



DAM SAFETY PROGRAM

TECHNICAL NOTE 7

GUIDELINES FOR CONDUCTING A SIMPLIFIED FAILURE

MODE ANALYSIS FOR MONTANA DAMS

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December 2011

TABLE OF CONTENTS

LIST OF TABLES	iii
LIST OF FIGURES	iii
LIST OF APPENDICES	iii
EXECUTIVE SUMMARY	iv
1.0 INTRODUCTION	1-1
2.0 TECHNICAL NOTE PURPOSE.....	2-1
2.1 TARGET AUDIENCE	2-1
3.0 WHAT IS AN FMA AND WHAT ARE THE BENEFITS TO ME?	3-1
3.1 DEFINITION OF A FAILURE MODE ANALYSIS	3-1
3.2 BENEFITS AND EXPECTED OUTCOMES OF AN FMA	3-2
4.0 GUIDANCE FOR CONDUCTING A SIMPLIFIED FMA	4-1
4.1 FMA EXPECTATIONS AND REQUIREMENTS.....	4-1
4.2 STEP-BY-STEP GUIDANCE FOR CONDUCTING AN FMA	4-2
5.0 FAILURE MODE ANALYSIS RESULTS.....	5-1
5.1 DOCUMENTATION OF MAJOR FINDINGS AND UNDERSTANDINGS	5-1
5.1.1 Facilitator and Core Team Review	5-2
5.2 ALTERNATIVE DOCUMENTATION – SPREADSHEET RESULTS.....	5-2
5.3 FMA BENEFITS – A ROADMAP FOR FUTURE OPERATION	5-3
5.3.1 Additional Investigations	5-3
5.3.2 Maintenance and Repairs Priorities	5-4
5.3.3 Guidance for Rehabilitation Decisions	5-4
6.0 EXAMPLES OF RECENT MONTANA FMAS	6-1
6.1 LAKE FRANCIS DAMS	6-1
6.2 EUREKA DAM	6-2
6.3 KOOTENAI DEVELOPMENT IMPOUNDMENT DAM	6-2
6.4 PPL MONTANA DAMS.....	6-3
7.0 REFERENCES	7-4

LIST OF TABLES

TABLE 4-1.	CATEGORIES OF IDENTIFIED FAILURE MODES (Modified from FERC, 2005).....	4-16
TABLE 4-2.	SUMMARY OF AFTERNOON BRAINSTORMING SESSION	4-18

LIST OF FIGURES

FIGURE 4-1.	FAILURE MODE DOCUMENTATION EXAMPLE.....	4-15
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LIST OF APPENDICES

APPENDIX A	TEMPLATE FOR ORGANIZING ELECTRONIC DATA
APPENDIX B	FMA QUESTIONNAIRE
APPENDIX C	EXAMPLE VISUAL AIDS
APPENDIX D	GENERAL FORMAT FOR FMA REPORTS
APPENDIX E	EXAMPLE SPREADSHEET SUMMARY OF FMA

EXECUTIVE SUMMARY

Technical Note 7 (TN7) presents Montana's Simplified Failure Mode Analysis (FMA) procedures, which are used by owners to improve their knowledge of their dams, as well as provide insight into potential modes of failure and to enact procedures to prevent dam failure.

An FMA is a tool that helps identify priorities for rehabilitation as well as improvements to operation, maintenance and data collection. This is accomplished by looking systematically at all of the potential ways a dam could fail and the likelihood that this failure could happen. Results are often surprising – in many instances, the most obvious deficiency at a dam that gets the most attention is not the most serious. The FMA combines the thinking power of a team to comprehensively look at the dam. The team typically includes the dam owner, the dam tender, the engineer and the state regulatory agency. Often other board or company members are involved. It is the diversity of the team that makes this process unique.

An FMA is not just “another study.” Rather, an FMA team looks at existing studies and data and completes an unbiased assessment of the dam. The team also identifies missing data that is necessary to make a conclusion about the risk of a dam failing from a certain condition. The difference from a typical engineering study is the involvement of the dam owner, and the unique perspective and information they possess regarding operation of the dam.

The Montana simplified procedure is different from procedures used by other government agencies. The process developed by FERC (the Federal Energy Regulatory Commission) to conduct a Potential Failure Mode Analysis (PFMA) is intended for larger hydroelectric projects and can take several days to do a thorough evaluation. The FERC procedures are quite expensive and time consuming. Our goal is to make the simplified FMA process somewhat streamlined from the FERC procedures to address issues at considerably smaller, typically earthen, dam projects. We feel this process will not cost the owner much because the process typically can be completed in one day. There are four basic components to the Montana FMA: 1) identify a facilitator/organizer and assemble the team (dam owner, engineer, state regulator); 2) collect and organize all available data and transmit to the team for review; 3) conduct the FMA following procedures outlined in TN 7; and 4) summarize results in a brief, easy to follow report or spreadsheet.

The FMA results can then be used by the dam owner to improve operation and maintenance of the dam and confidently focus rehabilitation dollars.

DAM SAFETY PROGRAM
TECHNICAL NOTE 7
GUIDELINES FOR CONDUCTING A SIMPLIFIED FAILURE MODE
ANALYSIS FOR MONTANA DAMS

1.0 INTRODUCTION

The **Montana Dam Safety Program** is pleased to provide this **Technical Note 7 (TN7), Guidelines for Conducting a Simplified Failure Mode Analysis for Montana Dams**. Our intent is to provide straightforward, cost effective procedures for conducting a failure mode analysis (FMA). An FMA is a tool that helps identify priorities for rehabilitation as well as improvements to operation, maintenance and data collection.

This is the seventh Technical Note developed by the Dam Safety Program and we want it to be a useful document for those engaged in dam safety analyses. We welcome and encourage your feedback on its contents. Please send your comments to:

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DNRC would like to acknowledge Hydrometrics, Inc. of Helena, Montana for the development and preparation of Technical Note 7. TN7 will be revised and updated as new procedures are refined and new technical references are made available.

2.0 TECHNICAL NOTE PURPOSE

The Montana Dam Safety Program has developed the procedures outlined in this technical note to help dam owners conduct cost-effective Failure Mode Analyses (FMA). These guidelines incorporate the general procedures used in FMAs for hydropower dams, but are modified and reduced in scope to help reduce costs. These guidelines can be applied to any dam, but they are specifically applicable to those classified as high hazard which fall under the jurisdiction of the DNRC.

2.1 TARGET AUDIENCE

TN7 is intended as guidance for engineers, dam owners and state regulatory personnel.

Professional judgment may be required when applying this guidance document to conducting an FMA. Unique circumstances may require modifications to the process. Users of TN7 are expected to be familiar with dam safety terminology and common problems associated with dams. DNRC and the Dam Safety Program are not responsible for the use and interpretation of TN7 contents.

3.0 WHAT IS AN FMA AND WHAT ARE THE BENEFITS TO ME?

Owners of dams may wonder what a failure mode analysis is and why they would want to subject themselves and their dam to the scrutiny of a team of professionals looking at ways the dam could fail. Good questions. In this section we hope to help answer those questions. The reservoir behind the dam holds a valuable resource for the owner. The last thing an owner wants is for the resource to disappear. By keeping the dam safe and in good working condition, the owner is assured, at least to the best of his ability, that the dam will maintain his water resource. By having fresh eyes and perspectives looking at the dam through an FMA process, the owner may discover some things about the dam that was not previously realized and could extend the life of the dam and preservation of the water resource.

3.1 DEFINITION OF A FAILURE MODE ANALYSIS

An FMA is a tool that helps identify priorities for rehabilitation as well as improvements to operation, maintenance and data collection. This is accomplished by looking systematically at all of the potential ways a dam could fail and the likelihood that this failure could happen. Results are often surprising – in many instances, the most obvious deficiency at a dam that gets the most attention is not the most serious. The FMA combines the thinking power of a team to comprehensively look at the dam. The team typically includes the dam owner, the dam tender, the engineer and the state regulatory agency. Often other board or company members are involved. It is the diversity of the team that makes this process unique.

An FMA is not “another study.” Rather, an FMA team looks at existing studies and data and completes an unbiased assessment of the dam. The team also identifies missing data that is necessary to make a conclusion about the risk of a dam failing from a certain condition. The difference from a typical engineering study is the involvement of the dam owner, and the unique perspective and information they possess regarding operation of the dam.

An FMA can also be viewed as a tool to enhance the overall safety program of a dam. It is not intended to be a substitute for other safety measures such as periodic inspections, focused

maintenance and monitoring, or repairs. But it definitely can improve monitoring programs or provide direction for rehabilitation.

3.2 BENEFITS AND EXPECTED OUTCOMES OF AN FMA

Even though identifying potential failure modes is the primary focus of an FMA, there are other beneficial outcomes that result from the process:

- Gathering all information about the dam for the specific purpose of identifying potential failure modes, plus the involvement of a diverse group of people, can result in uncovering information that previously was not thought of. Frequently, this information plays an important role in identifying a potential failure mode.
- Potential failure modes and scenarios will be documented for future use by other consultants and inspection teams.
- Obvious concerns with the dam may be found to be of lesser significance than previously perceived from the standpoint of consequence, remoteness or physical possibility.
- Enhancements to monitoring and inspections are developed. Monitoring can be directed on important issues.
- A broader range of individuals (from the dam tender to state dam safety officials) become aware of the dam's most significant vulnerabilities and how monitoring can help identify and track these vulnerabilities.
- Gaps in data or analyses are identified and corrective action can be planned.
- Risk reduction opportunities in monitoring, operation, maintenance and emergency preparedness are identified.

4.0 GUIDANCE FOR CONDUCTING A SIMPLIFIED FMA

This chapter will provide step-by-step procedures for conducting a simplified FMA. Changes to the procedures can be implemented depending on the dam, the parties involved, and the overall focus of the analysis.

