

RECLAMATION

Managing Water in the West

Identifying, Describing, and Classifying Potential Failure Modes

Dam Safety Risk Analysis Best Practices



U.S. Department of the Interior
Bureau of Reclamation

Presentation Taken From One Developed for Reclamation Best Practices

- **This is an abbreviated version and not meant to be a complete look at the Reclamation Best Practices**
- **The presentation is to provide an introduction to important concepts that Reclamation has developed over many years**

Key Concepts

- **Collect all relevant background material**
- **Take a fresh look**
- **Review background material diligently (by more than one qualified engineer)**
- **Perform site examination with eye toward potential vulnerabilities**
- **Involve operating personnel in the potential failure modes discussions**
- **Think beyond traditional analyses**

Identifying

- Done in team setting with diverse group of qualified personnel
- Facilitator (or senior-level engineer) elicits candidate potential failure modes based on team's understanding of vulnerabilities
- Facilitator (or senior-level engineer) makes sure each potential failure mode is understood and described thoroughly
- Post large size scale drawings/sections and sketch out the failure modes (as appropriate)

Describing

- **Three elements of a potential failure mode description are:**
 - **The Initiator (e.g. Reservoir load, Deterioration/aging, Operation malfunction, Earthquake)**
 - **The Failure Mechanism (including location and/or path) (Step-by-step progression)**
 - **The Resulting Impact on the Structure (e.g. Rapidity of failure, Breach characteristics)**

