Objective of Chapter

- Understand slope stability issues that may affect a dam’s or levee’s risk of breach.
- Provide guidance on consideration and selection of soil strengths, pore pressures and loading conditions for slope stability analysis for risk assessments.
Key Concepts

• Formational processes, stress history and current state of stress will affect whether it is “dense” or “loose”

• “Dense/overconsolidated” soils dilate and “loose/normally consolidated” soils contract during shear

• Drainage condition (i.e., drained or undrained loading) is a function of the permeability of the soil and the rate of consolidation and shear loading

• Negative (dense) or positive (loose) shear-induced pore pressures can develop dependent on drainage condition and can increase or decrease the soil’s strength

• Soil strength changes with time
• USACE slope instability issues
  • “during construction and end of construction” conditions
  • A few dams have had issues on “sunny days” or during sudden drawdown conditions.
    ▪ Levees have had more serious issues that have occurred from during construction to flood loading conditions
      ▪ New Orleans
  • Reclamation has had few instability issues
    ▪ Belle Fouche Dam, SD and Meeks Cabin Dam, WY
    ▪ San Luis Dam, CA
Ft Peck Dam Upstream Slide 1938

Partial failure of Fort Peck Dam as seen from the air.

Sept. 22, 1938

N 303
Coles Photo
PAKE-PHOTO
View Looking East Towards the Right Abutment, Note Slide Area.
Key information for doing proper embankment slope instability analysis

• Geometry and geology
• Shear strength
• Stresses (total stresses and pore pressures)
• Pore pressures from hydrostatic, seepage conditions and shear induced
Slope Instability Triggers

• Rainfall Infiltration (from cracks or poor drainage at crest)
• Removal of toe support (from erosion or excavation)
• Surcharge loading at crest or foundation
• Rapid drawdown
• Changes in seepage or groundwater (e.g. irrigation on abutment)
• Other conditions that change vertical or horizontal stresses (e.g. water line)
CASE I
END OF CONSTRUCTION
T = 0 years
(minimum NC undrained strength)
CASE I

END OF CONSTRUCTION

T = 0 years
(minimum NC undrained strength)

CASE II

SUDDEN DRAWDOWN

T = 0 years to end of Primary Consolidation
**CASE III**

**FLOOD LOADING**

*T = 0* years to end of Primary Consolidation

- **SLOPE:** LANDSIDE
- **LEVEE EL:** (i) or Existing
- **WATER LOAD:** (i) & (c)

**SHEAR STRENGTH**
- LOW PERMEABLE: UU (i-2)
- LOW PERMEABLE: CD (i-2)
- FREE DRAINING: CD (i) or (c)

**FACTOR OF SAFETY:**
1.4 MINIMUM LOADING (i)
1.3 MINIMUM LOADING (c)

**NOTES:**
1. *T = 0* (New Levee): Undrained shear strengths based on pre-construction in situ conditions.
2. *T > 0* yrs and OCR < say 2 - 4: Undrained shear strengths based in existing in situ conditions at time of evaluation.
3. OCR > say 2 to 4: Drained shear strengths.

