Embankment Dams on Karstic Limestone, Soluble and Erodible Foundations: Challenges and Solutions

Donald A. Bruce, Geosystems, L.P.
Keith Ferguson, Kleinfelder, Inc.

The Problem

Large number of major dam safety incidents involving complex seepage/piping failure mode development processes
Large number of other dams in similar environments with similar design and construction provisions

USGS map of Karst in the US.

Centerhill Dam, TN – 1983 Muddy Show
Clearwater Dam, MO – Sinkhole
15 January 2003
## Typical Well Known Examples

<table>
<thead>
<tr>
<th>Name of Dam</th>
<th>Date(s) of Incidents</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wolf Creek Dam, KY</td>
<td>1960’s</td>
<td>Increasing seepage, sinkholes along downstream toe of dam, muddy show</td>
</tr>
<tr>
<td>Center Hill Dam, TN</td>
<td>1969 - 1983</td>
<td>Increasing seepage, sinkholes along downstream toe of dam, muddy show</td>
</tr>
<tr>
<td>Quail Creek Dam, UT</td>
<td>1980’s</td>
<td>Increasing seepage, toe drain failure, dam failure.</td>
</tr>
<tr>
<td>Mosul Dam, Iraq</td>
<td>1970’s to present</td>
<td>Sinkholes along downstream toe, abutments and increasing seepage</td>
</tr>
<tr>
<td>Clearwater Dam, MO</td>
<td>Jan 2003</td>
<td>Increasing seepage, sinkhole on Upstream face of dam.</td>
</tr>
<tr>
<td>Horsetooth Dam, CO</td>
<td>Early 2000’s</td>
<td>Sinkholes along upstream toe of dam and increasing seepage</td>
</tr>
<tr>
<td>Arapuni Dam, NZ</td>
<td>1927 to 1995</td>
<td>Increasing seepage</td>
</tr>
</tbody>
</table>

Numerous other case histories exist.

## Failure Modes

![Failure Modes Diagram]

- Head Loss Components:
  - Upstream Head Loss
  - Seepage Flatters
  - Dead Carbon
  - Head Loss (Hc)
  - Downstream Head Loss (Hd)
  - Tailwater Head (Hw)

Legend:
- Head measurement points
- Normal head loss (colored components: waterlogging (W), O.D.)
- Failure Mode: development head loss
- Upstream piping, downstream erosion (L.U.)
- Erosion
- Failure Mode: development head loss, gravity curtain breach (L.U.)
## Failure Modes

<table>
<thead>
<tr>
<th>Foundation or Bedrock</th>
<th>Failure Mode – Erosion</th>
<th>Failure Mode – Solutioning</th>
<th>Failure Mode – Combination Erosion and Solutioning</th>
<th>Example Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karstic, Erodible</td>
<td>X</td>
<td></td>
<td></td>
<td>Wolf Creek, Center Hill, Clearwater, Arapuni</td>
</tr>
<tr>
<td>Soluble</td>
<td></td>
<td>X</td>
<td></td>
<td>Horsetooth, Quail Creek</td>
</tr>
<tr>
<td>Karstic/Erodible and Soluble</td>
<td></td>
<td></td>
<td>X</td>
<td>Mosul</td>
</tr>
</tbody>
</table>

Figure courtesy of USACE

## Erosion Failure Modes

![Image of Progressively Developing Pipe Diagram](image)

Figure courtesy of USACE
Solutioning Failure Modes

Source: Drybrodt et al., 2001
Distress Indicators

Factors Contributing to Location and Rate of Failure Mode Development
Geologic Characteristics of Karst, Erodible and Soluble Foundations

Stratigraphically controlled Karst with no connection to base of dam

Structural Controlled Karst with connection to base of dam

Clay Filling

Open flowing 20 to 30 gpm under low head

Geologic Characteristics of Karst, Erodible and Soluble Foundations
Design Features leading to development of safety incidents/failures
- Inadequate treatment of foundation defects
- Incomplete or inadequate grout curtains and/or cutoffs
- Inadequate embankment filter/drainage provisions

Caves along cutoff trench – Wolf Creek Dam

Key Factors in Assessing Risk Profile
Site geology
Design Features
  - Depth of foundation treatment
  - Interface treatment
  - Embankment provisions
Depth of reservoir
Time since first filling
Erodibility of Karst or open joint infilling materials
Solubility and reservoir water chemistry

All these factors must be considered when assessing the risk profile and potential risk of future failure mode development. Current performance may not be an indicator of future safety. Solution and erosion processes are dynamic.
Reservoir Completion

Risk Profile Development
Predictive Model

Failure Mode Development Stage

First Filling

Normal Behavior

Breach Formation

Time – yrs.

Wolfcreek

Center Hill

Emb.

Clearwater

Teton

Quail Creek

Center Hill

Abut.