Potential Failure Mode Assessment



Identifying and Describing



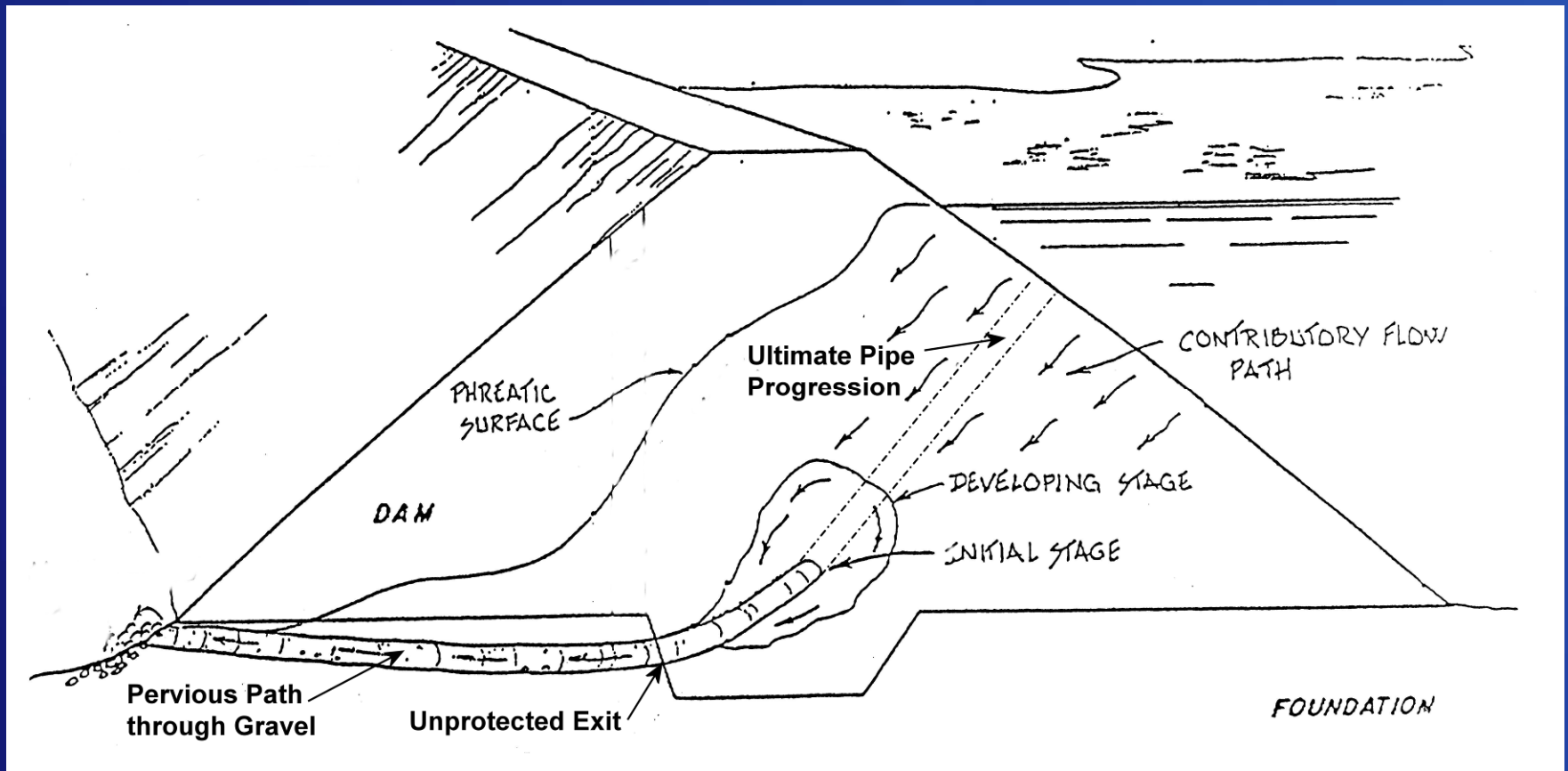
Identifying and Describing



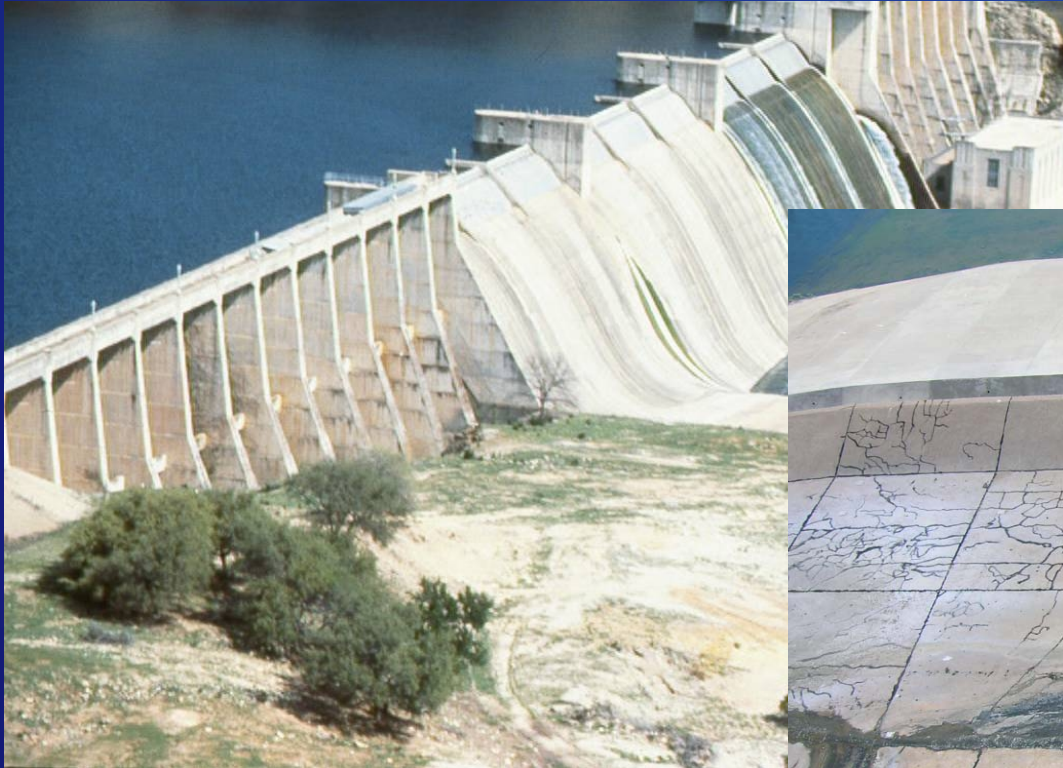
Potential Failure Mode Description

- Unedited (insufficient detail): **Piping from the embankment into the foundation**
- Edited: **During a period of high reservoir elevation, piping of the embankment core initiates at the gravel foundation interface in the shallow cutoff trench near Station 2+35 (where problems with the sheet pile and sinkhole occurred). Material might or might not exit at the toe of the dam. Backward erosion occurs until a “pipe” forms through the core exiting upstream below the reservoir level. Rapid erosion enlargement of the pipe occurs until the crest of the dam collapses into the void, and the dam erodes down to the rock foundation.**

Sketch of Potential Failure Mode



Identifying and Describing



Surveying results indicated the dam had moved several inches since monitoring began

