United States Society on Dams

Routine Instrumented and Visual Monitoring of Dams Based on Potential Failure Modes Analysis

March 2013

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Prepared by the USSD Committee on Monitoring of Dams and Their Foundations

U.S. Society on Dams

Vision

To be the nation's leading organization of professionals dedicated to advancing the role of dams for the benefit of society.

Mission — USSD is dedicated to:

- Advancing the knowledge of dam engineering, construction, planning, operation, performance, rehabilitation, decommissioning, maintenance, security and safety;
- Fostering dam technology for socially, environmentally and financially sustainable water resources systems;
- Providing public awareness of the role of dams in the management of the nation's water resources;
- Enhancing practices to meet current and future challenges on dams; and
- Representing the United States as an active member of the International Commission on Large Dams (ICOLD).

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FOREWORD

The importance of monitoring programs for dam safety is widely accepted. There are many historical cases of dam failures where early warning signs of failure might have been detected if a good dam safety monitoring program had been in place. A monitoring program can provide information that is needed for a solid understanding of the on-going performance of a dam. Monitoring programs, including instrumentation and visual inspection, provide dam owners with knowledge that a dam is performing as expected, and the ability to detect a change in performance. This knowledge and ability is critical because the dam owner is directly responsible for the consequences of a dam failure. Therefore, a good dam safety monitoring program should be a key part of every dam owner's risk management program.

This paper is part of a series of White Papers by the USSD Committee on Monitoring of Dams and Their Foundations to address important topics with respect to the development and successful implementation of dam safety monitoring programs:

- Why Include Instrumentation in Dam Monitoring Programs?
- Routine Instrumented and Visual Monitoring of Dams Based on Potential Failure Modes Analysis
- Development of a Dam Safety Instrumentation Program
- Operation and Maintenace of an Instrumentation Program
- Instrumentation Data Collection, Management and Analysis

While each of the above White Papers addresses its topic in a "stand-alone" manner, there are interrelationships between these papers. Readers of this paper may find it beneficial to refer to one or more of the other White Papers for a broader understanding and perspective with respect to dam safety monitoring programs.

This series of White Papers primarily addresses the programmatic aspects of instrumentation for dam safety monitoring rather than technological advances in instruments. These papers should provide dam owners, large and small, with basic information to evaluate or implement an adequate dam safety monitoring program. These programs become more and more critical as our nation's dams (and other infrastructure) reach and extend beyond their design lives.

The Lead Author for this White Paper was Jay N. Stateler (Bureau of Reclamation, Denver, Colorado). The co-author was Manoshree Sundaram (MWH, Chicago, Illinois). The Lead Reviewer was Christopher Hill (Metropolitan Water District of Southern California). The Publication Review Committee (PRC) was headed by USSD Board Member Keith A. Ferguson (HDR Engineering, Inc., Denver, Colorado), with PRC members David D. Moore (Grant County Public Utility District, Ephrata, Washington), Kim de Rubertis (Consultant, Cashmere, Washington), and Wayne Edwards (Consultant, Novato, California). The work of these individuals, as well as the other members of the USSD Committee on Monitoring of Dams and Their Foundations that provided input regarding this paper, is acknowledged and appreciated.

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1.0 INTRODUCTION

Potential Failure Modes Analysis (PFMA) and similar processes have become a fundamental part of dam safety program efforts for many organizations in the United States and around the world. In the PFMA process, the credible threats to the safety of a dam (the potential failure modes) are identified considering all loading conditions, so that appropriate responses can be formulated to address those threats. Responses could involve dam modification, further investigation/analysis of the matter, restrictions in reservoir operation, and/or improved emergency action planning, but in many instances the response is simply development and implementation of a dam safety monitoring and surveillance program aimed at specifically addressing the threats identified during the PFMA effort.

The goal of the PFMA process is to reduce the potential for failure of the dam, and the resulting adverse consequences due to the identified threats. Adverse consequences could involve uncontrolled reservoir releases or dam failure, which could result in loss of life and substantial property damage.

Routine dam safety surveillance and monitoring methods/programs using instrumented and visual monitoring methods are critical to the PFMA process in two basic ways: (1) to help in identifying potential dam safety threats (the potential failure modes), and (2) to detect the possible initiation/progression of a potential failure mode so that timely actions can be taken to prevent failure. This paper will describe the relationship between the PFMA process and instrumented and visual monitoring of dams.

2.0 BACKGROUND CONCERNING POTENTIAL FAILURE MODES ANALYSIS WORK

In one form or another, the concept of delineating potential failure modes for dams has been around for a number of years. The “Federal Guidelines for Dam Safety Glossary of Terms,” defines a potential failure mode (PFM) as:

> *“[a] physically plausible process for dam failure resulting from an existing inadequacy or defect related to a natural foundation condition, the dam or appurtenant structures design, the construction, the materials incorporated, the operations and maintenance, or aging process, which can lead to an uncontrolled release of the reservoir.” (FEMA, 2004).*

It is believed that the first effort to directly tie instrumented and visual monitoring efforts to potential failure modes was by the U. S. Bureau of Reclamation (Reclamation) in the early 1990s. Reclamation’s Dam Safety Office was concerned about the effectiveness and efficiency of its dam instrumentation program and initiated a study effort in this area. The study team quickly recognized that to assess the effectiveness of a project’s instrumentation and visual surveillance program they needed to determine the intended purpose of the monitoring program. The team concluded that for existing dams, monitoring efforts should be directed towards the identified potential failure modes for the structure.

