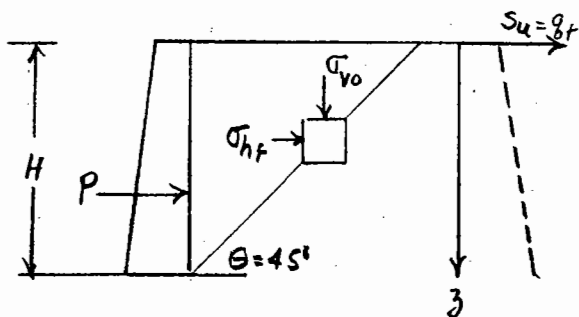
3.5 Examples of Applying Total Stress Analyses

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

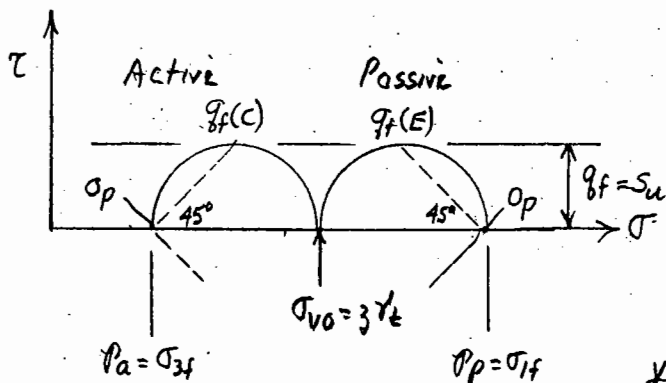
(NOTE: Plots assume  $s_u(c) = s_u(E)$ , i.e. they neglect  $s_u$  anisotropy)

Problem

Rankine Active & Passive (Fundamentals)



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

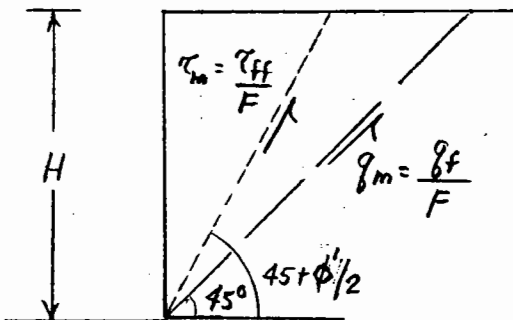


$P_p = \frac{1}{2} \gamma z_c H^2 + 2s_{u(E)} \text{Ave} \cdot H$   
 $P_A = \frac{1}{2} \gamma z_c H^2 - 2s_{u(c)} \text{Ave} \cdot H$   
 (.  $P_A$  unsafe due to tension crack of depth  $z_c$ )

\* For most clays,  $s_u(E) < s_u(c)$

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

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



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

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

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

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

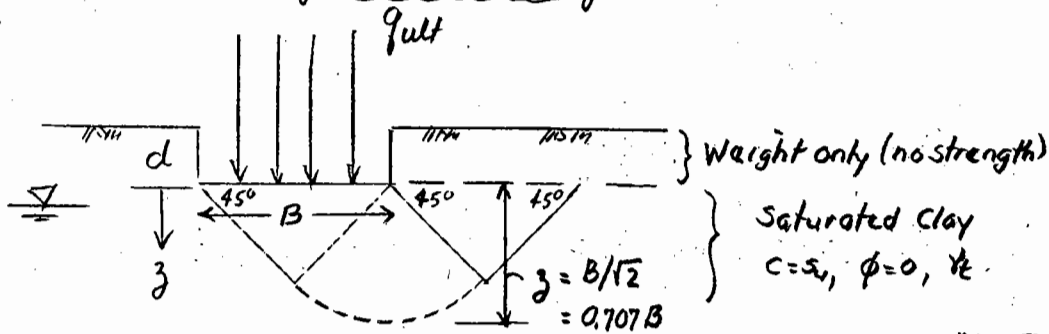
FYI: Not discussed in class

42 381 30 SHEETS 3 SQUARE  
42 382 100 SHEETS 3 SQUARE  
42 383 700 SHEETS 3 SQUARE



3.5 Continued

2) Footing on Saturated Clay



Strip:  $q_{ult} = c N_c + \frac{1}{2} \gamma B N_q + \gamma d N_q$   
 $= s_u N_c + \frac{1}{2} \gamma d$  for  $\phi = 0$

