I-3 STABILITY EVALUATION: COHESIVE SOILS

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4.4 Summary

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      - Drained Strength Analysis (ESA) is unsafe
      - Should perform Undrained Strength Analysis (USA)

1. Classes of Stability Problems: Types of Analyses

1.1 Problem Definition

1) Does construction involve loading or unloading?

\[ \text{LOADING (L)} \]
\[ + \Delta p + u_e \]
\[ \text{(Drainage \ to \ increase \ strength \ with \ consolidation)} \]

\[ \text{UNLOADING (U)} \]
\[ - \Delta p - u_e \]
\[ \text{(Drainage \ to \ decrease \ strength \ with \ swelling)} \]

2) For calculation of Factor of Safety, \( FS = \frac{\text{Available Shear Strength (s)}}{\text{Required Shear Stress (Tm)}} \)

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 \( \rightarrow \) undrained analysis
After construction, critical for U \( \rightarrow \) drained analysis)

1.2 Three Classes of Stability Analyses

Have 3 cases directly analogous to the 3 types of (frictional) shear test 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 = \( S_d = c' + \sigma' \tan \phi' \)
- Hence conduct Drained Strength Analysis (DSA), where \( FS = \frac{S_d}{T_m} \)

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

2) Unconsolidated-Undrained (UU Case) = "end of construction" = [No Drainage = Undrained]
   - Have $\Delta w = 0 \rightarrow \Delta \gamma = \gamma_w$ (no drainage during construction or failure)
   - Therefore available strength = Undrained Strength = In-situ $\gamma_w$ that existed prior to construction
   - Hence conduct Undrained Strength Analysis (USA), where $FS = \text{index} \gamma_w / \gamma_m$
   - **NOTE**: Also called Total Stress Analysis (TSA) à la Section 3.2.
     (If $S = 100\%$, then $\phi = 0^\circ \therefore \varepsilon = \varepsilon_w$)

3) Consolidated-Undrained (CU Case) = "Intermediate" = [Partial Drainage]
   - Either during or after construction, have partial or full drainage
     - $\Delta \varepsilon \geq 0$ for loading problems
     - $\Delta \varepsilon \leq 0$ for Unloading problems
     - $\Delta \varepsilon$ profile has changed from preconstruction profile
     - But assume No Drainage during potential (rapid) failure
     - Therefor available strength = In-situ $\gamma_w \cdot \varepsilon / \text{OCR that existed just prior to potential failure}$
     - Hence conduct USA, where $FS = \text{index} \gamma_w / \gamma_m$

   **Comments**: CU & 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 assumption: $\Delta \varepsilon = 0$ requires extremely slow construction or very long time after construction (full consolidation or swelling); $\Delta \gamma = 0$ requires extremely slow failure (Not possible for Loading Condition à la Section 6)

2) Compute drained strength $\gamma_d = \gamma_w + \gamma_v$ (where $\Delta \gamma_v = \text{steady state condition} (\text{hydrostatic or steady state seepage})$

3) Perform Drained Strength Analysis (DSA) $FS = \gamma_d / \gamma_m$. However, usually called Effective Stress Analysis (ESA) Aime computing $\gamma_d = \text{index}(\text{index})$
2.2 Examples (From prior Notes)

Part IV-3 1) Retaining Wall; Rankine: \( P = P + P_m \)

Part III-2 2) Infinite Slope

Part III-7 3) Bearing capacity ship footing

2.3 Evaluation of \( c' \) & \( \phi' \) In Practice

1) C/D Testing: Must shear slowly so that \( u_{sh} = 0 \)

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

b) Triaxial: Usually CIQC (L/D)

Low Cost & Quick, BUT
- ESE too low if \( \theta_h > \theta_{ff} \)
- No shear stress curve
- LARGE ERROR WITH HANO CRANKED (\( u_{sh} \neq 0 \)): \( c' \) too high
\( \phi' \) too low

Most Accurate ESE (especially at low \( \sigma' \)) to obtain \( E_{an} = \phi' + \omega \)

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

2) CU testing with u measurement - Usually CIUC

(Widely Used since cost much less than CIUC, but)
- Difficult to define e at low u
- If run too fast (especially high OCR)
  LARGE errors in ESE
  (c too high, \( q' \) too low)

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

3.1 Basic Assumptions and potential failure
- Rate of construction too rapid compared to rate of consolidation
  that amount of drainage is negligible \( t << t_p \)
- For \( d_w = 0 \), \( w_f = w_N \) are in UU type testing

3.2 Basis for \( \phi = 0 \) Total Stress Analysis (S=100%)
- Illustrated for plane strain condition & low OCR

PS \( (\) PS \( ) \)

Stress Paths

--- ESP
--- TSP

Some ESP \( + s_u \) \( \rightarrow \) TSA with
\( \phi = 0 \), \( c = s_u = q_f \), existing in situ
prior to construction
3.2 Continued

Conclusion: For same mode of failure:
- \( \phi = 0 \) and \( C = 9_f = 3_u \) for Total Stress Analysis (TSA)
- \( 3_u \) independent of TSP, it equals in situ \( 3_u \) exciting prior to construction.