Reclamation developed the “Performance Parameter Process,” which involves the following three basic steps:

1. Identify the most likely potential failure modes for the dam and associated structures.

2. Identify the key monitoring parameters that will provide the best indication of the possible development of each of the identified potential failure modes, and define an instrumentation and visual monitoring program to gather the necessary information and data.

3. Define the ranges of expected performance relative to the instrumentation and visual monitoring program, and define the action to be taken in the event of unexpected performance.

The Performance Parameter Process (Process) and the reports developed from use of the Process were intended to address the following question: “What should be done to properly look after the dam in the future, from a dam safety perspective, given what we know today?” Beginning in 1994, Reclamation developed Performance Parameters Technical Memoranda (PPTMs), and over the course of the next five years, a PPTM was developed for the majority of Reclamation dams.

Beginning in 2000, Reclamation started preparing Comprehensive Facility Review (CFR) Reports, which included delineation or updating of a dam’s potential failure modes and future monitoring program, along with records review and evaluation, a site exam, and a risk analysis for the dam. The CFR process has been adjusted in various ways since its inception, but the basic work concerning definition of potential failure modes and definition of an appropriate monitoring program in light of the identified potential failure modes, has remained consistent over time.

In 2002, the Federal Energy Regulatory Commission (FERC) initiated efforts that led to the development of the Potential Failure Modes Analysis (PFMA) program. The PFMA process is used to identify the potential failure modes at each component of a project, and the project as a whole, under static (normal), flood, and earthquake loading conditions, and to assess those potential failure modes to determine if they are sufficiently likely to warrant new or continued monitoring/surveillance efforts, or to possibly warrant new remediation or repair efforts. The PFMA procedure begins with review of the existing information on the project, including design reports, analyses, rehabilitation reports, soils information, past inspection reports, construction photographs, construction documentation, etc. The PFMA includes a site visit followed by discussion of available information. The discussion is informal and involves a team of individuals with knowledge of the project’s features and operation, as well as individuals with expertise in a variety of areas including civil, geotechnical, mechanical, controls systems and hydraulics engineering, geology, and operations and maintenance of the specific project. First-hand input is received from field and operating personnel for the dam. Potential failure modes (PFMs) are then identified and prioritized based on their significance in terms of the need for awareness, monitoring and surveillance, analyses and investigation, operational changes, structural repairs, and/or modifications. In all respects, the process currently used in the PFMA process by FERC parallels the basic process currently used by Reclamation in their CFR work to carry out potential failure mode evaluations.

The PFMA process can help to:

- Enhance the dam safety visual surveillance/inspection process and the instrumented monitoring program by helping to focus on the most critical areas of concern unique to the dam under consideration.
- Identify PFMs not covered by commonly used analytical methods (e.g. slope stability and seismic analyses), such as seepage-related potential failure modes.
- Identify PFMs associated with possible misoperation, or other human oversights or errors.
- Identify shortcomings and oversights in data, information, or analyses necessary to evaluate dam safety and each PFM.
- Identify the most effective dam safety risk reduction measures.
- Document the results of the process for guidance regarding future dam safety inspections and future monitoring of the project.

3.0 PFMA AS RELATED TO ROUTINE INSTRUMENTATION AND VISUAL MONITORING PROGRAMS

The potential failure mode discussions that occur during the PFMA process include a focused discussion of potential problems by a multidisciplinary team of engineers and operators that leads to a greatly improved understanding of the events that could occur at a dam that could lead to its failure. This understanding then allows an assessment of efforts that could be undertaken to:

(1) Reduce the potential for development of the identified potential failure modes.

(2) Improve the detection capability with respect to initiation/early development of any of the identified potential failure modes.

A dam’s routine instrumentation and visual monitoring program directly relates to item (2) listed above. Focused monitoring can detect a developing problem at an early stage so that steps can be taken to avert a dam failure. Alternatively, timely detection can enable a timely evacuation that can reduce loss of life in the event dam failure cannot be averted. (ASCE 2000)

Data from instrumented and visual monitoring programs can also be used to better understand the potential for development of a potential failure mode. If a previously unrecognized potential failure mode is identified in the PFMA process, information associated with having a full understanding of the potential failure mode may be lacking. Instrumented and visual monitoring programs may result in information that improves the understanding of the potential risks associated with a potential failure mode. In some instances, the level of concern about the potential failure mode may be greatly reduced when monitoring data are available concerning key parameters related to the potential failure mode.

Outcomes of the PFMA as related to surveillance and monitoring can include:

- Identification of enhancements to the surveillance and monitoring programs, and tailoring of existing programs to focus monitoring efforts on early identification of the initiation/development of PFMs;
- Identification of gaps in data, information and analyses, that may prevent characterization of the significance of a PFM; and
- Identification of risk reduction opportunities applicable to the surveillance and monitoring programs, operations, etc.

