Calibration of Seepage and Stability Models for analysis of Dams and Levees

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Focus

• Use of models for;
  – Evaluation of existing dams and levees
  – Rehabilitation

• Role of model calibration for improved characterization
Models

Some historical perspective
Flow Nets: Harry Cedergren
Levees: Blanket Theory Analysis

a. \( L_3 = \infty \)

\[
x_a = \frac{1}{c} \\
\hat{h}_a = h_a e^{-\alpha x}
\]

\[
x_3 = \frac{1}{c} \tanh(\alpha l_3) \\
\hat{h}_3 = h_3 \frac{c}{c_3} \frac{2(l_3 - x)}{\cosh \alpha l_3} \\
\hat{h}_a \text{ (for } x=L_a) = \frac{h_a}{\cosh \alpha l_3}
\]

b. \( L_3 \) is finite to a seepage block

\[
x_3 = \frac{\tanh(\alpha l_3)}{c} \\
\hat{h}_3 = h_3 \frac{\sinh \alpha l_3}{\cosh \alpha l_3} \\
\hat{h}_a \text{ (for } x=L_a) = 0
\]

c. \( L_3 \) is finite to an open seepage exit

BASIC DEFINITIONS AND EQUATIONS

SEEPAGE PER UNIT LENGTH OF LEVEE \( Q_i = S k_i H = \frac{d k_i H}{x_i + L_2 + x_i} \)

HEAD BENEATH TOP STRATUM AT LANDSIDE LEVEE TOE \( h_e = \frac{H x_2}{x_i + L_2 + x_i} \)

THE FACTOR \( c = \sqrt{\frac{k b l}{k z d}} \)

Figure B-7. Equations for computation of underseepage and substratum pressures for Case 7
Force Equilibrium Slope Stability
Analysis Models for Dams and Levees

• Seepage: typically FE or FD
• Slope Stability:
  – usually Limit Equilibrium, satisfy both force and moment
  – Deformation analysis (Seismic)
• Often used computer codes
  – UTEXAS
  – SEEP/W, SLOPE/W (GeoStudio)
  – SLIDE (Rocscience)
  – FLAC (ITASCA)
Model Calibration

• Verification vs calibration
• Verification: can model get correct answer, i.e. are the mechanics correct? Ex. Development of UTEXAS
• Calibration for project, site specific:
  – Get correct result for historic performance event
  – enhance the model inputs so that the model will predict dam/levee performance for a given future load condition
Model Inputs

- Geometry
- Geology/Stratigraphy
- Boundary conditions
- Water level
- Material Properties
Geotechnical Data

• Survey both land and bathymetry
• Site Recon
• Geomorphology studies
• Subsurface investigations
• Borings, drilling and sampling
• Insitu testing SPT, CPT, geophysics, pump tests
• Instrumentation
• Laboratory testing
Other Very Important Data

• Historic Performance Data associated with previous loading
  – Often overlooked
  – Usually think of instrumentation data records
• But also observations of distress and level of distress
• Often a **full scale field test**
Historical Performance

• Best indicator of future performance is past performance
• Value of historical performance, construction history and methodology vs geotechnical investigations for characterization of embankments and foundations
Historic Performance Data

- Back analysis of historical performance
- Can be used to
  - Check reasonableness of model results
    - Assumptions
    - Input parameters
  - Calibrate model: adjust to match performance
- Provides confidence in model results
- Allows model to better predict future performance
- Provides improved parameters for rehab design
Seepage models
SEEPAGE-Historic Performance

• Instrumentation
  – Dams-piezometers
  – Levees not likely
• Observations of distress
• Level of seepage
• Clear vs turbid
• Pin boils – larger boils
• Heave of ground surface
• Spongy to mattress ground consistency
### Seepage Level of Distress

<table>
<thead>
<tr>
<th>Exit Gradient, $i$</th>
<th>Level of Distress</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i &lt; 0.5$</td>
<td>Light to Medium Seepage</td>
</tr>
<tr>
<td>$0.5 &lt; i &lt; 0.8$</td>
<td>Heavy Seepage, Boils Flowing Clear</td>
</tr>
<tr>
<td>$i &gt; 0.8$</td>
<td>Boils Carrying Material (Action Required)</td>
</tr>
</tbody>
</table>
Seepage: Hydraulic Conductivity Parameters

- Classification based
- Laboratory tests
- Equations from grain size (Chapuis, 2003/2004)
- Field pump tests

But don’t forget other field based:

- Values based on historic performance of levees
  - Turnbull and Mansur (1959)
  - USACE, Kansas City District (flooding early 1950’s)
- Correlations ($D_{10}$ vs $k$) (Turnbull and Mansur)
b. Effective grain size, $D_{10}$ versus coefficient of permeability, $k_h$ (from WES TM No. 3-424, ref. A-1)
Field Data from Historic Floods