3.3 Preliminary Discussion of \( 3_u \) Evaluation

1) Common assumption in conventional practice (5=100%):
   - Since \( 3_u \) uniquely related to \( u_f = u_w \) by the Principle II,
     
   Can obtain \( 3_u \) via any "UU" type shear test, e.g.:
     - In situ: Field vane (FV) Lab: Triaxial UUC or unconf. comp.

2) But in reality, \( 3_u \) not uniquely related to \( u_f = u_w \) due to:
   - Sample disturbance (\( \to \) decrease in measured \( 3_u \); test UU tests)
   - Strain rate (\( \text{incr. } \varepsilon \to \text{decr. } f \to \text{incr. } 3_u \))
   - Stress system = value of \( 3_u = f(0) \) \& isotropy = \( 3_u \) direction (single)

   Conventional practice methodology \( \rightarrow 3_u \)

3.4 Definition of \( 3_u \) & TSA vs USA: SHAHSEP methodology \( \rightarrow 3_u \)

Illustrate based via lab UUC test (\( 3_f = q = \) cell pressure)

- \( \phi = 0 \) Assumption: Actual failure

\[
\begin{align*}
\sigma_3^f & \rightarrow \sigma_3^f \\
\Theta = 45^\circ & \rightarrow \Theta = 45 + \phi/2
\end{align*}
\]

- \( 3_u = 9_f = 3_u = \cos \phi \)
- TSA: \( \phi = 0 \), \( C = 9_f \)
- Undrained strength analysis = USA

FYI: Not discussed in class
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 (Fundamental)

For $\phi = 0$ ($N_f = 1$) $C = S_u = q_f$, $\sigma_f = S_f N_f + 2C \sqrt{N_f} \rightarrow \sigma_f = S_f + 2C$

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

$P_a = 0 \rightarrow \frac{1}{2} \gamma F H^2 = 2S_u H$ at failure $\rightarrow H_c = \frac{4S_u}{\gamma F}$, where $S_u = q_f = q_f(C)$

For $H < H_c$, $\phi = 0$ analysis $\rightarrow$

$F = \frac{H_c}{H} = \frac{4S_u}{\gamma F} = \frac{9f}{F}$

And: For actual failure surface at $g = 45 + \phi'/2$

$$FS = F = \frac{9f}{F_m} = \frac{9f \cos \phi'}{g_m \cos \phi} = \frac{9f}{g_m} = \text{same}$$
3.5 Continued

2) Footing on Saturated Clay

\[ q_{ull} = \frac{C_N c + \frac{1}{2} \gamma B N_k + \delta d N_k}{z} \]

Weight only (no strength)

\[ z = \frac{B}{12} \approx 0.07B \]

Saturated Clay

\[ c = s_u, \phi = 0, N_k \]

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

Strip:

\[ q_{ull} = s_u N_c \delta + \delta d N_k \]

where \( s_u = q_f \)

\[ \delta = \frac{N_c}{5.14} \text{ for strip (} L = \infty \text{)} \]

\[ = 1.2 \times 5.14 \approx 6.2 \text{ for } B = L \]

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

\[ = 1 + 0.2 \frac{B}{L} \text{ for } \phi = 0 \]

* Practical: Use \( c = \text{average } s_u \text{ within} \)

\[ z = \frac{2}{3} B \]

3) Footing: Partially Saturated Clay

Since \( B < 1 \rightarrow \phi > 0 \)

Run UWC tests (regulating disturbance & \( E \) of anisotropy)

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

Circular Arc Analysis

\[ F_s = F_i = \frac{s_u}{\gamma_m} \{ = \frac{W_d \delta}{\gamma_r} \} \]

How define \( s_u \)? Controversial

- Most practitioners \( \phi \in [0(\%)] \) use

\[ s_u = q_f \text{ for Total Stress } \phi = 0 \text{ analysis} \]

- CCL: \( \phi \) arc approximates an actual failure surface, then should use

\[ s_u \geq \gamma_f \gamma_f \cot \phi' = (0.85 \times 0.9) q_f \]

\[ \phi = 29^\circ \pm 3^\circ \]
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
      
      \[
      \begin{align*}
      \Delta \sigma_v & \quad \text{loading} \\
      k \Delta \sigma_h & \quad \text{unloading (Excavation)}
      \end{align*}
      \]