4.1 FMA EXPECTATIONS AND REQUIREMENTS

There are nine basic steps that should be followed when conducting a simplified FMA. The nine steps are briefly mentioned here, but are discussed in more detail in Section 4.2.

1. Identify the FMA facilitator – this is the individual who will lead the FMA, as well as help develop the final report.
2. Identify the organizer – this is the individual who will handle the logistics of the FMA.
3. Identify core team members – dam owner/tender, engineer, and state regulatory agency – these are the individuals who will carefully review all existing data and attend the site visit.
4. Identify other participants, or observers. These are individuals who have an interest in the dam, but are not required to review existing data or attend the site visit (i.e., board or company members, county officials, etc.).
5. Collect all data, studies and information on the project in electronic format. Organize according to subject matter and transmit the data to core team members two weeks in advance of the FMA.
6. Review by core team members of all the background information provided for the dam.
7. Conduct Pre-FMA activities. These include:
 - Set up a meeting schedule and location.
 - Prepare and send out a questionnaire to the core team members.
 - Prepare visual aids for the FMA.
 - Hold a conference call for all core team members.

8. Conduct the FMA. This entails two basic activities:
 - Visit the project site. Consider potential failure modes, structural and geologic conditions, operation procedures, and input from owners and operators.
 - Brainstorm potential failure modes and failure scenarios with the team. Record the identified potential failure modes, the reasons why each potential failure mode is either less likely or more likely to occur. Identify possible actions that could help reduce risk (i.e., monitoring enhancement, investigation, analysis, and/or remediation). Identify possible inspection and monitoring enhancements or risk reduction measures for each potential failure mode. Identify and document major findings and understandings.
9. Document the results and conclusions of the FMA in a brief report.

Details for completing the first eight steps are included in Section 4.2 below. Step 9 for documenting the results and conclusions of the FMA is detailed in Section 5.0.

4.2 STEP-BY-STEP GUIDANCE FOR CONDUCTING AN FMA

The following sections are detailed steps to help plan and conduct an FMA. This is a simplified procedure compared to FERC or the U.S. Department of Interior Bureau of Reclamation (USBR) PFMA procedures. The intention is to have a simplified FMA completed in one day, after all data and information is gathered and the team is assembled. This is a deliberately shortened process to save owners of small dams time and money, yet gain the benefits of an FMA.

Step 1 - Identify a Team Facilitator

The team facilitator for an FMA will be the leader of the FMA process. Suggestions on who should be a team facilitator and roles of the facilitator are described below.

Role and Duties of Team Facilitator

Key to this role is a working understanding of the FMA process and the ability to identify FMA goals. At a minimum, the team facilitator should have experience being a participant

of at least two FMAs prior to leading an FMA. A solid understanding of dams and their potential failure mechanisms is also necessary for a facilitator. The facilitator should possess good organizational skills and have the ability to efficiently run meetings with diverse participants. As leader of the FMA process, a facilitator is expected to perform the following duties (these can vary), as suggested by the USBR (2007):

- Prepare for the session.
- Conduct the session.
- Maintain a basic set of principles.
- Provide instructions and set goals.

Details of these duties will be discussed later in sections describing how to conduct the FMA.

Potential Team Facilitators

Who should be considered to be a team facilitator? The following are suggestions based on DNRC experience in facilitating and observing FMAs:

- *State Dam Safety Engineer:* An engineer from the Montana Dam Safety Program is a logical choice, as they are often familiar with the dam. Another reason for considering a State dam safety engineer is they represent a no-cost option and will help the owner keep overall costs down.
- *Designated Engineer for the dam:* In most cases, the dam's owner has retained a professional engineer to conduct inspections and provide engineering services. The engineer is familiar with the dam and potential failure modes and would be a good choice based on a history of working on the dam.
- *Independent Consultant:* If the owner prefers a fresh view of issues related to the dam, an outside consultant familiar with dam safety issues and the FMA process would make a good choice.

Step 2 - Identify A Team Organizer

The team organizer is someone who will take a lead role in scheduling meetings, contacting team members, and collecting data related to the dam. The team facilitator and the owner will appoint the team organizer cooperatively. This person should be familiar with the dam and willing to take direction to organize most aspects of the FMA.

Role and Duties of Team Organizer

The team organizer will be responsible for collecting and disseminating all important data and reports of the dam, organizing and scheduling the FMA meeting and making sure all arrangements for the FMA process are in order.

Potential Team Organizers

The following are suggested candidates for the role of team organizer:

- *A member of the owner's technical staff:* This would apply for owners who have a technical staff. The advantages of using this person would be that they are familiar with the dam and they would not command a fee.
- *An officer of a water user group or district:* For water user groups or irrigation districts, the organizer could be an officer or member of the district. This person should be familiar with the dam. Again, this person would represent a cost savings in running the FMA.
- *State dam safety staff:* If an engineer from the State dam safety program is the facilitator, a member of the program staff could serve as an organizer for the FMA under the direction of the facilitator. Cost savings would be realized for this person also.
- *Staff member of engineering company:* This would apply if the engineer were the facilitator of the FMA. The staff member could work under the direction of the facilitator.
- *The Facilitator:* Depending on the scope of the project, it may be reasonable for the facilitator to be in charge of organizing the FMA.

Step 3 - Identify Core Team Members

The core team is a select group of individuals who will review the historic data and information for the dam and who will be the main contributors to the FMA process. Selection of the core team members is very important. The core team's diligence and actions will dictate the effectiveness of the FMA process. It is important to get members who are willing to communicate, brainstorm and think outside of the box. Selection of core team members will be the responsibility of the team facilitator and the owner. Core team member selection will depend on availability of candidates and their willingness to participate.

Role and Duties of Core Team Members

Core team members must bring open and inquisitive minds to the process. Team members must be diligent in reading the material, in inspection of the dam and facilities, and in participating in the FMA session. It is important for core team members to keep in mind that their role is to defend their position but not to defend their turf – in other words; they should base their decisions on sound technical judgment, not on any advantage they may gain by their decisions.

The primary duty associated with core team members that is different from other participants in the FMA is they will conduct a thorough review of background data and information prior to the actual FMA. Core team members will take part in the dam inspection and then be responsible for brainstorming on potential failure modes and their consequences. They will be expected to play lead roles in moving the FMA in a beneficial and productive direction.

Potential Core Team Members

The core team should have no more than four members, which means the core team would consist of the team facilitator plus three others. Here are suggestions for potential core team members and how they can enhance the FMA process:

- *Regulatory Engineer:* This person should be an engineer from the Montana Dam Safety Program or other dam safety agency. This person should be familiar with the

dam and who has experience in dam safety issues. This type of person represents a cost savings to the owner.

- *Private Professional Engineer:* This person should be an engineer familiar with dam safety issues. There are definite benefits if this person is familiar with the dam being analyzed. Consideration should be given for an engineer of a specialty that represents potential problems with the dam (i.e., a geologic or geotechnical engineer if stability or seepage issues are dominant).
- *Owner or Owner's Representative:* Possibly one of the most important people to have on the FMA team. While the owner's perspective is obviously skewed to save money for monitoring or repairs, they are also the person with the most to lose if the dam were to fail. The owner is the person or organization to pay for any work on the dam and will likely address the economic side of the discussion. The owner may also bring a non-engineering perspective, perhaps focused on practical operation and maintenance issues, which is beneficial to the process. The educational experience of having the owner or owner's representative on the team will benefit all involved, including the owner.
- *Independent Engineering Specialist:* The intent of including this type of person is to make sure that local expertise, for example a regional USDA-Natural Resources Conservation Service (NRCS) engineer or specialist is not overlooked. If the specialist is a government employee, this will help with cost efficiency.
- *Note Taker:* This position is very important and it is imperative that the note taker be experienced in dam safety issues, in taking meeting notes and adept at documenting important points during the FMA process. The notes will be invaluable in creating the documentation of the FMA. Cost savings can be realized if the owner or the state dam safety organization employs the note taker or if a core team member agrees to take notes while participating in the FMA.
- *Report Writer:* There is efficiency associated with having this person be the note taker as well. Regardless who takes on this role, the report writer needs to be experienced and proficient at writing succinct and readable reports. Experience with engineering reports is a plus. Since the report that is produced out of the simplified

procedure is not lengthy, it is reasonable to ask any of the core team members or facilitator to also be the report writer.

Step 4 - Identify Participants

The rest of the group involved in the FMA should be individuals who are directly involved in the operation and maintenance of the dam, or who are connected to the dam in some way. Participants should have knowledge of the dam and of dam safety issues. It is not necessary to have FMA experience in order to be participant, but participants should be willing to communicate openly, have inquisitive minds, and have the ability to freely think and look at issues from many angles.

Role of Participants

Participants will be expected to conduct an inspection of the dam with the Core Team and then participate in the FMA brainstorming session. They will not be expected to review the background information prior to the actual FMA.

Potential Participants

Here are some suggestions for participants in an FMA:

- Dam tender.
- Owner organization officer or member (such as for an irrigation or water district).
- Conservation district member.
- NRCS engineer or technician.
- Independent engineer.
- Municipal or county official (if the dam is owned by a local government).

Step 5 - Collect and Disseminate Data and Information

Under the direction of the team facilitator, the team organizer will gather all available data and information pertinent to the dam and potential failure modes in electronic format. Not having to copy or mail reports can be a significant cost savings. It is worthwhile making sure core team members have the ability to review the data and information electronically before

choosing them to participate. Gathering and disseminating the data to the core team should be done two weeks in advance of the actual FMA meeting. The following are possible data and information for a dam and appurtenant works:

- Investigation, design, and construction reports.
- Construction and other project photographs.
- Construction and as built drawings.
- Construction inspection reports by the owner and engineer, and by state and federal agencies.
- Geologic reports.
- Seismic studies.
- Stability and stress analyses.
- Hydrologic and hydraulic studies.
- Laboratory test results on rock, soil, and concrete.
- Instrumentation monitoring data.
- Visual inspection reports.
- Periodic dam safety reports.
- Emergency Action Plans.
- Operation and Maintenance Plans.
- Photographs of key elements and features showing present condition and any remedial work.
- Correspondence related to the dam and appurtenant works.
- Topographic survey maps and data.
- Cross-section at the maximum section of the dam.

