Reference:
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PFMA Process

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23 July 2010

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Team Effort!

- Risk Cadre: RMC, MVS, MVP, LRH, LRL, NWD, NWK, SWL, NWO, SWT, and RAC
- Sacramento District: Engineering, Planning and Operations staff; Kaweah Delta
- Multi-Disciplined Team: Geotechnical, structural, H&H, and mechanical engineers; geologist; economists; and field and maintenance personnel

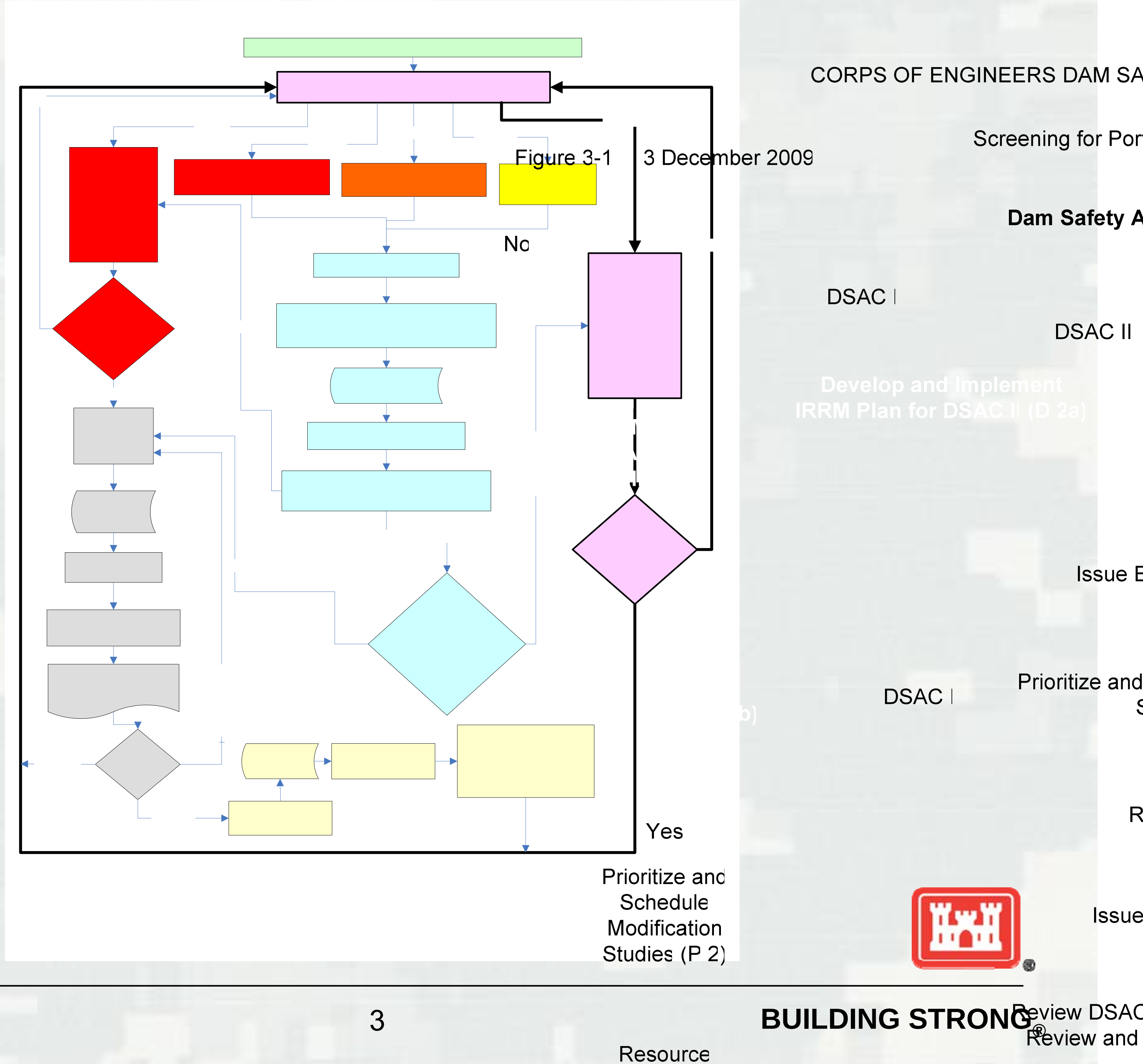
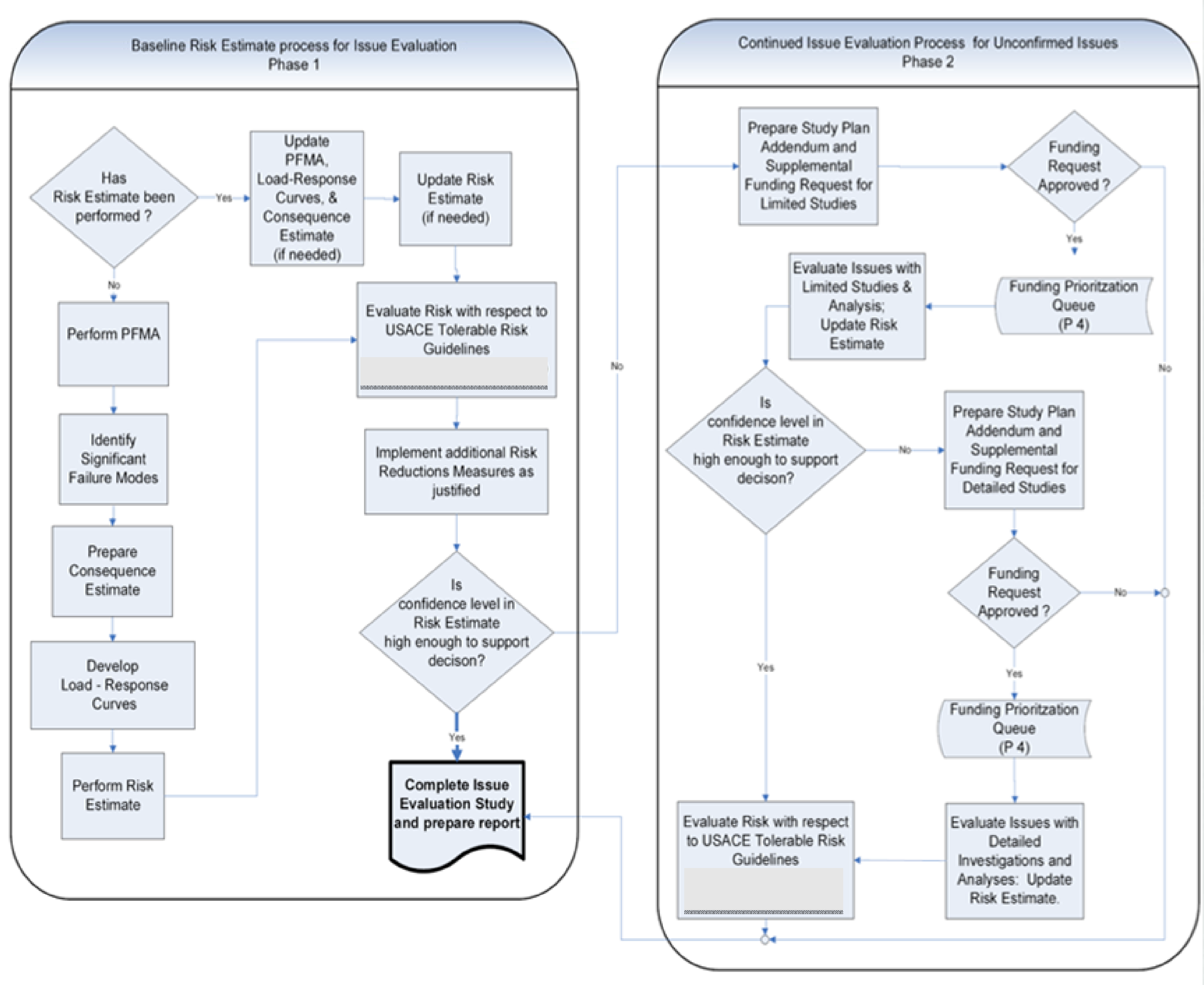