The PFMA process also educates all parties involved with the dam's performance and operations regarding the dam's instrumentation and monitoring program, and how this program is critical in the identification of specific symptoms, behaviors, or evidence of conditions that might warn of an initiating or developing failure. In addition, the importance of "general health monitoring" for the dam is emphasized. "General health monitoring" includes high value, relatively low cost activities, such as drain flow monitoring at concrete dams, surveying of settlement and deflection monitoring monuments at both embankment and concrete dams, etc., which provide valuable diagnostic information about key aspects of the dam's performance at relatively low cost.

If not already available, documentation of the project's visual and instrumented monitoring program should be developed for each project as a result of the PFMA process. This would include documentation of visual surveillance requirements and procedures; details of the instruments installed and their purpose(s); instrumentation monitoring procedures; reporting requirements; expected ranges which may be established for some of the features; and procedures to be used to address results that fall outside those expected ranges.

4.0 PFM – MONITORING RELATIONSHIP FOR VARIOUS POTENTIAL FAILURE MODES

Up to this point, the discussion of the relationship between potential failure modes and monitoring programs at dams has been general. To better illustrate this relationship, four categories of potential failure modes will now be explored, including specific discussion concerning surveillance and monitoring that may be appropriate with respect to the potential failure modes (PFMs). It is hoped that through the use of these examples, the process associated with developing effective surveillance and monitoring programs will be illustrated.

The four categories of potential failure modes explored herein are as follows:

- Seepage-related potential failure modes for embankment dams under normal and flood loading conditions;
- Earthquake-related potential failure modes for embankment dams;
- Potential failure modes for concrete dams under all loading conditions; and
- Flood-related potential failure modes associated with spillway failure.

4.1 PFM – Monitoring Relationship for Seepage-Related Potential Failure Modes for Embankment Dams Under Normal Operating Conditions and Flood Loading Conditions

Failure due to seepage-related problems accounts for roughly half of embankment dam failures historically (Foster et al., 2000). Seepage-related issues can arise due to poor designs; poor construction practices; inappropriate drilling methods; a lack of protective filter zones; poor compaction of embankment materials adjacent to conduits or instrumentation installations; animal burrows; roots of woody vegetation in the embankment; embankment cracking due to excessive settlements, and others. A wide variety of potential failure modes relate to poorly controlled seepage.

Table 1 below shows some monitoring considerations associated with one seepage-related potential failure mode, for illustration purposes. Table A1 in Appendix A provides similar information for a number of other common seepage-related potential failure modes for embankment dams. Tables 1 and A1 are intended only as examples of monitoring activities that might be undertaken to address the potential failure modes. The monitoring program developed for a seepage-related potential failure mode for a dam needs to be site-specific for the issues and circumstances for that dam and damsite, and therefore could be significantly different than what is indicated in Tables 1 and A1. Additionally, the specific circumstances of a dam and damsite will also need to be considered when determining the appropriate monitoring frequencies.

Table 1.

Monitoring Considerations Regarding a Seepage-Related Potential Failure Mode for an Embankment Dam (See Table A1 in the Appendix for information regarding some other seepage-related potential failure modes for embankment dams.)	
Potential Failure Mode (PFM)	***Monitoring Considerations***
Seepage-related failure due to breaching, caused by **<u>flow through the dam embankment</u>** that erodes and transports embankment material and exits at the downstream slope of the dam or into the toe drain system	• Perform regular visual inspections of the dam and dam site that include inspection of: **(1) the downstream slope and toe area of the dam embankment**, looking for animal burrows, sinkholes, depressions, areas of unusual or excessive settlements, new or increased seepage, changes at existing wet areas, and any evidence of material being transported (such as turbid or discolored water, sediment deposits along flow paths, etc.); **(2) the dam crest**, looking for animal burrows, sinkholes, depressions, and areas of unusual settlement; **(3) the upstream slope,** looking for signs of animal burrows, sinkholes, depressions, and areas of unusual settlements; and **(4) the reservoir water surface,** looking for whirlpools. Photographic documentation should occur when unusual/unexpected conditions are observed. • Regularly monitor toe drain flows and seepage flows associated with flow through the dam embankment, looking for increased flows, and particularly looking for any evidence of material being transported by the flow. • Regularly monitor water pressures or levels from piezometers and observation wells in the dam embankment and foundation, looking for increasing or decreasing trends, or any otherwise anomalous data. • During a major flood event, when reservoir levels are unusually high, perform frequent visual and instrumented monitoring as described above. • Occasionally perform camera inspections of the toe drain system to ensure its integrity.

In general, monitoring water pressures and subsurface water levels at a damsite provides valuable information towards understanding seepage patterns at the site. However, it is important to understand that these data are associated with discrete points and most likely the monitoring locations will not happen to be right along, or in close proximity to, the flow path of a developing seepage-related problem. Consequently, regular visual inspections combined with monitoring of all seepage flows and drain flows, provide more valuable monitoring information and data regarding the possible initiation/development of seepage-related potential failure modes. This monitoring, in conjunction with monitoring of water pressures and subsurface water levels, will help detect changes at all areas of the site, and not just at a limited number of monitored points where water pressure monitoring instruments happen to be located. It also is worth noting that drilling in embankment dams can possibly result in hydraulic fracturing of materials, if not done carefully, with proper equipment, methods, and controls. Consequently such drilling to install instruments such as piezometers or observation wells in or beneath embankment dams should only be carried out when the risks and benefits of the work are carefully and fully assessed, and appropriate steps are taken so that hydraulic fracturing of materials is avoided.