The facilitator needs to review the data to make sure only pertinent and applicable data and information is disseminated. The information can be saved on a computer disk (CD) or thumb drive. Another option is to set up a file transfer protocol (FTP) site to allow access to data. This may be accomplished through various web sites if an organization does not have an FTP site. Providing electronic information may mean having to scan hard copies or gather electronic versions of reports, data and photographs. To this end, the Montana Dam Safety

Program has already scanned many regulated dam files and may be a good source of electronic data. It is also very important that a clear and organized index of data be prepared to avoid unnecessary searching through the informational packet. Appendix A provides a template for organizing electronic data that should be followed if possible. When data is sent to the core team, it should be accompanied by a Questionnaire, which is described in Step 7, below.

Step 6 - Core Team Review of Data

The team organizer or facilitator should send the background data and information to core team members approximately two weeks in advance of the FMA. The organizer or facilitator should contact each core team member directly to make sure they are aware of what they are getting and to make sure each member is cognizant of their role to diligently review all pieces of information to become familiar with the project. The core team should review the data with the following questions in mind:

- What could make this dam fail?
- What happens if the dam fails?
- Are the potential failure modes recognized and being appropriately monitored by inspection or monitoring?
- What actions (immediate or long term) can be taken to reduce dam failure likelihood or to mitigate failure consequences?

As discussed below, it is recommended that a conference call be held between core team members and the facilitator to discuss data and address questions about the data approximately three to four days prior to the FMA. The core team may identify additional data needs – this will allow the facilitator time to acquire data requests of the core team.

Step 7 - Pre-FMA activities

The team facilitator and organizer will be responsible for initiating the FMA process. Several items need to be accomplished before the team gathers for the actual FMA. The following sections describe the items in detail.

Meeting Schedule and Location

The team facilitator and organizer will be responsible for scheduling the FMA meeting and providing for a convenient location to hold the meeting. This means the organizer will have to contact core team members to work out a mutually acceptable meeting time. The location should be in a facility reasonably close to the dam site and in a room where there is adequate space and with acceptable accommodations to enhance the FMA process. Cost savings can occur by holding the meeting in a public facility to avoid room charges. Options could include a public library, government office (NRCS, Conservation District or State), or a meeting room of a local engineering company or other organization involved in the dam. Keep in mind economical options for food and refreshments. It is recommended to plan on a working lunch with inexpensive but plentiful snacks, drinks, and sack lunches available for participants.

Questionnaire

The team facilitator should send a questionnaire on potential failure mode identification and inspection and monitoring to core team members in advance of the FMA to get all members “thinking potential failure modes.” The questionnaire should be sent out approximately two weeks in advance of the FMA and can be sent at the same time background data and information is made available to the core team. The questionnaire will help remind core team members to gather relevant materials and information that may be helpful to the session. A sample questionnaire is located in Appendix B.

Visual Aids for the FMA

Pre-planning the FMA meeting will prove to be very beneficial to the whole process. The team facilitator is responsible for putting together meeting visual aids and working materials

to keep the team interested and focused on the tasks at hand. Below are suggestions for visual aids that will enhance the pre-FMA conference call and the meeting itself:

- You will need three separate flip charts, one for each failure modes category: hydrologic (flood), seismic (earthquake) and normal (static) conditions. These flip charts will be used to record the FMA discussions.
- A large sheet listing the different causes of piping.
- An enlarged plan view of the dam with piezometer or other instrumentation locations.
- An enlarged dam cross section that shows dam geology: include elevations of embankment zones and foundation as well as location, depth and perforation intervals of piezometers. Note normal pool reservoir elevation on this cross section, and static water levels in piezometers that correspond to this normal pool.
- An enlarged dam cross section that shows relative elevation of spillways and outlet works – include outlet invert, principal spillway (normal pool), auxiliary spillway, and dam crest elevations. Annotate with maximum capacity as appropriate. Include elevation of routed inflow design flood if available.
- Enlarged list of pertinent dam data (height, length, reservoir capacity, drainage area, age of dam, year of repair/modifications, stream or diversion).
- An enlarged list of pertinent conclusions from past studies and analysis: inflow design storm flow/return period, embankment stability safety factors, etc.

The word “enlarged” is emphasized in this section – a key to a successful FMA is having everyone being able to see what is being discussed. It is recommended that the above visual aids be on paper at least 24 inches by 36 inches, using large font and bold colors and mounted on poster board. Flip charts or other hand-written visual aids should have large print. The visual aids will be referred to frequently during the FMA. Examples of these visual aids are included in Appendix C.

It may be necessary to have a projector available to zoom in on other engineering plans or drawings during the course of an FMA. Note that experience has shown that use of a projector in lieu of the printed or hand-drafted figures discussed above is not effective.

Pre-FMA Conference Call or Meeting

Prior to the actual FMA meeting, the team facilitator will either assemble core team members or initiate a conference call with the core team to allow for an efficient group setting in sharing the collected data. This conference call/meeting should be held approximately three to five days prior to the actual FMA meeting. The conference call/meeting will help create a “captive” condition to ensure that all core team members review the material. If a conference call is conducted, the team facilitator should photograph all visual aids and make them available for core team members during the conference call. Bringing the core team together allows for collaboration on items that may need clarification by the entire team. The individuals on the core team responsible for specialty areas of concern, such as geologic or geotechnical, hydraulic, or seepage items, should ensure that relevant data is available for the team.

Step 8 - FMA Meeting

The actual FMA meeting is the central part of the process. For a simplified FMA, every attempt should be made to keep the meeting to one day to save costs. It is divided into two sessions: a morning site visit to the dam and appurtenant works, and an afternoon brainstorming session to discuss and categorize potential failure modes.

Morning Dam Visit

The core team and all participants should attend the site visit. The morning session site visit is to familiarize the core team and participants with the dam features and conditions so they can effectively carry out the FMA in the afternoon session. The core team and participants should physically inspect all aspects of the dam and appurtenances that are relevant to dam safety. All attending should try to observe and discuss potential circumstances and conditions that could lead to a potential failure.

After the core team and participants are assembled at the dam site, it is a good time for the facilitator to take five or ten minutes to review the basic concept of the FMA process and the objectives of the dam visit. The basic purposes of this inspection are:

1. To let those participating in the FMA see the dam, especially those who have not seen the site.
2. To have the team “think and see” potential failure modes in the field.
3. To discuss the site and operations with the dam tender and other site personnel in their own environment. Owners may find it valuable to include all or most of the employees that they plan to have participate in the FMA also participate in the site visit. The site visit will also allow core team members to relate field conditions to the data they reviewed during the pre-FMA meeting or conference call.

Afternoon Meeting and Brainstorm Session

The following sections provide a brief description of the FMA session, which is usually held the afternoon of the FMA meeting. It is important for the team facilitator to involve all participants in the discussions and give everyone an opportunity to provide their knowledge and understanding of the potential failure modes, consequences and possible risk reduction measures. Just as discussed for the pre-FMA conference call/meeting and the site visit, the facilitator, at the outset of the FMA session, should remind participants about the objectives and process for the FMA session. The facilitator may also want to discuss with the team that the product of the exercise is not a regulatory document but rather an informational and resource tool, developed from the combined input of the team that can be used to guide rehabilitation decisions and improvements to operation and maintenance procedures.

Site Review Using Visual Aids

Using visual aids discussed earlier, the facilitator will go over the dam layout and design visuals. This should be a brief overview and should serve only as a reminder of the main features of the dam and the monitoring instrumentation installed. Obvious problems can also be mentioned.

Failure Mode Brainstorming Session

The facilitator starts off with a brainstorming session of candidate potential failure modes for flood, earthquake and normal loading conditions for the structure. The core team and participants are each asked to suggest or propose “candidate” potential failure modes that

they have considered during the site visit, review of the background material, or when completing the advance questionnaire. The intent is to develop each potential failure mode considered realistic and credible by the team. Failure modes should be labeled sequentially Normal 1, Normal 2, Seismic 1, Seismic 2 Hydrologic 1, etc. according to the condition responsible for the failure mode and listed on the appropriate flip chart.

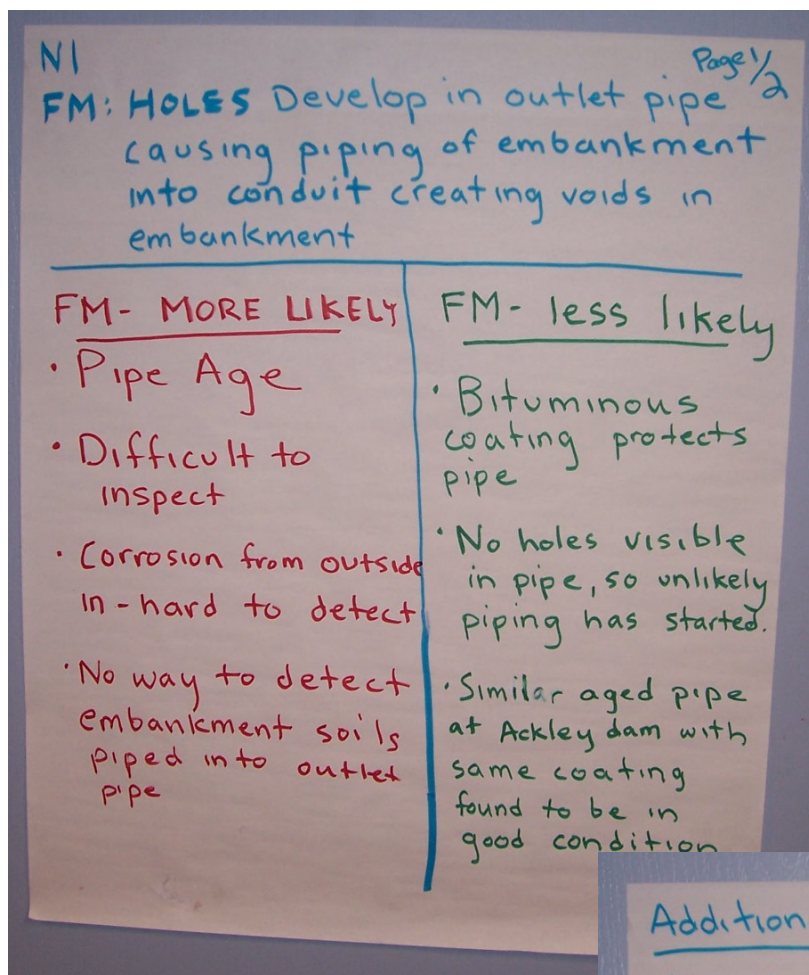
Recording the information on the flip charts is an important aspect of the process. A competent person, either a member of the core team or one of the participants, should do thorough and accurate notation on flip charts. Figure 4-1 shows documentation of a typical failure mode.