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

where  $s_u = q_f$

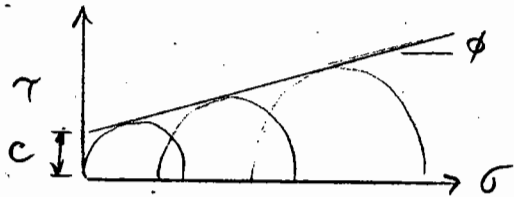
$N_c = 5.14$  for strip ( $L = \infty$ )  
 $= 1.2 \times 5.14 \approx 6.2$  for  $B = L$

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

Since  $S_c = (1 + \frac{B}{L} \frac{N_q}{N_c})$   
 $= 1 + 0.2 \frac{B}{L}$  for  $\phi = 0$

3) Footing: Partially Saturated Clay

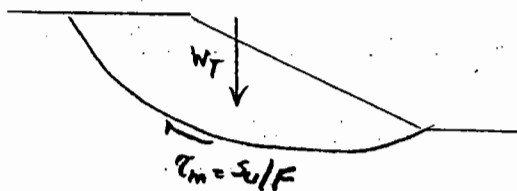
Since  $B < L \rightarrow \phi > 0$   $\therefore$  Run UUC tests (neglecting disturbance  $\epsilon$  & anisotropy)



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

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

Circular Arc Analysis



How define  $s_u$ ? Controversial

• Most practitioners & L & W ('89) use  $s_u = q_f$  for Total Stress  $\phi = 0$  analyses

• CCL: If arc approximates an actual failure surface, then should use

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

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

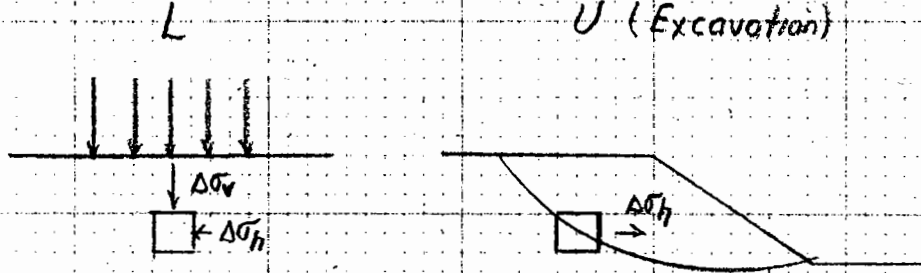
"TRUTH": Actual failure surface probably closer to log spiral



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
- $+\Delta p \uparrow +u_e$ : then drainage  $\rightarrow +\Delta\sigma'$  (consolidation)  $\rightarrow$  incr. strength  $\rightarrow$  incr. FS with time (always occurs for loading, esp. low OCR)  
**UU CRITICAL**
  - $-\Delta p \downarrow -u_e$ : then drainage  $\rightarrow -\Delta\sigma'$  (swelling)  $\rightarrow$  decreased strength  $\rightarrow$  decr. FS with time (usual case for unloading, esp. high OCR)  
**CD CRITICAL**