4.2 PFM – Monitoring Relationship for Earthquake-Related Potential Failure Modes for Embankment Dams

Embankment dams subjected to earthquake shaking historically have shown a wide range of responses from rare cases of rapid catastrophic failure to no damage (Seed et al., 1977). It is important to regularly collect and maintain baseline information including instrumentation readings, visual observations, survey information, etc. so that a prompt assessment of earthquake-related changes and damage to the dam can be effectively made after the earthquake.

Table 2 below shows some monitoring considerations associated with one earthquake-related potential failure mode for embankment dams, for illustration purposes. Table A2 in Appendix A provides similar information for a number of other earthquake-related potential failure modes for embankment dams. Again, as has been indicated previously, these tables are intended only as examples of monitoring activities that might be undertaken, and the specific circumstances at a damsite need to be considered so that an appropriate, customized monitoring program is provided for any particular potential failure mode for any particular dam. The specific circumstances of a dam and damsite will also need to be considered when determining the appropriate monitoring frequencies (which are not specified in Tables 2 and A2).

Table 2.

Monitoring Considerations Regarding an Earthquake-Related Potential Failure Mode for an Embankment Dam (See Table A2 in the Appendix for information regarding some other earthquake-related potential failure modes for embankment dams.)	
Potential Failure Mode (PFM)	***Monitoring Considerations***
<u>Seepage-related failure in the aftermath of an earthquake due to the formation of a transverse crack in the dam</u>, where seepage flows through the crack and eventually erodes a breach in the dam.	• Periodically obtain readings at all seepage and drain flow monitoring locations, to maintain baseline information to use for comparison purposes in the aftermath of significant seismic shaking at the damsite. • In the aftermath of significant seismic shaking at the damsite, perform an immediate visual inspection of the dam that includes inspection of: **(1) the downstream slope and toe area of the dam embankment, and downstream areas**, looking for signs of new seepage or wet areas, changes at existing seepage/wet areas, and any evidence that material may be being transported with any seepage flows (such as discolored or turbid water, sediment deposits, etc.); **(2) the dam crest**, looking for sinkholes, depressions, longitudinal cracks, horizontal displacements, and, in particular, for evidence of transverse cracks; **(3) the upstream slope** for signs of sinkholes, depressions, and areas of unusual or excessive settlements or deformations; and **(4) the reservoir water surface** for whirlpools. • In the aftermath of significant seismic shaking at the damsite, promptly obtain readings at all seepage and drain flow monitoring locations and evaluate the data for changed conditions from normal historical performance. [It may be appropriate to automate the monitoring of some of these installations, and consideration might be given to employing a seismic trigger that results in frequent readings following significant seismic shaking.] • Consider whether seismic monitoring equipment with telemetry would be appropriate for the damsite.

Whether the seismic shaking at a damsite is "significant," warranting an inspection of the dam, can be determined in various ways, including using guidance information from ICOLD Bulletin 62 (1988): "an earthquake occurs or one has been reported to have occurred with Richter magnitude of 4.0 or greater within a 25 km radius, 5.0 or greater within 50 km, 6.0 or greater within 80 km, 7.0 or greater within 125 km, or 8.0 or greater within a 200 km radius from the site." Other criteria include using a measured or estimated peak ground acceleration at the damsite (e.g. inspect if 0.05g or greater), and using customized fragility values developed for the dam in conjunction with measured or estimated peak ground acceleration information. If seismic shaking is felt at the damsite, then such seismic shaking should always be viewed to be “significant,” warranting a prompt inspection of the dam.

A prompt response, when warranted in the aftermath of an earthquake, is imperative to facilitate quick detection of changed conditions at the damsite. This will allow immediate emergency evacuations of the reservoir and/or the downstream population-at-risk. Where the risk of earthquake-related dam failure is significant and seismic events are prevalent, automated and/or remote detection capabilities may be appropriate. Clearly such capabilities must be designed to operate during and following a seismic event and still deliver the required information to personnel responsible for monitoring of the project.

Several key concepts emerge when thinking about a dam safety monitoring program associated with potential failure under earthquake loading conditions:

1. The routine monitoring program often involves obtaining and maintaining a good baseline of “pre-earthquake” conditions, so that whenever an earthquake may occur, sufficient information is available for comparison to post-event conditions to determine what changes that may have occurred as a result of the earthquake.

2. Nothing can be done during the seismic event to prevent dam failure. Hopefully earthquake-related issues with the dam have been recognized and addressed through the PFMA process prior to the occurrence of the earthquake. In a highly seismic area, development of a post-earthquake recovery plan might be appropriate.