**CASE IV**

**SEISMIC**

*T = 0* years to end of Primary Consolidation

SEE EIR 1110-2-1806 FOR GUIDANCE. GUIDANCE FOR SEISMIC STABILITY ANALYSIS OF LEVEES IS UNDER PREPARATION (ETL 1110-2-XXXX).
<table>
<thead>
<tr>
<th>Analysis Condition</th>
<th>Shear Strength&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Pore Water Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case I. During Construction and End-of-Construction</td>
<td>Free draining soils - use drained strengths</td>
<td>Free draining soils - Pore water pressures can be estimated using analytical techniques such as hydrostatic pressure computations for no flow or steady seepage analysis techniques (flow nets, finite element/difference analyses).</td>
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<td></td>
<td>Low permeability soils wet of critical – use undrained strengths based on pre-construction effective stress conditions for soils with OCR &lt; 2 to 4</td>
<td>Low permeability soils wet of critical – use total stresses with pore water pressures set to zero in the slope stability computations for materials with OCR &lt; 2 to 4.</td>
</tr>
<tr>
<td></td>
<td>Low permeability soils dry of critical – use drained strengths when OCR &gt; 2 to 4.&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Low permeability soils dry of critical – use effective stresses with appropriate construction pore pressures, often assumed to be hydrostatic OCR &gt; 2 to 4.</td>
</tr>
<tr>
<td>Case II. Sudden Drawdown Conditions</td>
<td>Free draining soils - use drained strengths</td>
<td>Free draining soils - First stage computations (before drawdown) - steady state seepage pore pressures as described for steady state seepage condition. Second and third stage computations (after drawdown) - pore water pressures estimated using same techniques as for steady seepage, except with lowered water levels.</td>
</tr>
<tr>
<td></td>
<td>Low permeability soils - Three stage computations: First stage use effective stresses; second stage use undrained shear strengths and total stresses; third stage use drained strengths (effective stresses) or undrained strengths (total stresses) depending on which strength is lower - this will vary along the assumed shear surface.</td>
<td>Low permeability soils - First stage computations – steady state seepage pore pressures as described for steady state seepage condition. Second stage computations - Total stresses are used, pore water pressures are set to zero. Third stage computations - Use same pore pressures as free draining soils if drained strengths are being used; where undrained total stress strengths are used, pore water pressures have no effect and can be set to zero.</td>
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<td>Case III. Flood Loading</td>
<td>Free draining soils - use drained strengths. Residual strengths should be used where previous shear deformation or sliding has occurred.&lt;br&gt;Low permeability soils wet of critical – use undrained strengths based on pre-flood effective stress conditions for soils with OCR &lt; 2 to 4&lt;br&gt;Low permeability soils dry of critical – use drained strengths using steady state seepage pore pressures. &lt;sup&gt;5&lt;/sup&gt;</td>
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<td>Case IV. Seismic</td>
<td>(see ETL 1110-2-XXX, Guidelines for Seismic Evaluation of Levees)</td>
<td>Low permeability soils dry of critical – use effective stresses under steady state seepage flood loading for materials with OCR &gt; say 2 to 4.</td>
</tr>
</tbody>
</table>

<sup>5</sup> Effective stress parameters can be obtained from consolidated-drained (CD) tests (either direct shear or triaxial) or consolidated-undrained (CU) triaxial tests on saturated specimens with pore water pressure measurements. Direct shear or Bromhead ring shear tests should be used to measure residual strengths. Undrained strengths can be obtained from unconsolidated-undrained (UU) and direct simple shear tests. Undrained shear strengths can also be estimated using consolidated-undrained (CU) tests on specimens consolidated to appropriate stress conditions representative of field conditions, but these strengths may be unconservative. The CU or “total stress” envelope, with associated $c$ and $\phi$ parameters, should not be used. OCR is estimated based on the maximum past pressure and the effective stress prior to the flood load.

<sup>6</sup> For saturated soils with OCR < 2 to 4, use $\phi = 0$. 

aka “Rapid Flood Loading” of Soft Materials
New Orleans Parish

Figure 1-1. Location of Orleans Parish canals

Photos from Brett Duke, Online Times-Picayune archive
Examples – “Soft” Wet-of-Critical Shear Induced Positive Pore Pressures – Use Undrained Strengths
Design v. IPET Strengths and Stability

Undrained Strengths

\[ \Phi = 0 \]
\[ C = f(\text{depth}) \]
\[ Su/p' \sim 0.24 \]


Design Higher  Design Same

It appears that the most important difference between the conditions used as the basis for design and the conditions defined in this report is related to the strengths of the marsh layer and clay soils beneath the slopes and beyond the toe of the levee. The design strengths and the IPET strengths are very nearly the same beneath the crest of the levee. However, beneath the levee slopes, and beyond the toe, the design strengths were higher than the IPET strengths.
Major sources of uncertainty in some cases:

- In situ large scale shear strengths versus lab testing results
- Actual pore pressures versus predicted or assumed for analysis
Embarkment Instability

Contributing Factor: Slope Stability (Embankment Slides)

- Spring 2007, Storm events saturate the levees following extended dry period.
- Several levee embankment slides develop throughout the system in < 72 hours.
- Floodway monitored using Dallas PD air support and ground surveillance.
- Temporary repair efforts from the levee crest were not successful.
Embankment Instability

Contributing Factor: Encroachments (Utilities)

- 30 November 2010, Leaking 48-inch water main that crosses over the levee caused a slide of the levee embankment.
- This line was thought to be abandoned per the available USACE design & construction documents.
- Deteriorated valves could not be completely shut off to restrict flow, thus repairs were made with partial flow.
- USACE and CoD are evaluating all similar utilities to determine the appropriate mitigation solution.
Comments and Questions