• For thin blankets (<15 ft.)
  – Laboratory and Presumptive k too low
  – Historic performance data from Mississippi and Missouri River floods demonstrate
    • Macro structure has huge influence
    • Riverside lower than landside

• Key parameter: $k_{hf}/k_{vbl}$
Eppley Airfield (Omaha)
Typical Section 1974 Levee

Documentation:
- Record drawings
- But no design document
Eppley Airport Field
Missouri River High Water 2011
Levee Mile 8.75

River Stage 988.4 - Existing/Calibration

Name: Levee (1e-5 cm/s)  Model: Saturated Only  K-Sat: 3.3e-007 ft/sec  Volumetric Water Content: 0.4 ft³/ft³  Mv: 0 / psf  K-Ratio: 1  K-Direction: 0 °
Name: Seepage Berm (1e-3 cm/s)  Model: Saturated Only  K-Sat: 3.3e-005 ft/sec  Volumetric Water Content: 0.4 ft³/ft³  Mv: 0 / psf  K-Ratio: 1  K-Direction: 0 °
Name: Assumed Silt Blanket (1e-4 cm/s)  Model: Saturated Only  K-Sat: 3.3e-006 ft/sec  Volumetric Water Content: 0.5 ft³/ft³  Mv: 0 / psf  K-Ratio: 0.25  K-Direction: 0 °
Name: Upper Aquifer (1e-2 cm/s)  Model: Saturated Only  K-Sat: 0.00033 ft/sec  Volumetric Water Content: 0.5 ft³/ft³  Mv: 0 / psf  K-Ratio: 0.25  K-Direction: 0 °
Name: Lower Aquifer (1e-1 cm/s)  Model: Saturated Only  K-Sat: 0.0033 ft/sec  Volumetric Water Content: 0.4 ft³/ft³  Mv: 0 / psf  K-Ratio: 0.5  K-Direction: 0 °

Scale: 1 Vertical:10 Horizontal

Gradient Calculation

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Head - Top</td>
<td>984.0</td>
<td>982.0</td>
<td>976.0</td>
</tr>
<tr>
<td>Total Head - Bottom</td>
<td>984.9</td>
<td>983.8</td>
<td>981.8</td>
</tr>
<tr>
<td>Elevation - Top</td>
<td>984.0</td>
<td>982.0</td>
<td>976.0</td>
</tr>
<tr>
<td>Elevation - Bottom</td>
<td>980.0</td>
<td>977.9</td>
<td>974.0</td>
</tr>
<tr>
<td>Gradient, I</td>
<td>0.2</td>
<td>0.4</td>
<td>2.9</td>
</tr>
</tbody>
</table>
LM 7.43 Cross Section
River Stage 987.5 - Distress Noticed

Name: Levee (1e-5 cm/s) Model: Saturated Only  K-Sat: 3.3e-007 ft/sec  Volumetric Water Content: 0.4 ft³/ft³  Mv: 0 /psf  K-Ratio: 1  K-Direction: 0 °
Name: Assumed Silt Blanket (1e-4 cm/s) Model: Saturated Only  K-Sat: 3.3e-006 ft/sec  Volumetric Water Content: 0.5 ft³/ft³  Mv: 0 /psf  K-Ratio: 0.25  K-Direction: 0 °
Name: Upper Aquifer (1e-2 cm/s) Model: Saturated Only  K-Sat: 0.00033 ft/sec  Volumetric Water Content: 0.5 ft³/ft³  Mv: 0 /psf  K-Ratio: 0.25  K-Direction: 0 °
Name: Lower Aquifer (1e-1 cm/s) Model: Saturated Only  K-Sat: 0.0033 ft/sec  Volumetric Water Content: 0.4 ft³/ft³  Mv: 0 /psf  K-Ratio: 0.5  K-Direction: 0 °
Name: Sand (2.5e-2 cm/s) Model: Saturated Only  K-Sat: 0.00032 ft/sec  Volumetric Water Content: 0.4 ft³/ft³  Mv: 0 /psf  K-Ratio: 1  K-Direction: 0 °
Name: Stone (1e-0 cm/s) Model: Saturated Only  K-Sat: 0.033 ft/sec  Volumetric Water Content: 0.4 ft³/ft³  Mv: 0 /psf  K-Ratio: 1  K-Direction: 0 °

Total Head Contours
Scale: 1 Vertical:10 Horizontal

Gradient Calculation

Total Head - Top = 977.3  Total Head - Bottom = 979.1  Total Elevation - Top = 977.3  Total Elevation - Bottom = 973.4  Gradient, I = 0.46
Scale: 1 Vertical:10 Horizontal