Figure 3-1
3 December 2009
No
Yes
Prioritize and
Schedule
Modification
Studies (P 2)
Resource
CORPS OF ENGINEERS DAM SA
Screening for Por
Dam Safety A
DSAC I
DSAC II
Develop and Implement
IRRM Plan for DSAC II (D 2a)
Issue E
DSAC I
Prioritize and
S
R
Issue
Review DSAC
Review and


Baseline Risk Estimate process for Issue Evaluation
Phase 1
Has Risk Estimate been performed ?
Yes
No
Update PFMA, Load-Response Curves, & Consequence Estimate (if needed)
Update Risk Estimate (if needed)
Perform PFMA
Identify Significant Failure Modes
Prepare Consequence Estimate
Develop Load - Response Curves
Perform Risk Estimate
Evaluate Risk with respect to USACE Tolerable Risk Guidelines
Implement additional Risk Reductions Measures as justified
Is confidence level in Risk Estimate high enough to support decison?
Yes
Complete Issue Evaluation Study and prepare report
Continued Issue Evaluation Process for Unconfirmed Issues
Phase 2
No
Prepare Study Plan Addendum and Supplemental Funding Request for Limited Studies
Funding Request Approved ?
Yes
No
Funding Prioritzation Queue (P 4)
Evaluate Issues with Limited Studies & Analysis; Update Risk Estimate
Is confidence level in Risk Estimate high enough to support decison?
No
Prepare Study Plan Addendum and Supplemental Funding Request for Detailed Studies
Funding Request Approved ?
No
Yes
Funding Prioritzation Queue (P 4)
Yes
Evaluate Risk with respect to USACE Tolerable Risk Guidelines
Evaluate Issues with Detailed Investigations and Analyses: Update Risk Estimate.

The First Step and the Blueprint

- Potential Failure Mode Analysis (PFMA) is an integral component of the USACE Dam Safety Portfolio Risk Management Process.
- PFMA is the first step in conducting a risk assessment of an existing dam or a risk-reduction action.

Potential Failure Modes Analysis

- A PFMA is a method of analysis where particular faults and initiating conditions are postulated, and the full range of effects of the fault or the initiating condition on the system are revealed.
- The methods of failure are indentified, described, and evaluated on their credibility and significances.
- PFMA can lead to a significant increase in dam safety awareness, a more efficient risk assessment process, and effective development of interim risk reduction measures and study plans.

Failure Modes

- Failure modes are a way that failure can occur, described by the means by which element or component failures must occur to cause loss of the sub-system or system function.
- The failure mode encompasses the full sequence of events from initiation (cause) through the realization of ultimate failure effect of interest to include physical, operational, and managerial systems.

Key Concepts

- It is important to include but also think beyond the traditional “standards-based” analyses when identifying potential failure modes.
- Identify operational-related potential failure modes.
- Identify the “non-standard” or “oddball” failure modes.
- Failure modes can be interrelated and cross disciplines (e.g., failure of outlet works during an earthquake leads to higher reservoir pool and initiation of seepage and piping).
- Multi-disciplined team effort

Overall PFMA Process

1) Assemble team and gather all background information.
2) Conduct site visit and interview field personnel.
3) Review all available background information.
4) Review loading conditions and baseline consequences.
5) Brainstorm potential failure modes.
6) Categorize failure modes as “credible” or “non-credible”.
7) Prioritize “significant” failure modes from the listing of “credible” failure modes for discussion and evaluation.

Failure Mode Categories

- "Non-credible" failure modes: either physically impossible or judged to be a negligible contributor to the project's total risk; excluded from the risk assessment
- "Credible" failure modes: physically plausible
- "Significant" failure modes: subset of "credible" failure modes; consensus opinion of the PFMA Team of prioritization of the "credible" failure modes to focus on PFMs that drove the DSAC I or II classification; included in the risk assessment

Terminus Dam

Added Fuse Gate Spillway
to increase Normal Pool

Mechanism to Tumble Gates

USU Model Study

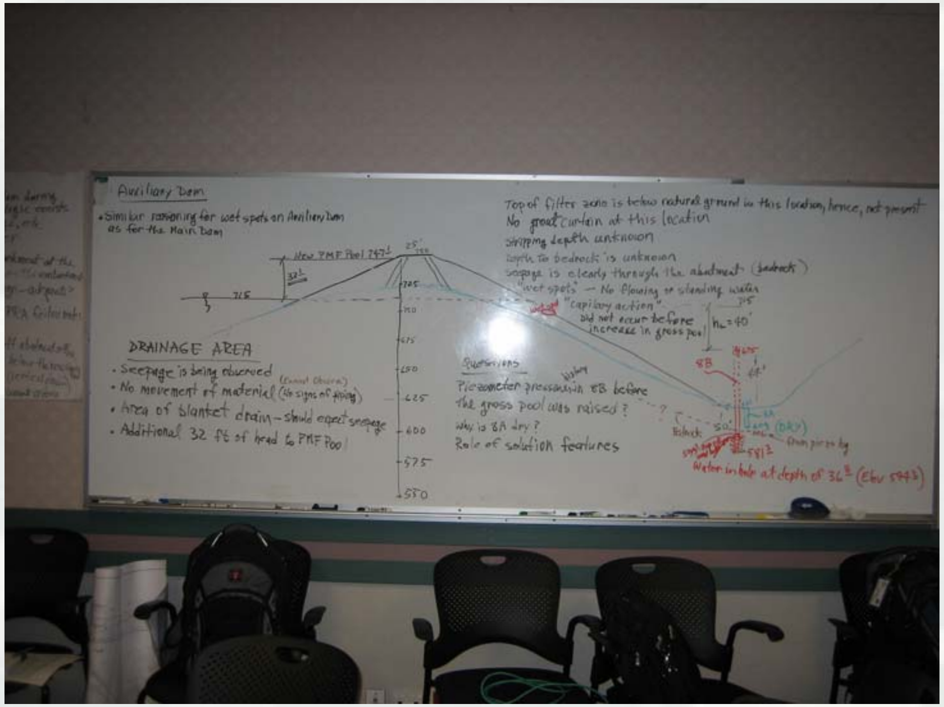
Fuse Gate Model Study at Utah State University