Systematic Analysis of Each Failure Mode

For each failure mode, the team brainstorms and lists all the factors that make the failure mode **less likely to occur** and all the factors that make the failure mode **more likely to occur**.

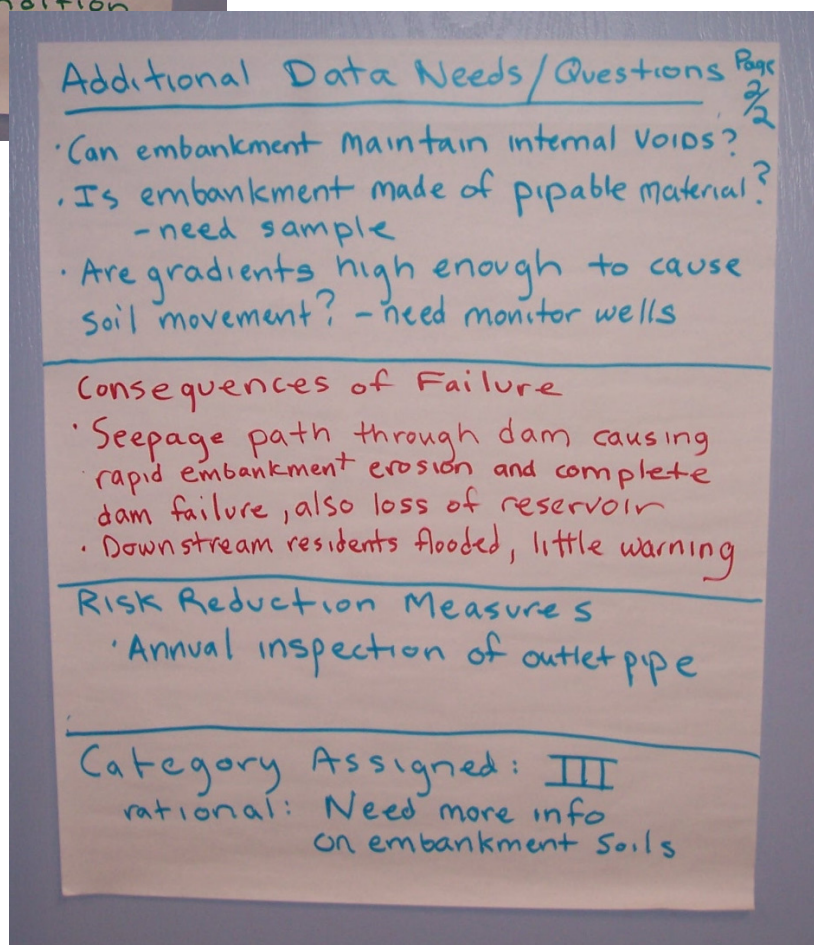
Consider the possibilities of failure for each component of the project (main dam, spillway, gates, dikes, outlet works, etc.).

The potential failure mode factors are noted on the appropriate flip chart (hydrologic, seismic, normal) by the facilitator and should be recorded in detail by the note taker at that time. The note taker can also use a computer with projector to record the potential failure mode information.



**FIGURE 4-1. EXAMPLE OF
 FLIP CHART**

DOCUMENTATION OF A
 FAILURE MODE. BEST TO USE
 2 SHEETS PER FAILURE MODE
 AND LARGE PRINT. RESIST
 TENDANCY TO CRAMP OR
 USE SMALL LETTERING.



Failure Categories

After a potential failure mode has been identified, described and discussed, it is categorized according to the classification system given in Table 4-1. Note that if team members do not reach consensus on the category, dual categorization is permissible (e.g., I/II or III/II). The reasons for assigning two categories must be documented. It is important to note that categorization of potential failure modes is not related to a possible need for additional surveillance, monitoring, maintenance or remediation. The categorization is intended to give participants a relative sense of the importance of the potential failure modes, to assist in developing monitoring plans, and to provide focus to inspections.

TABLE 4-1. CATEGORIES OF IDENTIFIED FAILURE MODES
(Modified from FERC, 2005)

Category	Title	Description
I	Highlighted Failure Modes	Failure modes of greatest significance considering need for awareness, potential for occurrence, magnitude of consequence and physical possibility is evident. A fundamental flaw or weakness is identified and conditions and events leading to failure seemed reasonable and credible.
II	Failure Modes Considered but not Highlighted	These are judged to be of lesser significance and likelihood. The reason for the lesser significance is noted and summarized in the documentation report or notes.
III	More Information or Analyses are Needed in Order to Classify	Failure modes that lack information to allow a confident judgment of significance and thus a dam safety investigative action or analyses are recommended. Because action is required before resolution the need for this action may also be highlighted.
IV	Failure Mode Unlikely But Not Ruled Out	Failure modes that are unlikely to occur, but cannot be completely ruled out. Low priority for initial investigation.
V	Failure Mode Ruled Out	Failure modes that may be ruled out because the physical possibility does not exist, information came to light which eliminated the concern, or the possibility of the failure mode is clearly remote.

Consequences

For each failure mode, the consequences of failure and the circumstances surrounding a failure should be discussed since these factors play a role in determining the significance of the failure mode. This may be a good time to look at the Emergency Action Plan to discuss reaction to the failure and examine any concerns with the plan.

Risk Reduction Measures

During each potential failure mode discussion, identify possible risk reduction actions. These might include monitoring, surveillance, investigations, analyses, remediation (structural or non-structural) and operational procedures and maintenance programs.

Future Data Needs

For each Category I, II or III failure mode, some sort of performance monitoring plan must be identified. A monitoring plan will produce data from which dam performance can be evaluated. Some failure modes may already have monitoring systems in place and data collection has already started, but this process may modify the monitoring plan to gather more meaningful data. Performance monitoring can vary from periodic visual inspections, to continuous recording instrumentation and may include monitoring of weather forecasts and monitoring of earthquake activity.

Major Findings and Understandings

To complete the FMA, the facilitator will solicit individual input from team members on the Major Findings and Understandings (MFU) reached during the FMA process (all the key things learned or more fully understood during the FMA session). An example of an MFU that corresponds to the failure mode in Figure 4-1: “The Bituminous coating on the outlet conduit appears to be providing protection from corrosion, even after 70 years.” The Major Findings and Understandings is the most important component of an FMA and contain the key conclusions made by the group. Typically the facilitator will go around the room to allow each participant to provide a MFU until all participants have had the opportunity to express their findings. Participants may have more than one MFU. MFUs may relate directly to a Failure Mode or may reflect a more general understanding about the dam or the FMA process.

The report writer prepares the “Major Findings and Understandings” immediately after the session. The items noted during the session are typically abbreviated and should accurately reflect what the individual participants stated as their major finding or understanding gained during the session. Where the MFU relates to a potential failure mode, a brief discussion

(three to five sentences) relating the MFU to the failure mode should be prepared by the report writer and included with the MFU. All the input should be recorded on flip charts (hand written) and can also be recorded electronically (computer). All participants should have their input and concerns listed. The facilitator or other team member should photograph hand written charts. After completing this item, the FMA meeting is ended.

Afternoon Brainstorming Session Summary

A condensed version of the brainstorming session is provided in Table 4-2.

TABLE 4-2. SUMMARY OF AFTERNOON BRAINSTORMING SESSION

Activity	Responsibility	Description	Expected Outcomes
Process and goals of FMA	Facilitator	Remind all participants of the process and goals of the FMA.	Refresh the purpose of FMA.
Review dam information	Facilitator	Brief overview of the dam and appurtenances and any issues that are evident after the dam visit and prior to the FMA. Use enlarged plans, maps, and data.	Refresh the features of the dam and any safety issues.
Failure mode brainstorming	Facilitator, Core Team and Participants	On three flip charts (Hydrologic, Seismic and Normal) list as many potential failure modes as possible according to the appropriate failure condition.	Identify potential failure modes.
Failure mode review	Facilitator, Core Team and Participants	For each potential failure mode: <ul style="list-style-type: none"> • <u>Describe</u> failure mode • <u>Label</u> failure mode (Hydrologic1, Seismic 1, Normal 1, etc.) • List factors that make the failure mode <u>more likely</u> (and <u>less likely</u>) <ul style="list-style-type: none"> • List <u>consequences</u> • Assign a <u>category</u> (I, II, III, IV, V) <ul style="list-style-type: none"> • Describe the <u>rationale</u> • <u>List risk reduction measures</u> • Describe <u>data and information needs</u> 	Refine, describe and categorize potential failure modes and any additional information needed.
Major findings and understandings (MFUs)	Facilitator, Core Team and Participants	Circulate around to all participants to list all major findings and understandings from the FMA process.	Describe all major findings and understandings from the FMA process.
Prepare for FMA report preparation	Facilitator, Note Taker and Report Writer	Identify all references to be included in the report. Photograph all flip charts developed during the FMA session. Document all MFUs.	Gather and organize all information to be included in the FMA report.