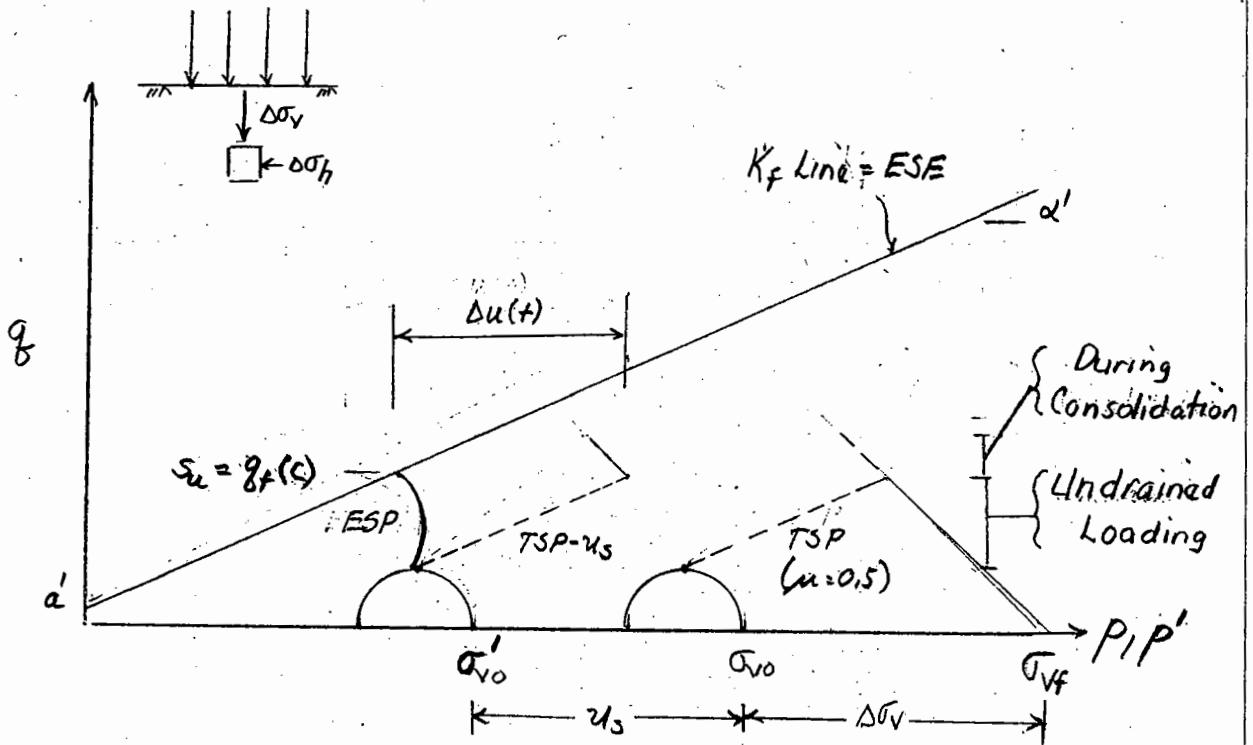
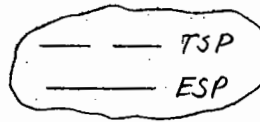
4.2 Illustration for Loading Problem (Fig B3-1(4) p 9; medium-low OCR)

- 1) TSP & ESP during undrained construction
- 2) " " " " consolidation
- 3) ESP if drained loading
- 4) Conclusions

See Section 3.2 of TL

- Undrained (UU) always critical  $\rightarrow$  failures during construction
- Discussion of why drained ESA (CD CASE); not applicable  
For loading cases, actual failure will always be rapid (minutes  $\rightarrow$  hours)  $\rightarrow u_{sh} > 0 \uparrow$  decr. in  $\sigma'$   
 $\therefore$  CD analysis UNSAFE since actual  $\sigma'_{ff} <$  preshear value (not generally recognized in practice)