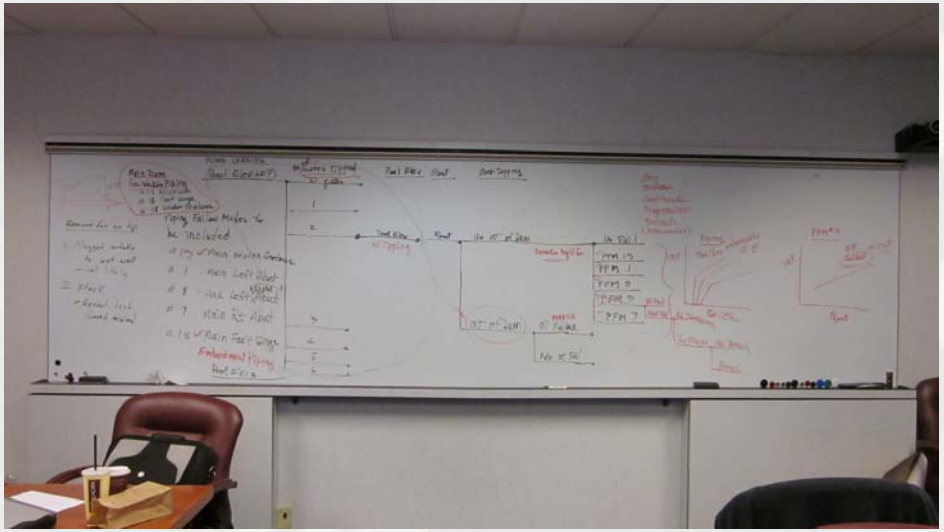
Wet spots developed on Main Dam and on Auxiliary Dam

Reviewed Construction Photos

Participants Develop List of Potential Failure Modes

Failure Mode Discussions and Event Tree Development During Team Meeting





Failure Mode Discussion

For each “significant” failure mode:

- Fully describe from initiation to uncontrolled release.
- Document pertinent background information.
- Document pertinent performance observations.
- Document “more likely” or “less likely” factors.
- Consider downstream impacts, time to breach, size and location of breach, and warning time.
- Discuss IRRM or recommend improvements to IRRMP.

Significant Failure Modes

- Identified 37 potential failure modes.
- Excluded 16 potential failure modes from further consideration in PFMA and risk assessment: non-credible or not a significant contributor to the project’s overall risk.
- Determined 8 to be significant
- RA team determining significance of remaining FMs

Significant Failure Modes

- Detailed 5 highest ranked significant failure modes:
  - ► PFM 1: Seepage & piping in left abutment of main dam
  - ► PFM 3: Erosion of the spillway abutment wall leading to failure of the main dam.
  - ► PFM 8: Seepage and piping in the left abutment of the auxiliary dam
  - ► PFM 19: Seepage & piping associated with solution features in foundation of main dam
  - ► PFM 22/35: Liquefaction of alluvium in the foundation and upstream embankment of the main dam