5.0 FAILURE MODE ANALYSIS RESULTS

It is important that the FMA results be documented quickly and thoroughly for future use. The documentation must describe the identified potential failure modes, include factors considered relative to the viability of each potential failure mode considered, discuss possible risk reduction actions for each credible potential failure mode, and clearly state major findings and understandings achieved as a result of the process.

5.1 DOCUMENTATION OF MAJOR FINDINGS AND UNDERSTANDINGS

The report writer prepares the draft Failure Mode Analysis Report within 20 days of the FMA meeting. Appendix D provides an example outline for documentation of the analysis. The outline in Appendix D is designed to take advantage of the information collected on flip charts during the failure mode analysis session in order to make the documentation process simple, fast and effective.

The FMA report should include the general items listed below. Appendix D provides more details on each item listed.

- Describe each potential failure mode considered, referencing key likely and not likely factors.
- Identify any suggested visual surveillance or instrumental monitoring.
- Describe consequences of potential failure.
- Note any potential actions identified (information inquiries, investigations, analyses or risk reduction opportunities). This type of information could be titled “Additional Monitoring or Performance Related Items Discussed.” Issues or items that are brought up during the FMA session that relate to dam safety and performance monitoring, but are recognized by all as something that does not or would not result in failure, are included here.
- The write up should include a brief statement as to the adequacy of the project documentation and overall quality of the data that formed the basis of the FMA.

- Document all reference material made available and used by the core team and participants in the Failure Mode Analysis.
- Include in an appendix any key items of data and information that led to important findings or conclusions.
- Incorporate in the body or in an appendix of the report photos of past or current conditions or other documentation like a short paragraph that depicts key information about a potential failure mode. Sometimes a figure or photo provides valuable information that words cannot express.
- Include in an appendix of the FMA report the listing of documents gathered by the owner for review in advance of the FMA (see Section 4.1 of this technical note). This type of list has been found to be a valuable tool for the core team to use to assure that they have seen all the materials collected.
- The report should state whether the findings are a consensus of the core team and participants. If not a consensus, the differences of opinion and reasons therefore should be documented in the report findings.

5.1.1 Facilitator and Core Team Review

The report writer then sends the write up of the major findings and understandings to the facilitator for review (this should be done within 20 days of the FMA meeting). Using a text editing tool such as Microsoft Word Track Changes[®] is suggested to consolidate all changes in the report. After reviewing the report, the facilitator may send it back to the report writer to forward on to the core team, or the facilitator could forward it directly to the core team. The core team will review the draft report and send all edits to the report writer to compile and produce the final version of the report. Core team review should not exceed 20 days. A final FMA report should be completed within 60 days of the FMA meeting.

5.2 ALTERNATIVE DOCUMENTATION – SPREADSHEET RESULTS

Documenting an FMA can be an intensive effort, especially if there are multiple issues and categorized failure modes for a dam. The document developed from the major findings and understandings can be extensive and it could take several weeks to finalize the report.

A fully developed FMA document can be expensive and can take considerable time to write. As an alternative to a report, the major findings and understandings and summary of the FMA can be presented in spreadsheet form. This can be a cost saving measure, especially for small privately owned dams. An example of a spreadsheet summary is found in Appendix E. The advantage of developing a results spreadsheet is that it is contained in a concise and cohesive document and the reader does not get lost in the details of pages of text. Potential failure modes are identified and major points are summarized. The disadvantage of this type of summary is that points of discussion and alternate points of view are not fully documented and tend to get lost with just a summary of high points. A spreadsheet table does not adequately represent opposing opinions or fine-point issues that may have come with a particular potential failure mode.

Spreadsheet results can serve either as a concise stand-alone document or as an effective summary that can be included as part of a larger FMA report.

5.3 FMA BENEFITS – A ROADMAP FOR FUTURE OPERATION

As mentioned in earlier sections of this technical note, the intent of an FMA is to be used as a guidance tool for future operation of a dam and help guide rehabilitation decisions. The results of an FMA can be used in different ways with the common goal of helping make the dam safer and more reliable. In the following subsections, the discussion will focus on what can result from an FMA and how it can be used.

5.3.1 Additional Investigations

If any potential failure modes are catalogued as Category III, which would require more information, additional investigations may be necessary. The major findings and understandings exercise will likely list the types of investigations needed and this will help the owner plan for future work to identify or quantify information needed to monitor a condition that may lead to a potential failure mode, or to obtain data that can be used in future repair work. The key benefit to an FMA is to provide sharper focus and more concentration to areas that have been identified as potential failure modes, which may differ considerably from what was being monitored prior to the FMA. This may significantly

change the monitoring plans already assigned to the dam but ideally the new efforts will result in more useful information and analysis.

5.3.2 Maintenance and Repairs Priorities

The direct result of an FMA is to prioritize maintenance, monitoring and repairs for the dam, in order to focus on areas identified as potential failure modes. Following an FMA, the owner is encouraged to meet with the designated engineer for the dam and establish maintenance and monitoring plans that reflect the major findings and understandings of the FMA. The effort may result in added instrumentation, such as piezometers and reservoir level indicators, which will have to be installed to begin monitoring in a timely manner. The FMA may significantly change the types and locations of monitoring equipment and may adjust the way in which data is gathered. This could require changes to the dam operation and maintenance plans, which would need to be modified as soon as possible.

5.3.3 Guidance for Rehabilitation Decisions

It is important to prioritize rehabilitation decisions in order to focus limited funds towards the dam deficiency that poses the biggest threat to public health and safety. For example, say you have a dam that passes the 1000-year storm, however the spillway standard is the 5000-year storm. This same dam however has a 100-year-old outlet pipe that is quickly deteriorating. A failure analysis would likely show the inadequate spillway to be a Category II concern. However, the deteriorating outlet may be a Category I issue and will clearly raise to the top as the foremost rehabilitation priority.

Federal agencies do not jump to rapid conclusions based simply on a Failure Mode Analysis. They take this one step further and proceed to a risk analysis – which assigns probabilities to various failure modes, allowing the decision makers to make quantitative comparisons. This level of effort is not needed for most Montana dams and is only recommended for larger structures with significant populations at risk.

6.0 EXAMPLES OF RECENT MONTANA FMAs

Several FMAs have been completed in Montana. In the following sections are brief summaries of the FMAs conducted and their results. The intent of providing this information is to demonstrate the variability of how FMAs can be conducted and how they might be tailored to suit individual dams. Keep in mind that these were facilitated by various entities and each followed an independent form of FMA procedures developed by FERC. This technical note (TN7) will hopefully provide consistent and clear information on a simplified FMA method that can be used in the future.

6.1 LAKE FRANCIS DAMS

The Lake Frances Failure mode analysis was done to help guide rehabilitation decisions. There was question as to the seriousness of embankment voids that were found during exploratory drilling on one of the two dams. The failure mode analyses concluded the following:

- Voids identified in the embankment are likely caused by material piping into the conduit upstream of the core wall. The seepage paths through the core wall or foundation sheet pile wall are capable of passing cement-size particles and could easily be transporting embankment material. Although this is a significant concern, it was not considered a Category I failure mode requiring immediate repair or mitigation.
- The spillway is adequate. Input from the dam owners was crucial to understanding how extremely unlikely it would be for this off stream reservoir to overfill, given the location and operation of the diversion structure.
- The north dam deserves some more attention.

Lake Frances East dam outlet works has subsequently been rehabilitated and the potential for piping of embankment materials into the outlet eliminated. Additional monitoring wells were installed on the North dam. Data is currently being collected to evaluate seepage through the dam and foundation.

6.2 EUREKA DAM

The Eureka dam failure mode analysis was done to determine rehabilitation priorities and guide additional data collection efforts. There are two problems at the dam: High foundation seepage and an old corrugated metal pipe (CMP) outlet that is past its design life and starting to show deterioration. The failure mode analyses concluded the following:

- It is likely that foundation seepage is moving through solid bedrock and less of a stability concern. This assumption needs to be verified with soil borings and monitor wells
- The CMP outlet pipe's age is beyond its intended design life and should be replaced. This is the highest priority for the dam. Since the bituminous coating appears to be protecting the pipe, it is not necessary to restrict the reservoir level at this time. Steadfast planning to replace the pipe is warranted.

Monitor wells were installed in 2010 to monitor seepage through the dam and foundation. Plans are underway to replace the outlet pipe in 2012 and add a seepage control berm in 2014.

6.3 KOOTENAI DEVELOPMENT IMPOUNDMENT DAM

The Kootenai Development Impoundment Dam failure mode analysis was completed to help understand problems with embankment drains and determine if further action is necessary. The failure mode analysis concluded the following:

- The drains are a concern, but mainly during a flood.
- Of higher priority could be the spillway, which may be structurally unsound and its ability to pass a flood safely is in question.

Alternatives to decommission the dam and reroute the inflow are being evaluated.

6.4 PPL MONTANA DAMS

Through FERC regulation, hydroelectric dams owned and operated by PPL Montana are subject to periodic Potential Failure Mode Analyses (PFMA). These are extensive exercises that focus on failure modes unique to each dam but which are intended to direct operation and maintenance efforts to reduce the risk to the residents of Montana and adjoining states. The PMFAs conducted for PPL Montana dams follow strict FERC guidelines and are far more involved than the FMAs suggested in this technical note. A recent PPL Montana PFMA was conducted for Kerr Dam on the Flathead River in northwest Montana. The Kerr Dam PFMA did not result in any potential failure modes of great concern, but it did generate discussion related to several issues, including:

- Flood gates that could stick and not open completely during a flood event (a concern in 2011 with record runoff in many areas of Montana). The concern is that overtopping could occur, however very unlikely. The main concern is with overtopping and potential failure of the right dike embankment.
- In addition to overtopping concerns, the right dike embankment is being actively monitored for seepage, however there are no safety concerns at this time.