Progression

Continuation

Uncertainty Limits

A – Low Risk Profile (RP)

B – Moderate RP

C – High RP

D – Very High RP

Solutions

Existing Dams

- Geologic models of site
- Modern grout curtains
- Composite cutoff wall systems
- Filters/Drains
- Replacement dams with adequate zonation and foundation treatments/cutoffs
Solutions

New Dams
- Excavation/treatment of defects
- Composite cutoff systems
- Concrete dams in lieu of embankments
- Combinations of the above

Review of Seepage Remediation Methodologies
Concrete Cut-Offs
Clamshells (cable or hydraulic)
Secant Pile Method “Conventional”

Khao Laem Dam, Thailand

Beaver Dam, Arkansas
Major Rehabilitation
Concrete Cutoff Wall
(Section - Looking Upstream)
Drilling Around the Clock

W.F. George, AL
Technologies for “Soilcrete” or “Soft” Walls (not otherwise discussed in this presentation)

4.2.1 Deep Mixing
4.2.2 CSM Method
4.2.3 TRD Method
4.2.4 Backhoe

DMM Method

Deep mixing methods as they are known involve the use of a variety of cutting and mixing tools, mounted to one or more vertical shafts, that are driven into the ground to produce columns of treated soil.

Some of the better known methods of deep mixing are summarized in the following chart:
Cutter Soil Mixing (CSM)

In 2004 Bauer developed a new method to carry out Deep Soil Mixing. The method is based on the use of diaphragm wall cutters mounted to a special frame that is driven into the ground by a Kelly bar to produce rectangular panels of treated soil.
TRD Method
Trench cutting & Re-mixing
Deep wall method since 1993
Up to July 2003,
Number of job sites : over than 220,
Max. depth : about 53m(170 ft.)

September, 2003
M. Aoi &
K. Tsujimoto
Backhoe Method
Concrete Cut-Offs

Soilcrete/Soft Cut-Offs

Depth Capabilities of Different Cut-Off Methodologies

Project Listing Showing Chronology
Type of Cut-Off and Specialty Contractor
Concrete Cut-Offs for Existing Embankment Dams

<table>
<thead>
<tr>
<th>Type of Construction</th>
<th>Number of Projects</th>
<th>Square Footage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Smallest</td>
</tr>
<tr>
<td>Clamshell</td>
<td>7</td>
<td>51,000</td>
</tr>
<tr>
<td>Hydromill</td>
<td>9</td>
<td>104,600</td>
</tr>
<tr>
<td>Secant Piles</td>
<td>4</td>
<td>12,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>20</strong></td>
<td></td>
</tr>
</tbody>
</table>

Note:
1. This is the cumulative result of 32 years of activity to date. During the next 5 years, USACE alone will likely conduct a similar dollar value again, on 3 dams.

Composite Grout/Concrete Cut-Offs

The New Way of Grouting

- Quantitative Design
  - Intensity of Grouting consistent with design assumptions and requirements
- Hole Orientation and Depth selected consistent with site geology
- Stable Grouts with multiple admixtures
- Pressures – Maximum safe pressure utilized
- Data Acquisition – Flowmeters and Pressure Transducers
- Data Recording – Computer Monitoring by experienced Engineer or Geologist
Clear example of equivalent performance of grouting to concrete cut-off wall construction. Modern grouting can provide a high quality durable treatment in rock masses with clean fissures.
Systematic drilling and grouting of the conceptual concrete cut-off wall alignment

- provides a very detailed geological picture (holes at effectively 5-foot centers as opposed to site investigation at, say 100-foot centers); this permits wall extent to be designed optimally;
- pretreats the epikarst (contact to mitigate against sudden, massive slurry loss during cut-off wall construction (to about 10 Lu);
- provides a durable, engineered cut-off in the “clean” rock below and beyond the concrete cut-off, at 5-10 times lower cost (to < 3 Lu).

BEST OF BOTH WORLDS!

Epikarst is found during pregrouting to an average of 30 ft. b.g.s. The concrete cut-off needs only to be installed to 35 ft. b.g.s.
Heavily karstified horizons are found at depth. Therefore the concrete cut-off is required for the full extent. The grouting has pretreated the karstic horizons to permit safe concrete cut-off construction.

Discrete karstic features have been found, structurally driven. Thus, individual concrete cut-offs can be installed, after drilling and grouting has confirmed the extent of these features and has pretreated them to permit safe concrete cut-off construction.
Conclusions

- Large number of major dam safety incidents involving complex seepage/piping failure mode development processes
- Timescales of different processes are highly variable
  - Solutioning of carbonates – millions of years
  - Solutioning of evaporites - < decade
  - Erosion of infilling in karst - < 1 engineer lifetime
- Goal of intervention/remediation is to create low (tolerable) risk profile
- Since 1975 proven specialty construction technologies exist in North America to achieve this goal
- However, industry resources are currently stretched (especially human)
- Potentially hundreds of existing “safe” dams may become unsafe in our lifetime
- Authors are developing predictive model for assessing vulnerability and risk of these dams currently performing satisfactorily in these environments