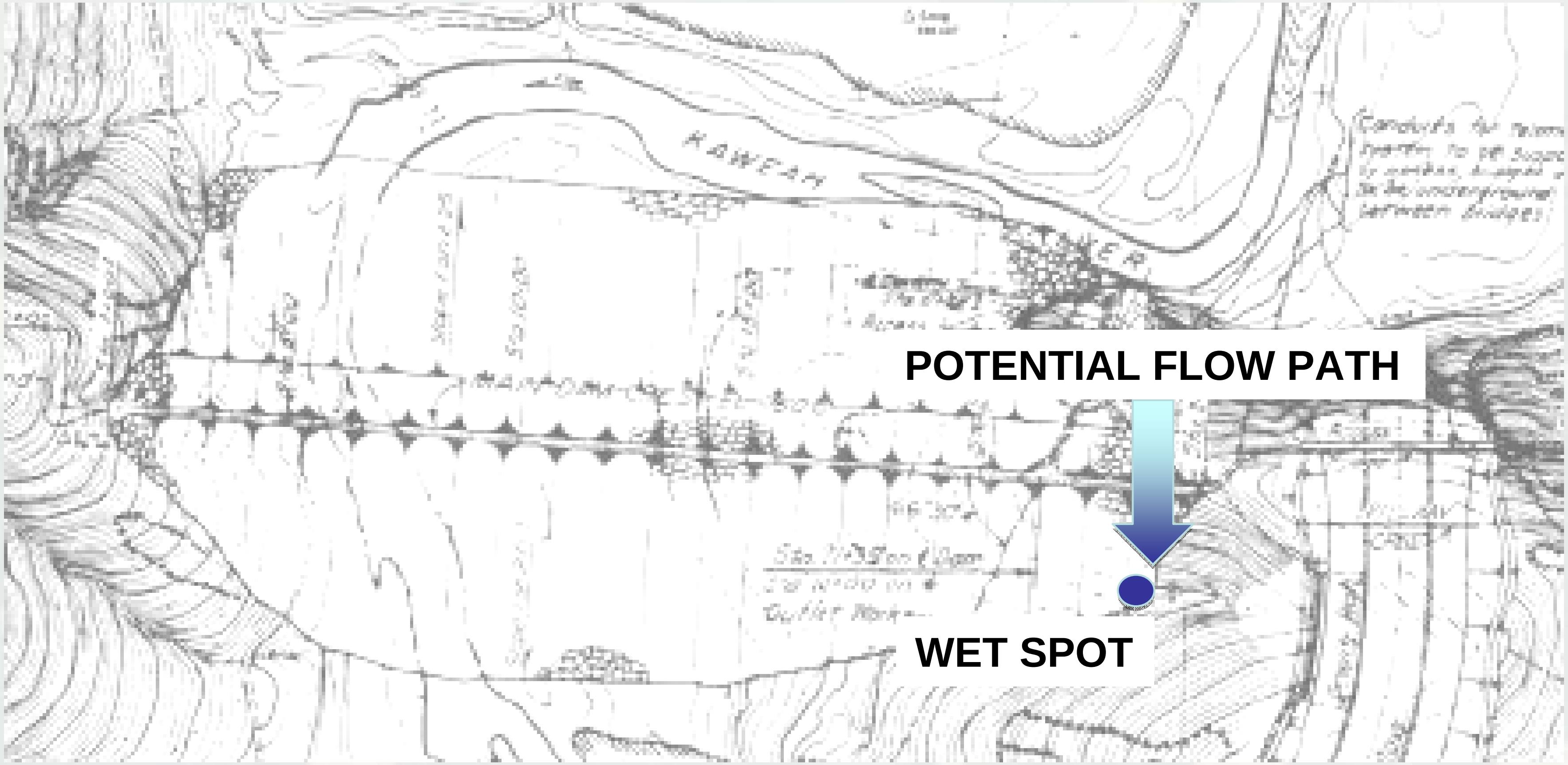
Significant Failure Modes

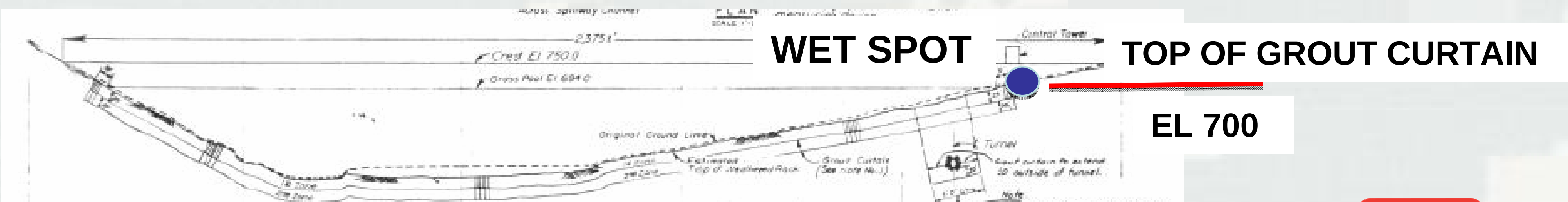
- Will include 8 failure modes in risk assessment
  - ► 5 seepage & piping
  - ► 1 liquefaction
  - ► 1 spillway erosion
  - ► 1 overtopping due to fuse gate failure to tip
- Determined 8 likely to be less “significant”
  - ► RA team following up to verify

PFM 1 Seepage and piping in the left abutment of the main dam

<u>Description:</u> The pool rises above a critical elevation, seepage begins through the rock in an area in the left abutment beyond the existing grout curtain that terminates at about Sta 22+60 (ground surface at El 712.8). The seepage exits at the downstream abutment embankment contact and begins to erode embankment material. The seepage through the rock is not limited and defects are not filled because the material on the upstream side of the embankment does not limit flows through the bedrock. As in-filled joint material is eroded, seepage increases. As the embankment materials erode the slope begins to slough until the slope begins to become unstable. The progressive slope failures continue until they intersect the core. At this point the pool could be lowered to stop the seepage, but if the inflow to the pool cannot be controlled the embankment breaches and the dam fails.