7.0 REFERENCES

- Federal Energy Regulatory Commission, 2005. Engineering Guidelines for the Evaluation of Hydropower Projects, Chapter 14 - Dam Safety Performance Monitoring Program, July 1.
- U.S. Department of the Interior, Bureau of Reclamation (USBR), 2007. Facilitator's Role in the PFMA Process. Training module by Pat Regan, October.

APPENDIX A

TEMPLATE FOR ORGANIZING ELECTRONIC DATA

Dam Failure Mode Analysis Data

STUDIES AND ENGINEERING REPORTS	Category	Subject	Document Name	Description	Date Published	Author
	Hydrology & Hydraulics	Extreme Storm / Design Storm Calculation				
		Lower Frequency Storms				
		Loss of Life Estimate				
		Spillway Adequacy Analysis	2000 DNRC Spillway Review	routing of Inflow design storm	13-Aug-00	DNRC Dam Safety
		Previous spillway analysis				
		Principal Spillway - Outflow Calculations				
		Auxiliary Spillway - Outflow Calculations				
		Basin Yield / Water Availability Calulations				
		Wave Runup Calculations				
	Geotechnical	Piezometer construction /Installation map				
		Drain construction /Installation map				
		Logs/ Soil Tests				
		Cross sections				
		Seepage Analysis				
		Stability Analysis				
		Seismic Analysis				
	Structural & Mechanical	Outlet Conduit				
		Stilling Basin / Energy Dissipation				
		Gates and Valves				
		Spillway				

You can add
hyperlinks in Excel
to specific
documents for
easy access

Subjects will need
to be customized
for each dam

Contact DNRC Dam Safety Program for a copy of this
template in MSEXcel

DATA	Category	Subject	Document Name	Description	Date Published	Author
	Measurments	Piezometer Measurements				
		Drain and weir flow measurements				
	Conversion Tables	Elevation Storage Table				
		Storage Outflow Tables				
		Flume & weir rating tables				
		Reservoir stake conversion tables				
	Survey Data	Survey Notes				
		Bathemetric Survey				
INSPECTIONS & PERMITS	Inspections	1980 Corp of Engineers Inspection				
		1980 DNRC Inspection				
		_____ Engineers Inspection				
		_____ Five y ear Engineers inspection				
		_____ Five Year Engineers Inspection				
		Annual Owner inspection reports				
	Operation Permits	General Correspondence				
		Operation Permit _____				
		Operation Permit _____				
CONSTRUCTION	Construction Records & Permits	_____ Construction Permit & Correspond.				
		_____ Construction Design Report				
		_____ Construction Specifications				
		_____ Construction Inspections				
		_____ Construction Plans				

_____ Dam Failure Mode Analysis Data

EMERGENCY PLANNING	Category	Subject	Document Name	Description	Date Published	Author
	Emergency Action Planning	Emergency Action Plan (EAP)				
		Correspondence				
		Annual Updates				
	Downstream Hazard Classification	DNRC Hazard assessment calculations				
		Clear Weather Breach Mapping				
	Operation and Maintenance	Standard operating procedures				
		Reservoir Operation Records				
		Maintenance Records				
OTHER	Photographs & Images	Print photographs				
		Digital Photographs				
	Misc	Newspaper Articles				

APPENDIX B

FMA QUESTIONNAIRE

FAILURE MODE QUESTIONNAIRE
for

Team Member's Name

Team Member's Experience / Role

Phone

Email

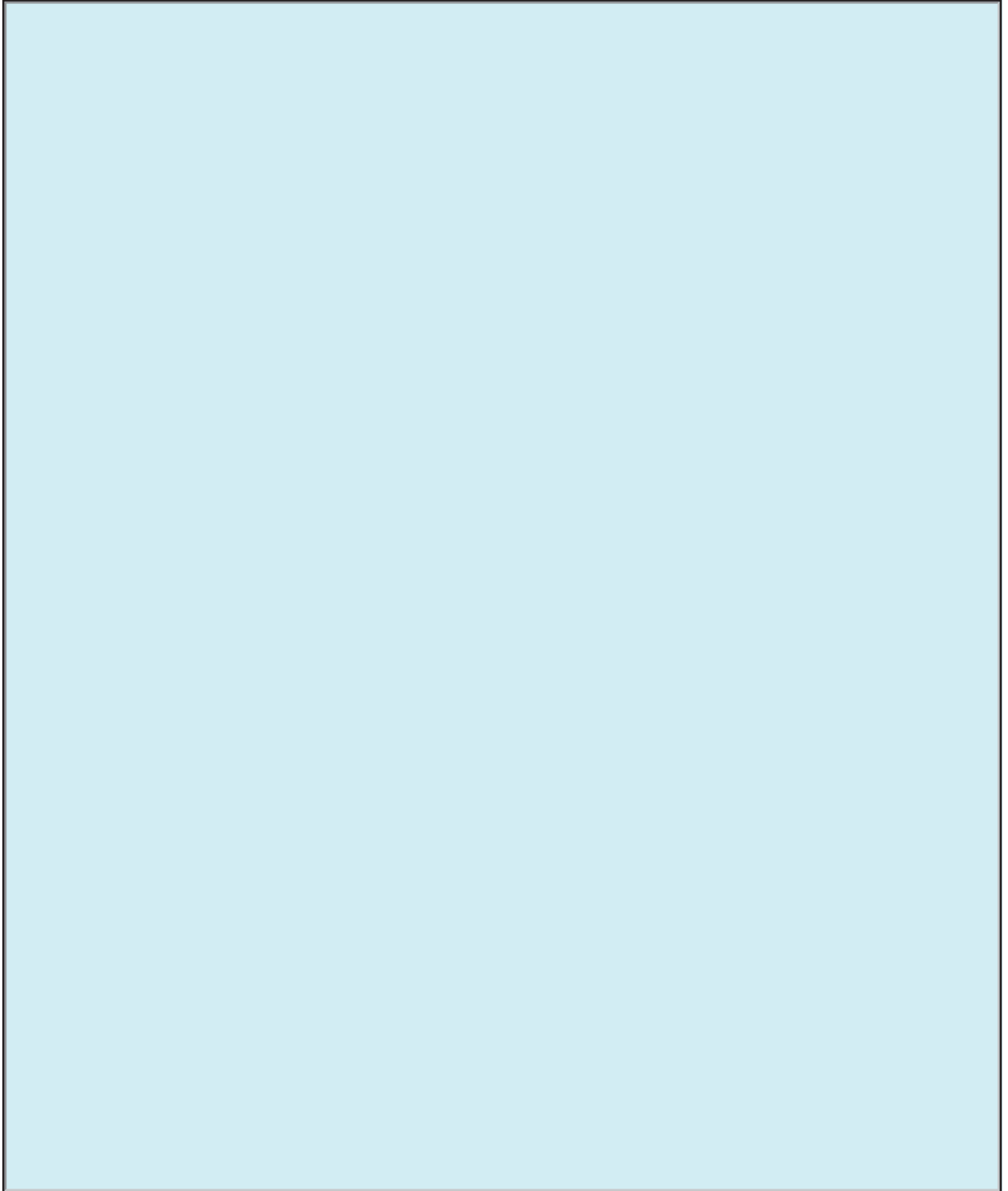
1. What potential failure modes do you think are of specific concern at this project? Please be descriptive! Include a specific description of the potential failure mode, including location of the area of concern. For example: "Piping of embankment material into deteriorated conduit causing voids in the embankment along outlet, creating a seepage path through the embankment to the reservoir."

Potential failure mode 1.

Potential failure mode 2.

Potential failure mode 3.

2. If you have visited the site either as part of an official inspection or a general site visit, please identify any conditions that are noteworthy from the standpoint of performance of the dam.

A large, empty rectangular box with a light blue background and a black border, intended for a response.

APPENDIX C

EXAMPLE VISUAL AIDS

Visual Aid #1 Causes of piping

Four conditions that must exist for piping

- Concentrated Flow Path
- Unfiltered exit
- Erodible material
- Ability to support roof

Von Thun, April 1996

Greatest piping resistance

- Plastic clay
- $PI > 15$
- well compacted or poorly compacted

Sherard, Jan 1953

Intermediate piping resistance

- well graded clay binder
 - Well compacted or poorly compacted
 - $6 < PI < 15$
- well graded cohesionless
 - $PI < 6$
 - well compacted

Least piping resistance

- Well graded cohesionless $PI < 6$; poorly compacted
- Very uniform fine cohesionless sand; $PI < 6$, well compacted or poorly compacted

Piping more likely

- Core: alluvial materials, dispersive clays, low plasticity silts, poorly & well graded sands no formal compaction
- Conduit through embankment
- No filter
- Untreated foundation irregularities
- Sheet pile wall/poorly constructed diaphragm
- Soil foundation