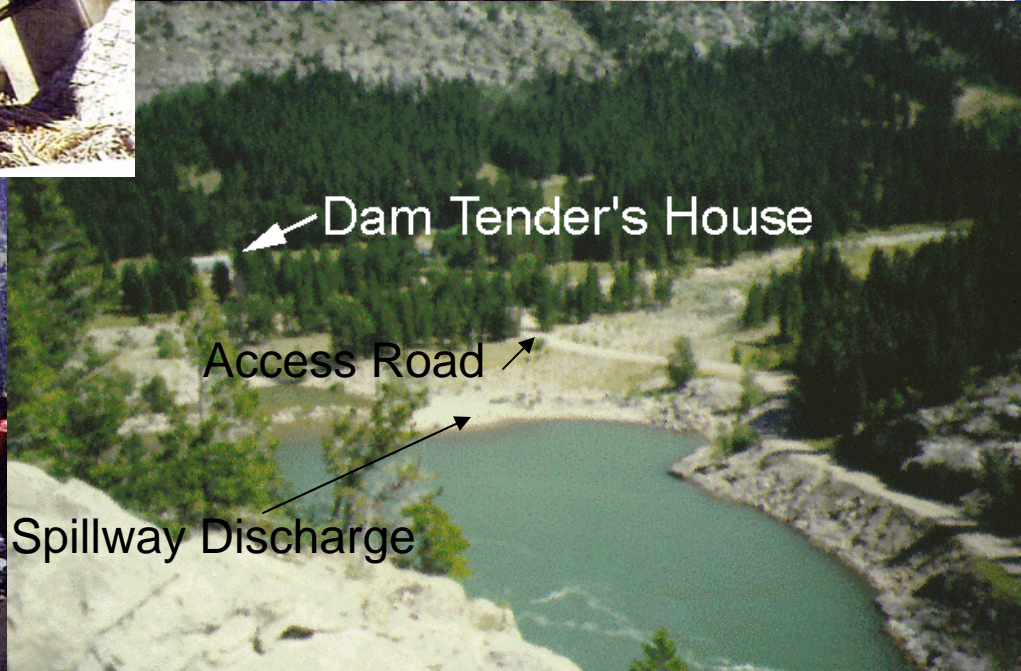
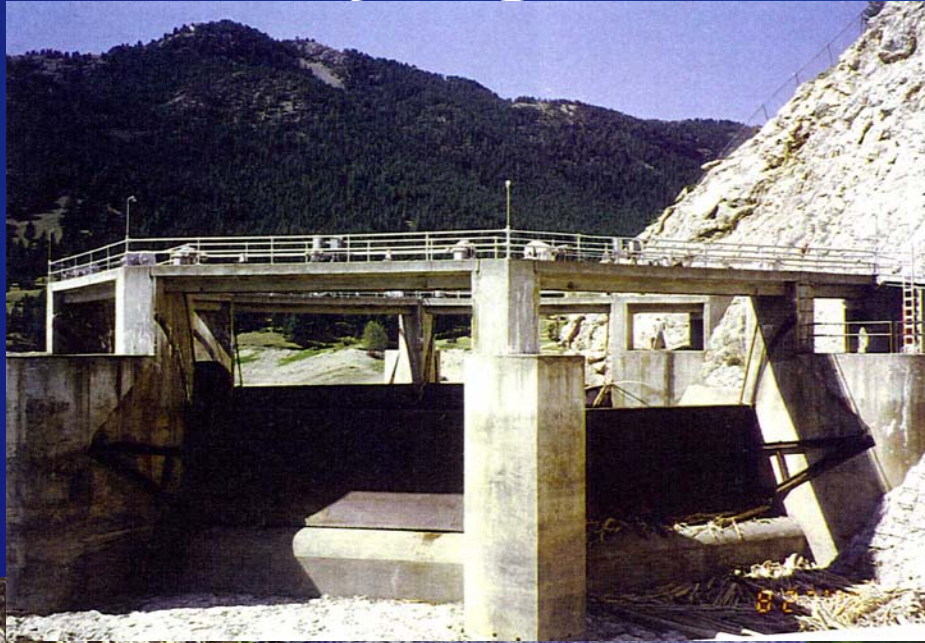
Potential Failure Mode Description

- Unedited (insufficient detail): **Sliding of the concrete dam foundation**
- Edited: **As a result of high reservoir levels and (1) a continuing increase in uplift pressure on the shale layer slide plane, or (2) a decrease in shearing resistance due to gradual creep on the slide plane, sliding of the buttresses initiates. Major differential movement between two buttresses takes place causing the deck slabs to be unseated from their simply supported condition on the corbels. Breaching failure of the concrete dam through two bays quickly results followed by failure of adjacent buttresses due to lateral water load.**

Operational Scenario

- An embankment dam has a gated spillway crest for passing flood flows. Of the four gates, one can be remotely operated from the power control center to pass normal flows. The remaining three gates must be operated manually from a control house on top of the spillway hoist deck. If a single gate is opened completely, the main access road is inundated. A limit switch keeps the remotely operated gate from opening more than half way without on-site intervention. The limit switch failed in 1994 and the road was washed out. The only other access to the spillway gate deck is a rough 4-wheel-drive road from the reservoir side that becomes muddy and treacherous when it rains.