PFM 1 Seepage and piping in the left abutment of the main dam





PFM 1 Seepage and piping in the left abutment of the main dam

<u>CONDITIONS MAKING PFM 1 LIKELY</u>

- from grouting program it seems that rock is more fractured near the surface
- areas of with grout takes on the upper left abutment (sta 22+00 and sta 22+60) that varied from 2 to 56 bags of cement
- may be seepage contribution to spillway area

<u>CONDITIONS MAKING PFM 1 UNLIKELY</u>

- Need significant flow through the crack system to establish needed seepage
- total duration of reservoir above spillway is 58 hrs for the PMF; 120hrs above EL 694
- at EL 717.8 damp spots not flowing/no springs appear
- req'd time for flow to develop; weeks or months
- photographic evidence that cracks are small and tight

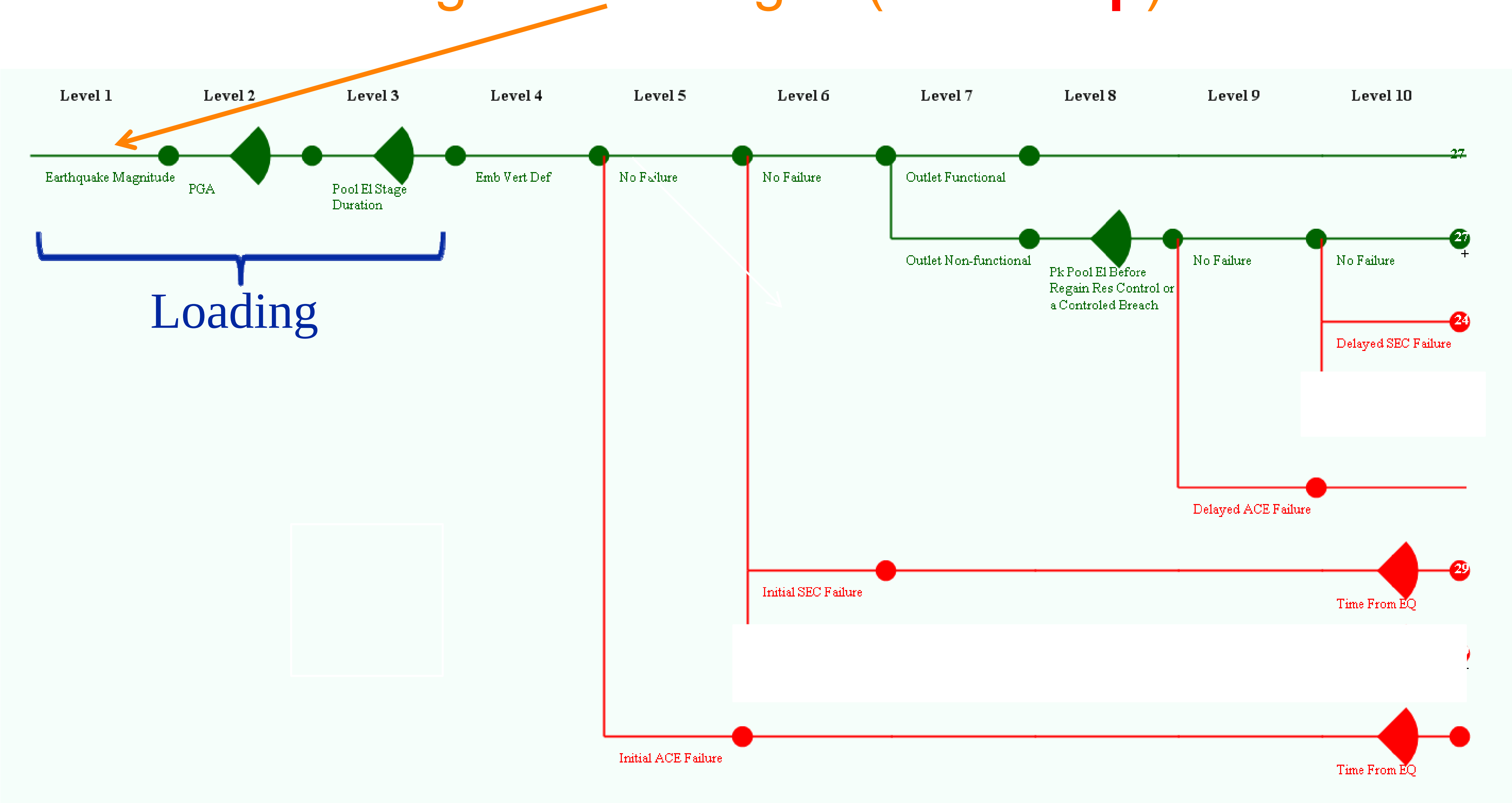
PFM 1 Seepage and piping in the left abutment of the main dam