Foster et al, 1998

Piping less likely

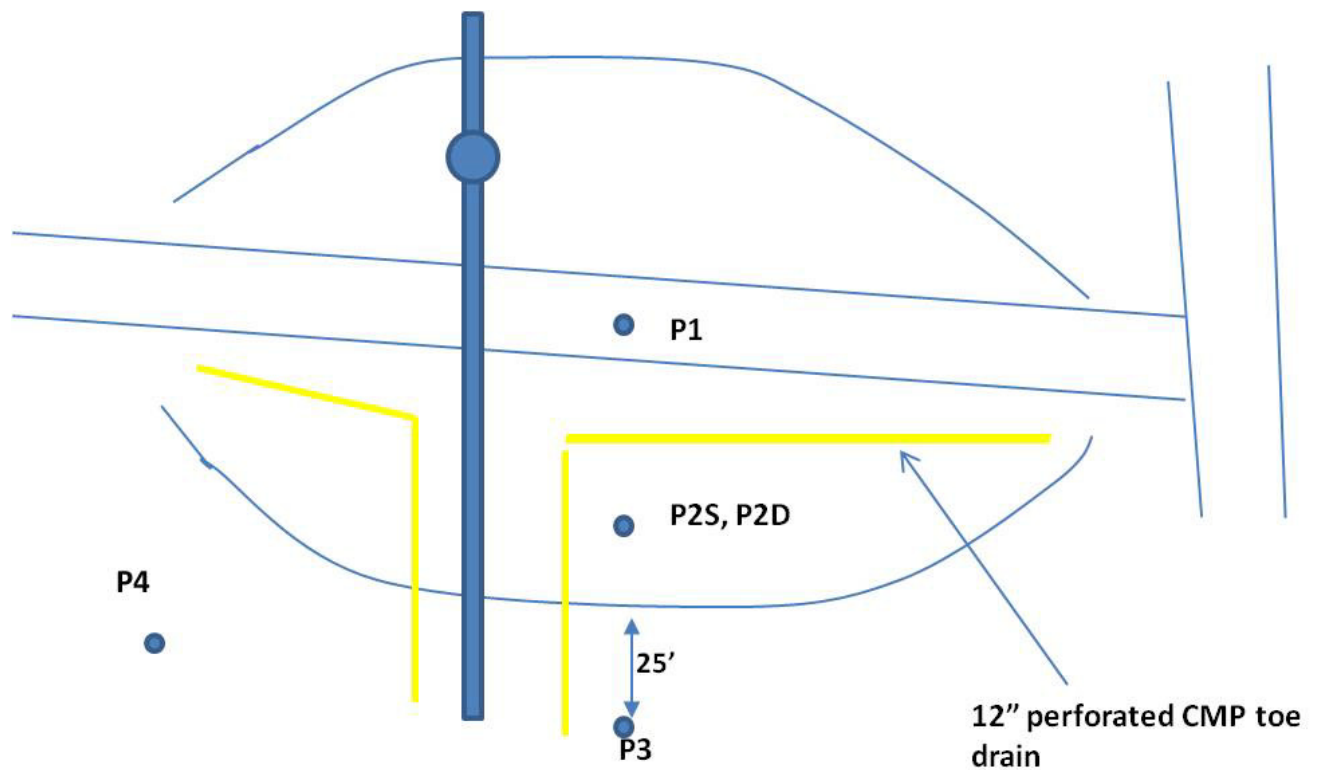
- Core: clayey & silty gravels, high plasticity clay, glacial origin, rolled with good compaction control
- Filters transition zones
- Well constructed cutoff trench/slurry wall

Visual Aid #2 Plan view of the dam

Include and clearly label:

- Instrumentation,
- Outlet
- Spillway
- Toe drains
- Manholes
- Distances between features where appropriate

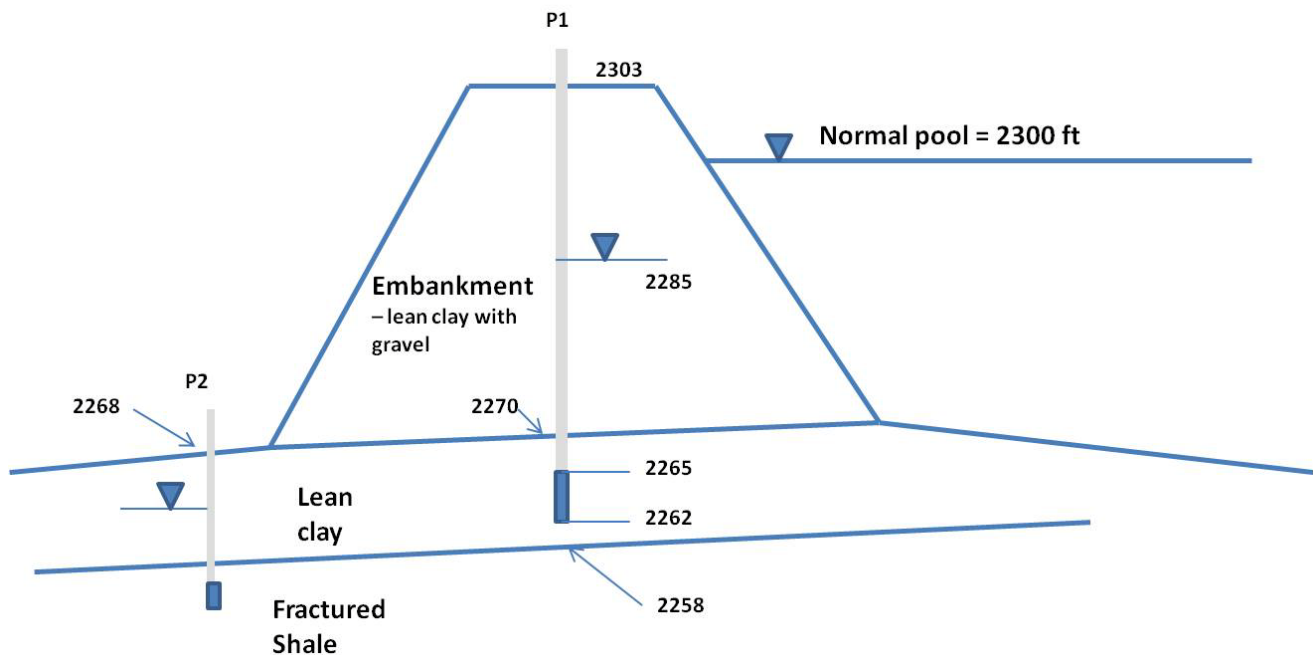
Redraft if necessary - make it simple – construction plans are often hard to see and understand



Visual Aid #3 Geotechnical Dam Cross Section

Include:

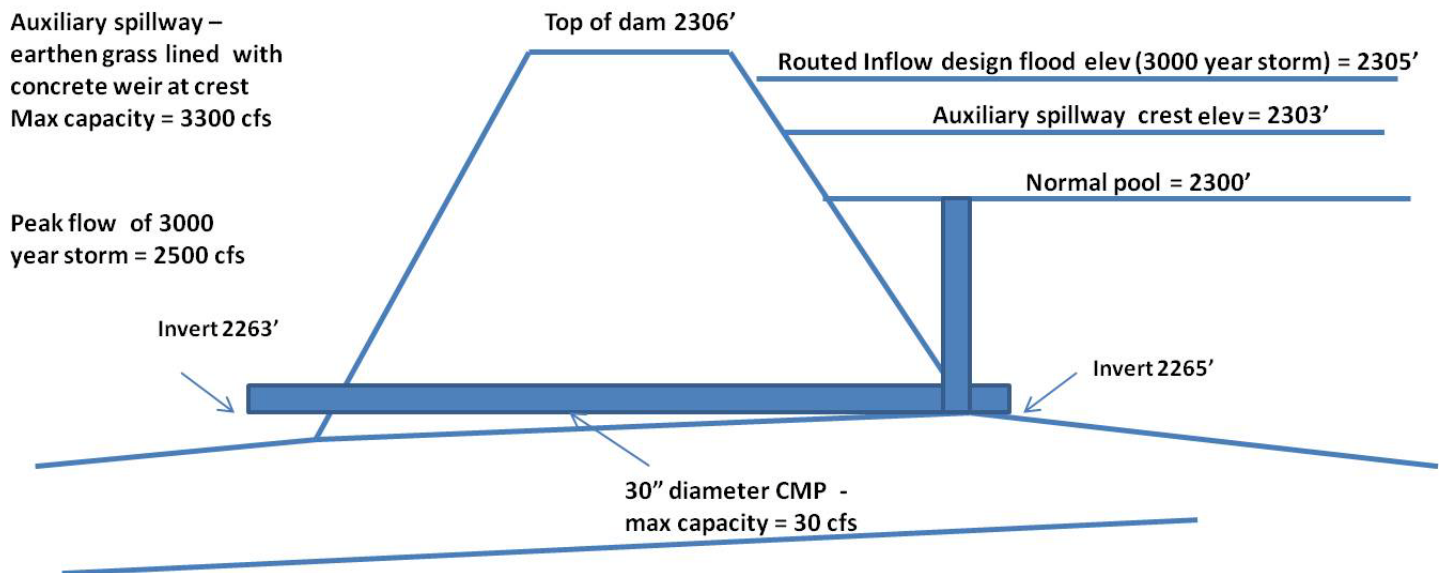
- Dam geology
- Elevations of embankment zones and foundation
- Location, depth and perforation intervals of piezometers.
- Normal pool reservoir elevation
- Static water levels in piezometers that correspond to normal pool



Visual Aid #4 Hydrologic/Hydraulic Dam Cross Section

Include:

- Elevation of spillways and outlet works
 - outlet invert
 - principal spillway (normal pool) crest elevation
 - auxiliary spillway crest elevation
- Dam crest elevation
- Maximum capacity as appropriate
- Elevation of routed inflow design flood if available



Visual Aid #5 Pertinent Dam Data

Include:

- Height
- Length
- Reservoir capacity
- Drainage area
- Age of dam
- Year of repair/modifications
- Stream or diversion
- Pertinent conclusions from past studies – be sure and note source
 - Inflow design storm flow/return period,
 - Embankment stability safety factors, etc.

Other Tips

- Print out on a 24 inches by 36 sheet and mount on poster board.
- Use large font and bold colors
- It may be necessary to have a projector available to zoom in on other engineering plans or drawings during the course of an FMA.

APPENDIX D

GENERAL FORMAT FOR FMA REPORTS

General Format for Failure Mode Analysis Reports

I. Introduction and Background

Purpose / description of study

I. Brief Description of Dam and Other Key Features of Project

II. Major Findings and Understandings from Study

General

Normal Operations

Flood Conditions

Seismic

III. Failure Modes Identified

The presentation of failure modes should be grouped by category:

- I Highlighted
- II Considered but not highlighted
- III Information needed to allow classification
- IV Ruled out / Not physically possible

For each Category I, II, III or IV potential failure mode identified, include:

- A detailed description of the potential failure mode and potential adverse consequence (scenario developed by the team [**including a sketch where applicable**] and a discussion of the potential adverse consequences of the formulated scenario). For some Category IV failure modes there may not be a detailed description if the failure mode was ruled out by the team prior to fully developing the failure mode.
- A listing of factors that indicate the potential failure mode is more likely or less likely to occur.
- The failure mode category selected by the team for each potential failure mode.
- A description of the rationale used for selecting that category (i.e., the factors with the greatest weight).