   2) General Guidance: if during construction, for representative element
      \[ \Delta \sigma \neq \Delta \sigma_0 : \text{then drainage} \rightarrow \Delta \sigma \text{ (consolidation)} \quad \text{increase strength} \]
      
      \* UU CRITICAL 
      \[ \Delta \sigma \neq \Delta \sigma_0 : \text{then drainage} \rightarrow -\Delta \sigma \text{ (swelling) decrease strength} \]
      
      \* CD CRITICAL

4.2 Illustration: for loading problem (Fig 3-1(e)p9; medium-low OCR)
   1) TSP if ESP during undrained construction
   2) " " " consolidation
   3) ESP if drained loading

4) Conclusions
   - Undrained (UU) always critical \[ \rightarrow \text{failure during construction} \]
   - Discussion of why drained ESP (CD CASE) not applicable
     \[ \begin{align*}
     \text{For loading cases, actual failure will always} \\
     \text{be rapid (minutes-hours) \rightarrow \text{high } \lambda \text{ dec. in } \sigma}
     \end{align*} \]
   - CD analysis UNSAFE since actual \[ \sigma' \] < preshear value
     \[ \text{(not generally recognized in practice)} \]

See Section 32 of TL
(L) Loading: Medium - Low OCR

During Consolidation

Undrained Loading

\[ TSP \quad ESP \]

\[ K_F \text{ Line: ESE} \]

\[ \Delta u(H) \]

\[ \sigma' \]

\[ q_b \]

\[ a' \]

\[ S_u = g_f(c) \]

\[ \Delta v \]

\[ U_0 \]

\[ \sigma' \]

\[ \sigma_0 \]

\[ \sigma_{vf} \]

\[ P/P' \]

(U) Unloading: Medium - High OCR

(Take \( K_0 = V \) \& Vertical Cut)

\[ F = \frac{4u}{f_i H} = \frac{g_i}{f_m} \]

\[ \Delta u(-) \]

Failure due to drainage

\[ S_d \]

\[ TSP - u_s \]

\[ ESP \]

\[ TSP \]

\[ U_0 \]

\[ \sigma_0 \]

\[ \sigma_{vf} \]

\[ \Delta \sigma_0(\gamma) \]

\[ q_0 \]

\[ q_b \]

\[ a' \]

\[ H \]

\[ \Delta u(H) \]

\[ \Delta v \]

\[ U_0 \]

\[ \sigma_0 \]

\[ \sigma' \]

\[ \sigma_{vf} \]

With Drainage (Swelling)

Undrained Excavation

\[ P, P' \]

Fig. II.3-1 Stress Paths for Loading \& Unloading: Undrained \& Fully Drained
4.3 Illustration for Unloading Problem (Fig 23-1 Upposed, High OCR)

1) TSP & ESP during undrained construction

2) """""" drainage (swelling)

3) Conclusions:

- Drained (CD) always critical (except for low OCR \( \phi_d \geq 1 \))
- 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 \( c' = 0 \), \( \phi_d = \phi' \) for NC clay
  \( \text{if prior failure at site, use } c' = 0 \) \( \text{ residual } \phi_d = \phi' \)

4.4 Summary

1) Loading Problems (increase in ave. total stress \( \Delta p \uparrow \), \( u_< 0 \))

\[
\text{Min. FS} = \frac{s_u}{C_m} \]

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

- \( \Delta s_v > (\sigma_p' - \sigma_v) \)
  "Soft Ground" condition \( \sigma_v' > \sigma_p' \) \( \rightarrow \) must check FS carefully

- \( \Delta s_v = (\sigma_p' - \sigma_w) \)
  "Stiff Ground" \( \sigma_v' < \sigma_p' \) \( \rightarrow \) FS should be OK

2) Unloading Problems (decrease in ave. total stress \( \Delta p \downarrow \), \( u_> 0 \))

\[
\text{Min. FS} = \frac{s_d + \phi}{C_m} = \frac{\tan \phi'}{\tan \phi_m} \]

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

- Use when initial in situ $s_u$ 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 $m$-factors $s_u$
  4) Stage 2

5.2 Comments on Stability Evaluation (after Fig. 3 of CA(1991) 174)

Illustrated for pt. 1 above

\[ F_S = \frac{S_d}{\tan \phi_m} \]

- UNSAFE since neglects $\Delta u$ shear

1) $E.S.A.$: Drained Strength Analysis
2) $U.S.A.$: Undrained Strength Analysis

- Correct approach for rapid, undrained failure.

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