3. It may be appropriate to consider installing seismic monitoring equipment with telemetry at the damsite. Such equipment would be helpful in determining the intensity of shaking at the site and thus whether a post-earthquake inspection is warranted, and the relative urgency of such an inspection for prioritizing an organizations’s post-earthquake response when a number of facilities may have potentially been affected by the earthquake. Also the information obtained from strong motion recordings can be helpful in evaluating the validity of the assumptions used in dynamic analysis work done for the dam. (Ik-Soo et al., 2009)

4.3 PFM – Monitoring Relationship for Concrete Dam Potential Failure Modes Under Normal, Flood, and Earthquake Loading Conditions

The majority of failures of concrete dams are caused by problems in their foundations (CETS, 1983). Foundation deficiencies that can cause foundation-related failures at concrete dams include weak bedding planes, foliation, low-strength layers in the foundation, shear zones, solution cavities, and weak contacts between different rock units. Weaknesses in the foundations of concrete structures should be treated during the design and construction of the project. However, one of the valuable aspects of the PFMA process is the ability to identify gaps in available information and analyses, particularly with respect to older dams. Construction photographs can indicate areas of weakness in the foundation, and can be quite valuable.

Another important category of potential failure modes for concrete dams is the potential for sliding or separation along lift lines within the dam. Flood and/or earthquake loads can add sufficient driving force to transform a marginally stable condition under normal loading conditions into a dam failure.

For many concrete dam failure modes, one failure mechanism can translate into three potential failure modes; one mode for static (normal) loading, a second mode under flood loading, and a third mode under earthquake loading.

Table 3 below shows some monitoring considerations associated with one concrete dam potential failure mode, for illustration purposes. Table A3 in Appendix A provides similar information for a number of other potential failure modes for concrete dams. Again, these tables are intended only as examples of monitoring activities that might be undertaken, and the specific circumstances at a damsite need to be considered so that an appropriate, customized monitoring program is provided for any particular potential failure mode for any particular dam. The specific circumstances of a dam and damsite will also need to be considered when determining the appropriate monitoring frequencies which are not specified here.

Table 3.

Monitoring Considerations for a Concrete Dam Potential Failure Mode (See Table A3 in the Appendix for information regarding some other concrete dam potential failure modes)	
Potential Failure Mode (PFM)	***Monitoring Considerations***
<u>Loss of abutment support, due to movement of a block or wedge of abutment rock</u> that leads to overstressing and failure of the dam's concrete and sudden dam failure. This potential failure mode could conceivably initiate under normal operating conditions, but the greatest concerns exist in the event of seismic shaking or additional reservoir loads in a	• Regularly monitor foundation drain flows from abutment areas, looking for unusual increases or decreases in flows. • Regularly monitor water pressures from abutment piezometers, looking for unusual increases or decreases in water levels. • Regularly monitor foundation uplift pressures to make sure that pressures near the abutments are within expected performance limits. • Regularly monitor abutment seepage flows, looking for unusual increases or decreases from historical patterns. • Regularly visually inspect the downstream face of the dam and the gallery walls, floors, and ceilings for evidence of new cracks or significant changes at existing cracks. • Provide scribe marks in gallery wall and floor locations at each joint between blocks in the dam that can be visually inspected for evidence of relative offsets. Regularly inspect the scribe marks for such offsets.

Table 3.

Monitoring Considerations for a Concrete Dam Potential Failure Mode (See Table A3 in the Appendix for information regarding some other concrete dam potential failure modes)	
Potential Failure Mode (PFM)	***Monitoring Considerations***
flood that may be sufficient to lead to initiation of movement of the rock block or wedge and consequent dam failure.	• Periodically perform surveys of structural measurement points on the dam, looking for evidence of unusual settlements or deflections, and to maintain baseline survey information to use for comparison purposes in the aftermath of an earthquake or major flood event. • Regularly monitor gate operations and gate testing results for difficulties in operation which may be caused by dam deformations resulting from foundation movements, misalignment and/or movement of monoliths. • In the aftermath of significant seismic shaking at the damsite, perform an immediate visual inspection of the dam (looking for changed cracking conditions) and scribe marks (looking for offsets), and promptly obtain readings of the foundation drain flows, abutment piezometers, foundation uplift pressures, and abutment seepage flows. Perform a survey of the structural measurement points if appropriate. • During a major flood event, perform frequent instrumented monitoring of foundation drain flows, abutment piezometers, foundation uplift pressures, and abutment seepage flows, and perform frequent visual monitoring for possible scribe mark offsets and changed crack conditions at the dam. Perform a survey of the structural measurement points at the conclusion of the flood event, as appropriate.

As seen in Tables 3 and A3, the potential failure modes for concrete dams can relate to possibly unidentified foundation weaknesses (e.g., sliding planes, blocks or wedges of abutment rock that could displace, faults in the foundation that could be active, etc.) which may pose a threat to dam safety. Monitoring to address such PFMs includes vigilant visual surveillance programs, documentation of observations to create a historic log of responses during various loading conditions, measurement point surveys, water pressure data, seepage data, and flow records and performance monitoring information regarding foundation drains. Re-evaluation of the dam’s stability based on postulated conditions may be required to provide a sense of the predicted response of the dam, and to identify the need to address potential shortcomings.

Regular observations during high reservoir levels and following the passage of a flood event provide knowledge of the response of the dam under these conditions.

Documentation of observations provides a sense of the dam's ability to safely withstand extreme loading conditions.

4.4 PFM – Monitoring Relationship for Flood-Related Potential Failure Modes Associated with Spillway Failure

Spillway erosion failure historically has been shown to be the root cause of nearly half of the embankment dam failures that have occurred during flood events (ASCE/USCOLD, 1975). A number of potential failure modes can be identified relative to this failure mode category.