SUMMARY

- PFM 1 is considered credible
- There is a high probability of continuous defects/fractures, less than 25 mm wide, within the left abutment
- The internal erosion toolbox was initially utilized to estimate the probability of failure due to PFM 1, however
- The toolbox does not fully address the complexity of the geologic conditions and the assumed initiating mechanism, therefore
- Expert elicitation was also employed to better determine a more realistic probability of breach, which is considered to be relatively low, <1x10-3 at the crest of the dam with a threshold elevation of 725
- Further development of the system response probabilities (SRP) for PFM 1 in conjunction with hydrologic loading is required

Earthquake Event Tree

Magnitude Ranges (**Data Gap**)



Major Findings and Understandings - General

- Fuse gates were installed in 2004, raising the gross pool by 21' (EL 694' to EL 715' NGVD '29)
- Project is located approximately 20 miles upstream of Visalia, CA.
- Downstream non-damaging channel capacity is 5500 cfs.
- Warning system in impacted area is EBS and reverse 911.
- Life risk downstream of dam is relatively small (as percentage of PAR) due to wide, shallow flood characteristics.
- Freeboard at PMF is 2.9 feet.
- Areas downstream of toe (tule drainage area) and downstream of main outlet works is inaccessible and/or difficult to inspect and flood fight due to vegetation.
- Rip-rap is gap graded and could be deficient
- Transition zone and vertical drain may not be filter compatible with core material

Major Findings and Understandings - Main Dam

- In general the dam is well maintained and seems to be exhibiting acceptable performance under Normal Operation conditions up to the Pool of Record of 715 NGVD29.
- The “wet spots” that have been reported on the downstream face of the main dam near the left abutment appear to be related to seepage through the abutment bedrock beyond the grout curtain which ends at about Station 22+60. At the wet spot locations there have been no signs of standing water or seepage taking place. These “wet spots” merit continued monitoring but the probability of a piping failure initiating at these locations, even at flood pool levels, seems very unlikely. At this location only a thin layer of embankment lies over the bedrock abutment. Consideration should be given to extend the grout curtain to the end of the dam on both abutments.

Major Findings and Understandings – Main Dam (cont.)

- Piezometers P-8A and P-8B are located at the toe of the embankment in the general areas of the “wet spots”. P-8A is at a depth of about 20 feet (tip elevation of about 606) and has always been dry. The tip elevation of P-8B is about 582, which is at a depth of about 50 feet below the ground surface, and at a lake level of about 715 feet the piezometer shows an artesian head of about 44 feet above the ground surface (Elevation 675). The high artesian pressure at a depth of 50 feet with a dry hole at 20 feet indicates that the bedrock provides a rather impermeable layer. Based on the piezometer boring log it appears that there is a fracture at a depth of about 30 feet that provides the connection to the reservoir. Piezometer P-8B is highly responsive to reservoir level and appears to indicate pressure increase of ??? with recent (post pool raise) annual cycling of reservoir.

Major Findings and Understandings – Main Dam (cont.)

- Seepage out of a drainage basin beyond the toe of the dam is monitored. The seepage into the tule filled basin appears to be clear and there are no signs of accumulation of material. Seepage into the tule area is expected due to horizontal drainage blanket.
- Construction photographs disclose rather large solution features in the foundation of the Main Dam. They were treated when encountered but it doesn't appear that additional voids were sought out during construction and it is likely that many solution cavities exist in the foundation. This may pose the greatest piping problem at the dam site.

Major Findings and Understandings – Main Dam (cont.)

- There are significant deposits of loose material in the alluvial foundation and upstream embankment of the dam. Based on Shear Wave Velocity tests the deposits have equivalent (N1)60 values of 5 to 14 indicating high liquefaction susceptibility.
- Evaluation of the seismicity of the area should be updated to current criteria (existing is 30 years old). It is needed to determine the liquefaction potential of the foundation and parts of the upstream embankment, and for structural seismic evaluations.