Identifying and Describing



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Potential Failure Mode Description

- Unedited (insufficient detail): **Dam overtopping due to gate operation failure**
- Edited: **During a large flood, releases in excess of those that can be passed through the automated gate are required. The limit switch on the automated gate fails (occurred in 1994) due to a loss in communications and the gate opens fully wiping out the only access road. An operator is deployed to the site, but cannot make it to the gate operating controls. The release capacity of the single automated gate is insufficient and the dam overtops, eroding down to the stream level.**

Screening

- For each potential failure mode:
- List adverse or “more likely” factors
- List favorable or “less likely” factors
- Flesh them out so they can be understood by others and years down the road (ask, “why did we say that?,” and write down the answer)
- Screen to decide whether to carry forward for risk estimates
- Highlight the key factors that affect the judgment

Screening

- Possible failure mode disposition:
- **Failure is in progress or imminent** (forget risk analysis and take interim action)
- **Failure mode is credible** (carry forward for risk estimates)
- **Insufficient information to determine credibility** (carry forward for risk estimates, perform sensitivity analyses on key parameters)
- **Failure mode is not credible** (do not carry forward for risk estimates)

Adverse “More Likely” Factors

- The gravel alluvium *in contact with the embankment core on the downstream side of the cutoff trench* is similar to the transition zones which do not meet modern “no erosion” filter criteria *relative to the core base soil*.
- The gravel alluvium may be internally unstable, *leading to erosion of the finer fraction through the coarser fraction and even worse filter compatibility with the core*.
- The reservoir has never filled to the top of joint use; *it has only been within 9 feet of this level; most dam failures occur at high reservoir levels; the reservoir would fill here for a 50 to 100-year snow pack (based on reservoir exceedance probability curves from historical operation)*.
- The core can sustain a roof or pipe; *the material was well compacted (to 100 percent of laboratory maximum), and contains some plasticity (average Plasticity Index ~ 11)*.
- There is likely a *significant seepage gradient from the core into the downstream gravel foundation, as evidenced by the hydraulic piezometers installed during original construction (and since abandoned)*.
- *It is likely that all flow through the foundation cannot be observed due to the thickness and pervious nature (transmissivity) of the alluvium.*

Favorable or “Less Likely” Factors

- *Very little seepage is seen downstream; the weir at the downstream toe, which records about 10 gal/min at high reservoir when there is no preceding precipitation, indicating the core is relatively impermeable; these flow rates may be too small to initiate erosion.*
- *The core material is well compacted (to 100 percent of laboratory maximum) and has some plasticity (average Plasticity Index ~ 11), both of which reduce its susceptibility to erosion.*
- *No benches were left in the excavation profile that could cause cracking and the abutments were excavated to smooth slopes less than 2H:1V.*
- *If erosion of the core initiates, the gravel alluvium may plug off before complete breach occurs (see criteria for “some erosion” or “excessive erosion”, Foster and Fell, 2001).*

Screened Disposition and Rationale

- This potential failure mode is CREDIBLE and will be carried forward for analysis of risk
- Rationale: The gravel transition zone (and likely the gravel alluvium) clearly does not meet modern “no erosion” filter criteria and a seepage gradient exists from the core into the downstream foundation alluvium. Although the seepage volumes are small, it is not clear that all of the seepage can be readily observed. Further evaluation of transition filtering characteristics is needed.

Another Example

- Consider a potential failure mode that involves overtopping due to inability to operate frozen gates
- The screening for this might look something like the following:

Screened Disposition and Rationale

- This potential failure mode is considered to be **NON-CREDIBLE** and will not be included in the analysis of risk or monitoring program.
- **Rationale:** Examination of historical weather data indicates that cold freezing temperatures at the lower elevations near the dam have never occurred at the same time warmer conditions and rain storms have occurred at the higher upper basin elevations. These conditions would not make sense within the meteorological regime at the site. Therefore, the chances of one or more spillway gates being frozen shut at the same time there is a large rain storm in the upper basin are considered to be negligible.

Another Example

- **And a case where a sand lens is discovered in cutoff trench map for a dam in a seismically active area, but no other information is available concerning the sand.**
- **The screening for this might look something like the following:**

Screened Disposition and Rationale

- There is **INSUFFICIENT INFORMATION** to determine the credibility of this potential failure mode. It will be carried forward for analysis of risk and sensitivity study. Heightened awareness in this area will be included in the post-earthquake monitoring
- Limited information (cutoff trench map) suggests there is possibly a layer of fine sand beneath the shells of the dam. However, there has been no exploratory drilling or testing to determine how far the layer extends upstream or downstream of the cutoff trench or how dense the layer might be. Therefore, this potential failure mode will be carried forward to a risk analysis with different assumptions made regarding the continuity and density of the layer to examine the sensitivity of the risks and the potential value of additional information.