(L) Loading : Medium-Low OCR



(U) Unloading : Medium-High OCR (Take  $K_0 = 1$ ) & Vertical Cut

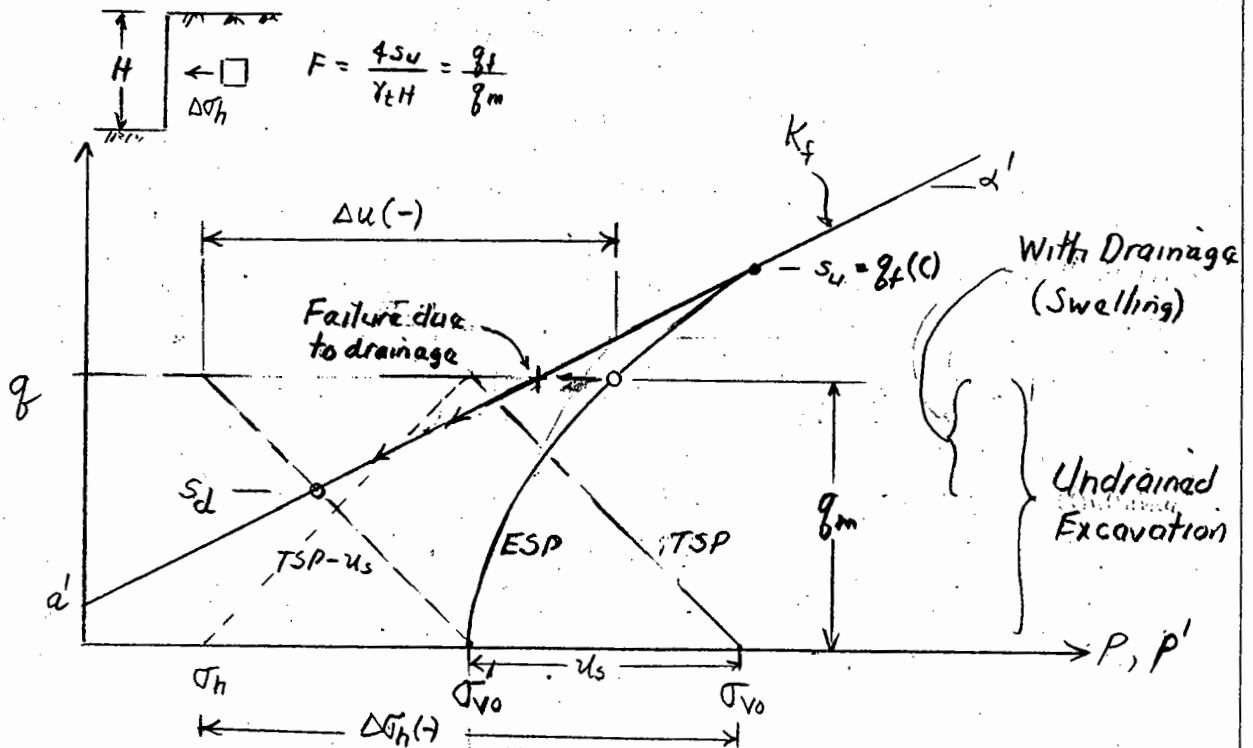


Fig I3-1 Stress Paths for Loading & Unloading : Undrained to Fully Drained

4.3 Illustration for Unloading Problem (Fig V3-1(U), p9: med. - high OCR)

- 1) TSP & ESP during undrained construction
- 2) " " " " drainage (swelling)
- 3) Conclusions

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

4.4 Summary

- 1) Loading Problems (increase in ave. total stress  $\Delta p$  &  $u_e > 0$ )

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. in part  $c = s_u$  ( $S = 100\%$ )