Major Findings and Understandings - Spillway

- New spillway configuration with fuse gates have not experienced significant flow.
- There is concern that the base of the right spillway training wall may be susceptible to scour during operation of the spillway. Original structural analysis indicated bench in spillway would limit erosion that could impact stability of wall. There is no current evidence that the wall was reanalyzed to account for removal of bench or increase head in spillway. Failure of the wall could allow spillway flows to be redirected down the left groin area of the Main Embankment. The spillway wall is in need of evaluation to understand this failure mechanism. Spillway erosion and slope stability require further analysis to gain better understanding of likely performance under high flow conditions.

Major Findings and Understandings – Auxiliary Dam

- No alluvial material in foundation of auxiliary dam
- Grout curtain does not extend to the end of the dam
- Piping problems around the end of the grout curtain of the Auxiliary Dam should be investigated.
- The irrigation tunnel in the foundation of the Auxiliary Dam has been plugged. The tunnel is well into the bedrock and it is very unlikely that there will be a future stability or piping problem associated with the old tunnel.
- Slush grouting of foundation was only placed in old roadway cut.

Additional IRRM

- Document surveillance plan to include continuous (24 hr) monitoring at high pool elevations
- Continue funding surveillance and monitoring as dictated by reservoir elevation (existing funding ends this FY).
- Install automated monitoring system on weirs and peizometers for main and auxiliary dams.
- Install additional piezometers in embankment and downstream toe.
  - ► Left abutment auxiliary dam
  - ► Left abutment of main dam
- Remove vegetation (tules) from downstream drainage area and install drainage blanket.

Additional IRRM

- Study feasibility of manually tipping one or more fuse gates to allow for increased ability to lower pool during emergency scenarios.
- Start/increase public education effort to inform PAR of risk from dam failure
- Conduct dam safety exercises with local EMA to evaluate effectiveness of EAP and evacuation plan.
- Improve warning system effectiveness (sirens, enhance reverse 911).
- Provide satellite phones to dam project office for communication after seismic event (when normal phone system is likely over-burdened and ineffective)

Additional IRRM

- Install additional survey markers to monitor crest movement
- Install alignment markers on toe of dam to monitor deformation
- Install inclinometers
- Armor upstream DSAP bench cut on main dam
- Extend concrete facing to cover exposed bedrock on foundation of right spillway wall
- Retrofit spillway bridge piers and protect footings
- Extend grout cutoff on both the main and auxiliary dams

The Path Forward

- Perform preliminary failure mode evaluation (cadre).
- Prepare background chapters of report (SPK).
- Reconvene team at SPK in 2-3 months to review preliminary models and evaluations and to obtain team consensus for all probability assessments.
- Complete baseline risk estimate (cadre).
- Complete draft IES report by 30 December (cadre).
- Perform QCC review in second quarter of FY 2011.
- Resolve review comments (cadre).
- Completes report and coordinate ATR (SPK).

IES Report Responsibilities

- Chapter 1: Introduction (District)
  - Project Purpose and Authorization
  - Project Location and Description
- Chapter 2: Background (District)
  - Dam Features and Components
  - Dam Operations
  - Performance History and Key Observations
- Chapter 3: Current Assessment (District)
  - Dam Safety Action Classification
  - Previous Risk Assessments
  - Approved Issue Evaluation Study Plan Objectives
  - Phase 2 Study Efforts and Investigations
- Chapter 4: Interim Risk Reduction Measures (District)
  - 4.1. Overview of IRRM
  - 4.2. Reservoir Restriction
  - 4.3. Non-Structural IRRM
  - 4.4. Structural IRRM

IES Report Responsibilities (cont.)

- Chapter 5: Potential Failure Modes (RMC)
  - Overview of PFMA 5-1
  - Potential failure mode evaluations
- Chapter 6: Hydrologic and Hydraulic Analysis (RMC)
- Chapter 7: Seismic Loading (RMC)
- Chapter 8: Consequences
  - Life Loss (RMC)
  - Economic Consequences (RMC)
  - Environmental and Other Non-Monetary Impacts (District)
- Chapter 9: Risk Analysis (RMC)
- Chapter 10: Conclusions and Recommendations (RMC/District)
  - Confirmed Dam Safety Issues
  - Unconfirmed Dam Safety Issues
  - Recommended Dam Safety Action Classification
  - Dam Safety Modification Study
  - Interim Risk Reduction Measures
- Chapter 11: Interim Risk Management Plan (District)
- Chapter 12: Risk Communication Plan (District)

Questions, Comments, or Discussion?