The Potential Risk Reduction actions identified during the discussion of each potential failure mode should also be documented in the report. These may include items such as:

- Surveillance and monitoring enhancements.
- Risk Reduction measures to evaluate.
- Investigations / analyses needed.
- Data and information needed to collect / prepare for decisions on prioritization of dam safety actions.

- Information needed to resolve Category III potential failure modes.

IV. Additional Monitoring or Performance Related Items Discussed

This section should include items that are brought up during the FMA session that relate to dam safety and performance monitoring or are of general concern but would not result in failure of the dam or other water retaining structure at the project. They need to be included in the documentation to illustrate that they were identified, considered and were left to be addressed (potential identification of action) by the owner.

V. Summary and Conclusions

This section should include a review of the number of potential failure modes identified within each category, any study specific comments related to the potential modes of failure, and a summary of potential actions identified in the FMA with respect to Surveillance and Monitoring.

Appendix to Report

Key supporting data and information and references, figures, sketches, and photos made during field review showing key elements of dam and auxiliary features should be included along with any photos that show conditions leading to potential failure modes.

Note 1: The report of the FMA session should be prepared as a stand-alone document.

Note 2: Use of tables to present potential failure mode information

Tables may be an effective way to present the information related to each potential failure mode identified. However, it may not be possible to fully describe the potential failure mode in a table format. It is important to remember that the description of the potential failure mode must provide a complete understanding of the intent of the team to reviewers 5 to 25 years in the future. Thus, if tables are to be used then extra care must be taken by complete description in Section IV text to ensure that future reviewers obtain a full understanding of the teams meaning and intent. Tables may be used as a means to summarize or supplement a more complete written description of potential failure modes. A possible table format is provided below.

Potential Failure Mode Description	Adverse Factors	Positive Factors	Risk Reduction Actions	Category

APPENDIX E

EXAMPLE SPREADSHEET SUMMARY OF FMA

Failure Mode Analysis – Eureka Main Dam

Category I – Greatest significance; physical possibility, conditions leading to failure are credible (**High Priority**)

Category II – Physically credible, but lesser significance

Category III – More info needed in order to categorize

Category IV – Unlikely to occur, but can't be completely ruled out Category V – not possible

Failure Mode	Factors that make Failure Mode more likely	Factors that make Failure Mode less likely	Consequences	Category	Rational for Category Assignment	Risk reduction measures	Data / Information Needs
Corrosion and failure where gate tower connects to outlet conduit, causing piping along outlet, progressive erosion	<ul style="list-style-type: none"> Settlement at connection, previous gap sealed recently Age of pipe Similar failure mechanism in many Montana dams Uncertainty with Bituminous coating in this area; difficult to inspect 	<ul style="list-style-type: none"> Bituminous coating appears to protect pipe well 	<ul style="list-style-type: none"> Failure of dam or Loss of reservoir contents 	I	Number 1 cause of dam failure in MT in similar aged pipes; difficult to inspect and past settlement	<ul style="list-style-type: none"> Increase inspections Add diaphragm filter around outlet pipe 	<ul style="list-style-type: none"> Can embankment withstand erosion? Need sample of embankment soils
Holes develop in outlet conduit causing piping of embankment material into conduit and development of voids in embankment	<ul style="list-style-type: none"> Pipe age – end of design life Difficult to inspect Corrosion often from outside in, not visible from interior inspection Embankment materials piped into conduit would not be visible 	<ul style="list-style-type: none"> Bituminous coating appears to protect pipe well; no visible holes present; unlikely that piping has occurred to date Similar pipe exposed at Ackley Lake Dam is in good shape 	<ul style="list-style-type: none"> Failure of dam 	I	Pipe is well beyond design life.	<ul style="list-style-type: none"> Annual inspection of pipe 	<ul style="list-style-type: none"> Can embankment maintain internal voids? Is embankment made of pipable material? Need sample of embankment soils Are gradients high enough to begin particle movement into voids?
Gate failure due to overtightening or overextending the gate operator	<ul style="list-style-type: none"> Lack of Limit nut Trained operator in similar facility failed gate by overextending gate stem 	<ul style="list-style-type: none"> No problems with past operation 	<ul style="list-style-type: none"> Loss of reservoir contents; Unable to make releases 	II	No past problems	Add limit nut or similar mechanism to prevent excessive gate movement; update O & M manual with clear instructions	

Failure Mode	Factors that make FM more likely	Factors that make FM less likely	Consequences	Category	Rational	Risk reduction measures	Data / Information Needs
Piping of embankment materials into foundation	<ul style="list-style-type: none"> • Some unexplained depressions on upstream face could be related to piping of embankment materials into foundation • No filters or drains in embankment • No knowledge about foundation preparation • Settlement of outlet pipe after construction suggests foundation problems and possible internal cracking of embankment 	<ul style="list-style-type: none"> • Embankment constructed under supervision of State Water Conservation Board • Beck piezometers show slight upward gradient from foundation • Dry embankment and wet foundation support idea that upward gradient is present (water is moving directly from reservoir through bedrock foundation) • Low percentage of piping failures in dams are from this failure mode • Since built by State water board, foundation was likely prepared 	<ul style="list-style-type: none"> • Failure of dam 	III	Knowledge of internal dam gradients necessary to classify failure mode		<ul style="list-style-type: none"> • Is embankment made of pipable material? Need sample of embankment soils • What is gradient within dam and foundation? Nested piezometers in embankment and toe are needed
Slide on downstream face of dam caused by uplift pressures in foundation that saturate and weaken the toe	<ul style="list-style-type: none"> • Beck piezometers indicate that uplift pressures are present • Bedrock is close to ground surface and has potential to transmit reservoir head to toe area • Toe area is saturated 	<ul style="list-style-type: none"> • Embankment slopes are adequate • Embankment is dry • Uplift pressures appear to be minimal 	<ul style="list-style-type: none"> • Failure or serious damage to dam 	III	Knowledge of internal dam and foundation gradients are necessary to classify failure mode		<ul style="list-style-type: none"> • What is gradient within dam and foundation? Nested piezometers in embankment and toe are needed

Failure Mode	Factors that make FM more likely	Factors that make FM less likely	Consequences	Category	Rational	Risk reduction measures	Data / Information Needs
Piping through embankment	<ul style="list-style-type: none">• Filters are absent, so unfiltered exit is possible• Largest percentage of dam piping failures are from this failure mode	<ul style="list-style-type: none">• Embankment is dry• Embankment is homogenous – no evidence of open work gravel paths• Embankment has long term performance history and no recent changes	<ul style="list-style-type: none">• Failure or serious damage to dam	III	Knowledge of internal dam and foundation gradients are necessary to classify failure mode		<ul style="list-style-type: none">• What is gradient within dam and foundation? Nested piezometers in embankment and toe are needed• Is embankment made of pipable material? Need sample of embankment soils
Piping through Foundation	<ul style="list-style-type: none">• Unfiltered exit is present• Foundation treatment not known	<ul style="list-style-type: none">• Dam is only 30 feet high – head may not be large enough to create a blowout• Bedrock in flow path is likely not erodible	<ul style="list-style-type: none">• Failure or serious damage to dam	III	Knowledge of internal dam and foundation gradients are necessary to classify failure mode		<ul style="list-style-type: none">• What is gradient within dam and foundation? Nested piezometers in embankment and foundation are needed• Does foundation contain pipable material? Need sample of foundation soils and bedrock

Failure Mode	Factors that make FM more likely	Factors that make FM less likely	Consequences	Category	Rational	Risk reduction measures	Data / Information Needs
Blow out in foundation below toe of dam	<ul style="list-style-type: none"> • Evidence that upward gradient is present • Saturated foundation below toe of dam is a sign of high upward gradient • Thickness of confining layer above bedrock is low 	<ul style="list-style-type: none"> • Dam is only 30 feet high – head may not be large enough to create a blowout' • Blowout would only go down to bedrock and could not progress back to reservoir (assuming bedrock is competent) 	<ul style="list-style-type: none"> • Failure of the dam 	III	Knowledge of internal dam and foundation gradients are necessary to classify failure mode		<ul style="list-style-type: none"> • How competent is bedrock? • Does bedrock extend the entire length of dam? – appears to be down as you proceed to west • What are uplift pressures in foundation • What is thickness of soil over bedrock
Overtopping of embankment during an extreme storm event or by diverting too much water into the reservoir (operator error)		<ul style="list-style-type: none"> • Dam is offstream 	<ul style="list-style-type: none"> • Failure of dam 	III	Spillway adequacy assessment needs to be done	Have state do preliminary analysis of spillway adequacy?	<ul style="list-style-type: none"> • Does spillway pass state's spillway design standard? • Could reservoir be overfilled by operator error?
Embankment cracking or other damage during earthquake		<ul style="list-style-type: none"> • Dam is in low seismic area • Dam has bedrock foundation; unlikely to be damaged during quake 	<ul style="list-style-type: none"> • Damage to dam; possible failure 	IV		Have state do preliminary analysis of seismic risk?	<ul style="list-style-type: none"> • Is foundation liquefiable?
Slide or slough on downstream face of dam caused by saturation of embankment materials		<ul style="list-style-type: none"> • Embankment appears to be dry • Slopes of embankment are adequate • No evidence of embankment instability 	<ul style="list-style-type: none"> • Failure of dam 	IV	No evidence of slope instability	Install and measure piezometers	<ul style="list-style-type: none"> • Collect seepage data through embankment to verify phreatic surface in dam and foundation