Table 4 below shows some monitoring considerations associated with one spillway-related potential failure mode, for illustration purposes. Table A4 in Appendix A provides similar information for a number of other spillway-related potential failure modes. Again, these tables are intended only as examples of monitoring activities that might be undertaken, and the specific circumstances at a damsite need to be considered so that an appropriate, customized monitoring program is provided for any particular potential failure mode for any particular dam. The specific circumstances of a dam and damsite will also need to be considered when determining the appropriate monitoring frequencies, which are not specified here.

Table 4.

Monitoring Considerations Regarding a Flood-Related Potential Failure Mode Associated with Spillway Failure (See Table A4 in the Appendix for information regarding some other flood-related potential failure modes associated with spillway failure)	
Potential Failure Mode (PFM)	***Monitoring Considerations***
<u>Spillway flow surfaces have flaws such that when subjected to large flows, cavitation or stagnation results</u>, leading to structural damage to the spillway and initiating a headward erosion process that eventually reaches the reservoir and results in uncontrolled reservoir releases	• Perform routine visual inspections of the flow surfaces for offsets at joints, areas of deteriorated concrete, and other imperfections in the flow surfaces that could give rise to this PFM when large discharges through the spillway are made during a flood event. Also observe for debris that needs to be removed from the spillway. • Perform routine visual inspections in the spillway gallery to identify anomalies, displacements, etc. which may contribute to or be indicative of irregular flow surfaces. • Perform close surveillance during spillway discharges for evidence of unusual flow patterns that could indicate problems with flow surfaces (such as rooster tails, obvious flow irregularities at joints, etc.) to (1) document performance for future analysis of this PFM, and (2) detect indications that this PFM may have initiated and could develop to the point that spillway failure is possible (for dam failure warning reasons). Surveillance efforts should include photographs and videos.

Table 4.

Monitoring Considerations Regarding a Flood-Related Potential Failure Mode Associated with Spillway Failure (See Table A4 in the Appendix for information regarding some other flood-related potential failure modes associated with spillway failure)	
Potential Failure Mode (PFM)	***Monitoring Considerations***
	• Perform a careful post-flood inspection to assess damage to the spillway that may have occurred (to determine if a re-evaluation of the risks associated with this PFM is warranted).

For this category of potential failure modes, several key concepts emerge when thinking about a dam safety monitoring program:

1. The routine monitoring program often involves obtaining and maintaining a good baseline of pre-flood conditions, so that when a flood event occurs, sufficient information is available for comparison to post-event conditions to determine what changes may have occurred during the flood event.

2. Careful monitoring during small flood events can identify performance problems that could result in potential threats to dam safety during a large event. Such "full-scale prototype testing" can provide a unique opportunity to obtain valuable information if advance preparations have been made to document performance during small flood events.

3. Nothing can be done during the flood event to prevent spillway failure. (Hopefully problems with the spillway have been recognized and addressed through the PFMA process prior to the occurrence of the large flood event.) During the flood event, the monitoring work involves documenting performance and being in a position to recognize when spillway failure may be imminent such that timely warnings can be issued and evacuation initiated for people located downstream of the dam.

5.0 SURVEILLANCE/MONITORING DATA RELATIONSHIP WITH IDENTIFYING AND EVALUATING POTENTIAL FAILURE MODES

The information provided in the previous four sections focused on detection of the possible initiation/development of identified potential failure modes, or detection of conditions that might make such initiation/development more likely. As noted previously, another role of instrumented monitoring and visual surveillance is to evaluate the significance and probability of a particular potential failure mode and its related risk. Information from instrumented and visual monitoring programs can improve the understanding of the potential risks associated with a potential failure mode.

Tables 1 through 4 and Tables A1 through A4 provide a good sense of monitoring information that may be central to a better understanding of the various potential failure modes listed. In some cases, instrumentation data will not help identify potential failure modes. In others, the availability or lack of availability of particular monitoring data can have a big impact on PFMA conclusions. Often, some but not all desired monitoring information may be available, and the PFMA team may find that the available information: (1) is sufficient to reach important conclusions about the potential failure mode, (2) is insufficient for reaching any conclusions, or (3) is useful, but important issues remain unresolved. A possible outcome from the PFMA process may be that more performance monitoring information/data are needed and the situation will need to be re-visited when sufficient new data become available.

6.0 CONCLUDING REMARKS

Routine dam safety surveillance and monitoring methods/programs using instrumented and visual monitoring methods are important to the PFMA process in two basic ways: (1) to help in identifying potential dam safety threats during the PFMA work itself, and (2) as an output of the PFMA, monitoring can provide timely detection of the initiation/progression of potential failure modes so that timely actions can be taken to prevent dam failure, or allow timely evacuation so that loss of life is minimized.

The quality of the surveillance and monitoring efforts will determine the extent to which the potential benefits are achieved. With clear focus on the ultimate goals of the PFMA activity, appropriate expertise and experience, and a willingness to be creative and unconventional in approach when necessary, the benefits expected from the surveillance and monitoring program should be achievable and an effective surveillance and monitoring program can be developed and implemented.

7.0 REFERENCES

ASCE/USCOLD (1975), “Lessons from Dam Incidents, USA,” Prepared by the Committee on Failures and Accidents to Large Dams, Jacob F. Redlinger, Chairman, United States Committee on Large Dams, and American Society of Civil Engineers, 1975.