Ponded Water to EL 976.5

Weighted Filter in Place

MO River

Silt

978 980 982 984 986

10076977 ft³/sec
Seepage Models: Important considerations for Levees

• Methodology
  – Performance/historic distress
  – Past investigations, design and construction history
  – Geomorphology
  – Target subsurface investigations

• Boundary conditions
  – Extend water side boundary to river
  – Seepage entrance conditions (landside blanket)

• Hydraulic conductivity
  – Consider macro structure
  – Consider $k_f/k_{bl}$

• Calibrate model to match performance history
Levees: Plan and Profiles
Selecting Analysis Sections

- Performance History
- Geomorphology
- HEM profiles
- CPT/boring logs
Slope Stability
Safety of Existing Dams

• Precedence of
  – Thorough investigations of site conditions and construction records

• Over
  – Stability analysis

Ralph Peck (1988)
Gardiner Dam

- Construction 1959-1967
- Main embankment:
  - 2500 meters long
  - 64 meters high
- Fdtn: pre-sheared bentonitic Bearpaw Shale
Gardiner Dam

FIGURE 7. Successive stages in flattening of slopes of Gardiner Dam (after PFRA 1980).

- Over 2 m of movement 150 m downstream but almost none at toe
- Flattened slopes several times
Gardiner River Section

- Movements occurred near end of construction
- Additional movements with reservoir filling
- Continued movements with each reservoir filling
- Rates are declining
- Limit equilibrium methods not definitive
The problem with stability analyses for existing dams

- If $F<1$ it must erroneous
- If $F>1$ it merely indicates the obvious
- If progressive movements are occurring it is irrelevant
  - Because $F$ is obviously close to one
  - Monitor movement with each successive pool cycle
- Real proof: Decreasing increments for comparable reservoir fillings

Ralph Peck (1998)
Leavenworth State Fishing Lake

• Dam designed and constructed early 1930’s
• 1994 buttressed downstream slope to improve stability
• After 10 years of adequate performance slumps in upper slope occurred
Past Performance vs Geotechnical Investigations

- Past Performance Downstream slope
  - Performed adequately for 70 years
  - Had not been well maintained
  - Surficial slump

- Stability calculations
  - Based on assumed strengths and internal water level
  - Led to low safety factors approaching 1.0

- With actual piezometric levels and more realistic strengths factor of safety probably acceptable
Leavenworth State Fishing Lake

- 1991 evaluation found concern for slope stability
- 1994 added additional embankment

FS = 1.5
Slump On Downstream Slope
(2005)
Previous Stability Analysis
Model

• Previous Stability Analysis
  – Doesn’t explain failure
  – Critical shear surface not consistent with observations
  – 1991 assumed water level and strength don’t support observations

• Model not calibrated
Back Analysis

- Shear strength = average “fully softened” and residual = 20°
Calibrated model

• Results Of Investigation
  – Back analysis of slide provides rational explanation for cause of slumps
    • progressive failure
    • triggered by rainfall
  – Consequences
    • Slumps are shallow, associated with rainfall infiltration
    • Not a threat to uncontrolled release of pool
  – Piezometric levels near base of embankment, global stability not an issue

• Use calibrated model for remediation
Role of Slope Stability Analysis
Existing Dams

• Peck, 1988
  – Cannot overemphasize importance of past performance
  – Engineers too quick to use stability calculations based on unsupported and unverifiable assumptions
  – More difficult to do careful investigations followed by application of judgment based on instrumentation data and observations of past performance

• Use calibrated model to get correct parameters for remedial design
Tuttle Creek Dam Seismic Rehabilitation

Case History using calibrated soil constitutive model for deformation analysis (both existing and remediated conditions)
Deformation Analysis (TARA-FL)
Fine Grained Blanket: Undisturbed Sample Testing

Figure 3. Undrained strength loss with increasing seismically induced shear strain for fine grained blanket
Undisturbed Sample Testing
Fine Grained Blanket Materials

Figure 4. Stress-strain behavior for post-liquefaction with static shear bias in the fine grained blanket captured by UBCTOT model.
Deformation Analysis: FLAC

Liquefaction of fine grained blanket but no significant strength loss

Figure 7. Extent of liquefaction within cohesive foundation layer
Figure 8. Time histories of surface displacement and horizontal design motion.
Figure 10. Comparison of crest settlements after Swaisgood (2003) and FLAC results.
Key Points

• Importance of construction and performance history
• Use to calibrate analysis models
• Improved input parameters
• Greater confidence in results
• Model better able to predict future performance