$\Delta \sigma_v > (\sigma_p' - \sigma_{v0}')$

"Soft Ground" condition :  $\sigma_{vf} > \sigma_p$  - must check FS carefully

$\Delta \sigma_v < (\sigma_p' - \sigma_{v0}')$

"Stiff Ground" :  $\sigma_{vf} < \sigma_p$  - FS should be OK

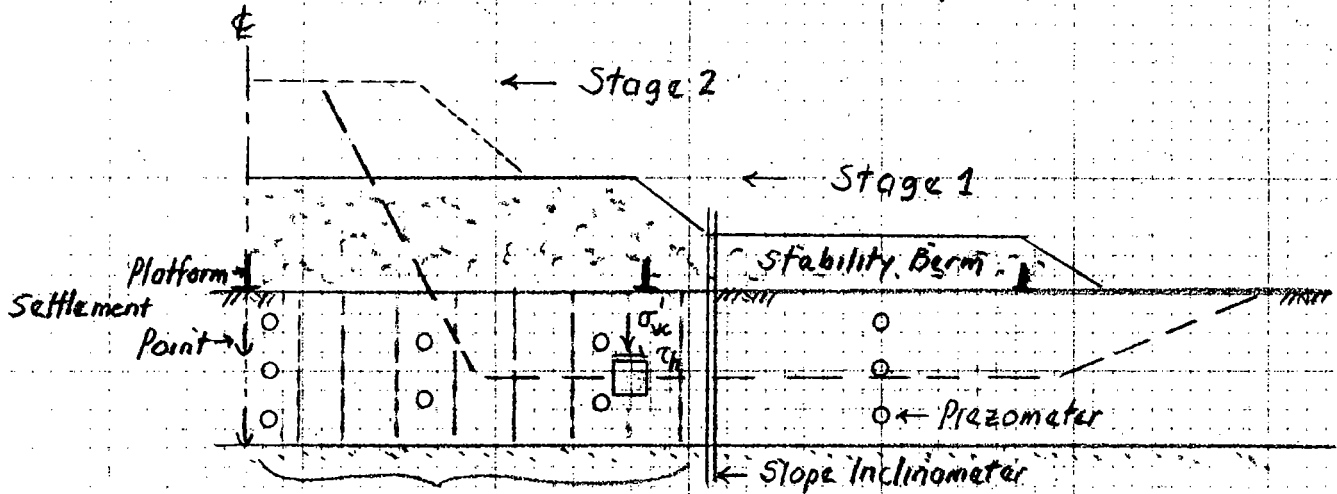
- 2) Unloading Problems (decrease in ave. total stress  $\Delta p$  &  $u_e < 0$ )

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

- Drained (CD) most critical since FS decreases with time
- Failures usually occur after construction (esp. at high OCR)
- Do Drained Strength Analysis, i.e. in part  $c', \phi'$  and equilibrium  $u$  (also called FSA)
- 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

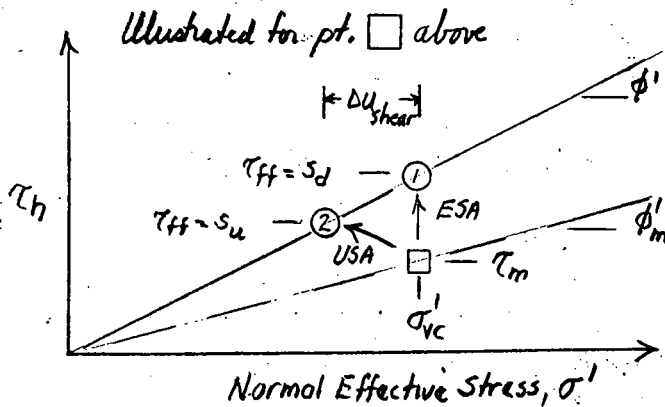
5.1 Example of "Intermediate" = Partially Drained CASE



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  $\rightarrow$  increase in  $f_{cm}$ ,  $s_u$
  - 4) Stage 2

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



NOTE:  $\sigma'_{vc}$  = Computed  $\sigma_v$  - measured  $u$

1) ESA = Drained Strength Analysis

$$FS = \frac{s_d}{\tau_m} = \frac{\tan \phi'}{\tan \phi'_m}$$

• UNSAFE since neglects +  $DU_{shear}$

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