ASCE/USCOLD (1988), “Lessons from Dam Incidents, USA-II”, United States Committee on Large Dams and American Society of Civil Engineers, 1988.

ASCE (2000), “Guidelines for Instrumentation and Measurements for Monitoring Dam Performance”, Reston Virginia, 2000.

CETS (1983), “Safety of Existing Dams: Evaluation and Improvement,” Commission on Engineering and Technical Systems, Report Prepared by Committee on the Safety of Existing Dams, National Research Council, 1983.

FEMA (2004), "The Federal Guidelines for Dam Safety: Glossary of Terms," prepared by the Interagency Committee on Dam Safety, FEMA 148.
http://www.ferc.gov/industries/hydropower/safety/guidelines/fema-148.pdf

FERC (2005), "Engineering Guidelines for the Evaluation of Hydropower Projects – Chapter 14, Dam Safety Performance Monitoring Program."
http://www.ferc.gov/industries/hydropower/safety/guidelines/eng-guide/chap14.pdf

FERC (2008), "Appendix J – Dam Safety Surveillance and Monitoring Plan Outline; Appendix K – Dam Safety Surveillance and Monitoring Report Outline," prepared as part of Engineering Guidelines for the Evaluation of Hydropower Projects, Chapter 14.
http://www.ferc.gov/industries/hydropower/safety/guidelines/eng-guide/appendices-j-k.pdf

Foster, Mark; Fell, Robin; and Spannagle, M. (2000), "The Statistics of Embankment Dam Failures and Accidents," Canadian Geotechnical Journal, 2000.

ICOLD (1988), "Inspection of Dams – Following Earthquake – Guidelines," Bulletin 62, 1988.

Ik-Soo, Ha, and Oh Byung-Hyunh (2009), "Inverse Calculation of Shearwave Velocity of Rockfill Zone Using Microearthquake Records", United States Society on Dams 29th Annual Conference, Nashville, Tennessee, April 2009.

Seed, H. Bolton, F.I.Makdisi, P. de Alba (1977), "The Performance of Earth Dams During Earthquakes", College of Engineering, University of California, Berkeley, California, Earthquake Engineering Research Center Report No. UCB/EERC-77/20, August, 1977.

Stateler, Jay N., Von Thun, L., Scott, Gregg, and Boernge, Jim (1995), "Development of Performance Parameters for Dam Safety Monitoring," Proceedings of the 1995 Annual Conference of the Association of State Dam Safety Officials, September 1995.

APPENDIX A
ADDITIONAL EXAMPLE TABLES RELATING POTENTIAL FAILURE MODES AND MONITORING CONSIDERATIONS

The tables included in this appendix are intended only as **examples** of monitoring activities that might be undertaken with respect to the indicated potential failure modes, and the specific circumstances at a damsite need to be considered so that an appropriate, customized monitoring program is provided for any particular potential failure mode for any particular dam. The specific circumstances of a dam and damsite will also need to be considered when determining the appropriate monitoring frequencies (which are not specified in the tables included in this appendix). The tables included in this appendix supplement the information provided previously in Tables 1, 2, 3, and 4.

Important Note: The tables included in this appendix may appear to be daunting in terms of the volume of information presented, and also can be seen to have numerous instances of repeated material in the "Monitoring Considerations" column (since similar information can apply to a number of different potential failure modes). However, the intent of this appendix is to give the reader the opportunity to access information regarding the particular potential failure mode (or potential failure modes) of current interest to the reader, as opposed to providing a write-up that is intended to be read from beginning to end. To effectively meet the reader's needs with respect to a particular potential failure mode, the information provided must be complete, tailored specifically to that potential failure mode, and not rely on the reader having also read information provided regarding other potential failure modes in this appendix. With this intent and understanding in mind, it is hoped that this appendix might be seen as more in the vein of an encyclopedia than a novel, and is found to provide a useful resource for potential failure mode-specific discussions to meet the reader's needs as they might arise both now and in the future.

Table A1.
(Supplements information previously provided in Table 1)

Monitoring Considerations Regarding Seepage-Related Potential Failure Modes for Embankment Dams Under Normal Operating Conditions and Flood Loading Conditions	
Potential Failure Mode (PFM)	***Monitoring Considerations***
Seepage-related failure due to breaching, caused by **flow through the dam foundation or dam abutments** that erodes and transports foundation or abutment material and exits in areas downstream of	• Perform regular visual inspections of the dam and damsite that include inspection of: **(1) the downstream toe area, areas downstream of the dam, and downstream abutment areas,** looking for sinkholes, depressions, signs of new seepage or wet areas, changes at existing seepage/wet areas, and any evidence that material may be being transported with any seepage flows (such as discolored or turbid water, sediment deposits, etc.); **(2) the upstream and downstream slopes and the dam crest,** looking for sinkholes, depressions, and areas

Table A1.

(Supplements information previously provided in Table 1)

Monitoring Considerations Regarding Seepage-Related Potential Failure Modes for Embankment Dams Under Normal Operating Conditions and Flood Loading Conditions	
Potential Failure Mode (PFM)	***Monitoring Considerations***
the dam or at downstream abutment areas or Seepage-related failure due to breaching, caused by **<u>flow through the dam embankment and into the dam foundation or dam abutments</u>** that erodes and transports embankment material and exits in areas downstream of the dam or at downstream abutment areas	of unusual settlement or deflection (e.g. deformed guardrails); and **(3) of the reservoir water surface,** looking for whirlpools. Photographic documentation should occur when unusual/unexpected conditions are observed. • Regularly monitor seepage flows associated with flow exiting in downstream or abutment areas looking for increased flows that are out of line with historical behavior, and particularly looking for any evidence of possible material transport by the flow (such as discolored or turbid water, sediment deposits along flow paths, behind weirs, in weir boxes, etc.). • Regularly monitor water pressures from piezometers and observation wells located in the dam foundation and areas downstream of the dam, looking for increasing or decreasing trends, or any otherwise anomalous data. • During a major flood event, when reservoir levels are unusually high, perform frequent visual and instrumented monitoring as described above.
Seepage-related failure due to breaching, caused by **<u>flow through the dam embankment or foundation along the alignment of the outlet works</u>** that erodes and transports embankment or foundation material and exits in the general vicinity of the downstream end of the outlet works	• Perform regular visual inspections of the dam and damsite in the vicinity of the alignment of the outlet works that include inspection of: **(1) the downstream slope and toe area of the dam embankment, and areas downstream of the outlet works discharge structure,** looking for animal burrows, sinkholes, depressions, areas of unusual settlements, signs of new seepage or wet areas, changes at existing seepage/wet areas, and any evidence that material may be being transported with any seepage flows (such as discolored or turbid water, sediment deposits, etc.); **(2) the dam crest and upstream slope,** looking for animal burrows, sinkholes, depressions, and areas of unusual settlement or deflection (e.g. deformed guardrails); and **(3) the reservoir water surface,** looking for whirlpools. Photographic documentation should occur when unusual/unexpected conditions are observed. • Regularly monitor toe drain flows and seepage flows associated with flow through the dam embankment or foundation in the vicinity of the outlet works discharge structure, looking for increased flows or decreased flows

Table A1.
(Supplements information previously provided in Table 1)

Monitoring Considerations Regarding Seepage-Related Potential Failure Modes for Embankment Dams Under Normal Operating Conditions and Flood Loading Conditions	
Potential Failure Mode (PFM)	***Monitoring Considerations***
	that are out of line with historical behavior, and particularly looking for any evidence of possible material transport by the flow (such as discolored or turbid water, sediment deposits along flow paths, behind weirs, in weir boxes, etc.). • Regularly monitor water pressures from piezometers and observation wells located in the dam embankment and foundation in the vicinity of the outlet works, looking for anomalous data that are inconsistent with historical performance. • During a major flood event, when reservoir levels are unusually high, perform frequent visual and instrumented monitoring as described above.
Seepage-related failure due to breaching, caused by <u>**flow through the dam embankment or foundation that exits into the outlet works**</u> through cracks, joint openings, etc. and erodes and transports embankment or foundation material into and through the outlet works	• Perform regular visual inspections of flow discharged from the outlet works, looking for any evidence of possible material transport by the flow (such as discolored or turbid water, sediment deposits along flow paths, etc.). • Perform regular visual inspections of the dam and damsite in the vicinity of the alignment of the outlet works that include inspection of: **(1) of the dam crest, upstream slope, and downstream slope,** looking for sinkholes, depressions, and areas of unusual settlements, and **(2) the reservoir water surface,** looking for whirlpools. Photographic documentation should occur when unusual/unexpected conditions are observed. • Regularly monitor water pressures from piezometers and observation wells located in the dam embankment and foundation in the vicinity of the outlet works, looking for anomalous data that are inconsistent with historical performance. • During a major flood event, when reservoir levels are unusually high, perform frequent visual and instrumented monitoring as described above. • Occasionally perform camera inspections or dive inspections of the interior of the outlet works, looking for evidence of cracks, deterioration, joint openings, settlement/collapse, blockage, etc. and any evidence of seepage water entering the outlet works conduit.

Table A1.

(Supplements information previously provided in Table 1)

Monitoring Considerations Regarding Seepage-Related Potential Failure Modes for Embankment Dams Under Normal Operating Conditions and Flood Loading Conditions	
Potential Failure Mode (PFM)	***Monitoring Considerations***
Seepage-related failure due to breaching, caused by **<u>pressurized flow exiting from the outlet works conduit</u>** that erodes and transports embankment or foundation material along the alignment of the outlet works and exits in the general vicinity of the downstream end of the outlet works	• Perform regular visual inspections of the dam in the vicinity of the alignment of the outlet works that include inspection of: **(1) the downstream slope and toe area of the dam embankment, and areas downstream of the outlet works discharge structure,** looking for sinkholes, depressions, areas of unusual settlements, signs of new seepage or wet areas, changes at existing seepage/wet areas, and any evidence that material may be being transported with any seepage flows (such as discolored or turbid water, sediment deposits, etc.), and **(2) of the dam crest and upstream slope of the dam,** looking for sinkholes, depressions, and areas of unusual settlements. Photographic documentation should occur when unusual/unexpected conditions are observed. • Regularly monitor toe drain flows and seepage flows associated with flow through the dam embankment or foundation in the vicinity of the outlet works discharge structure, looking for increased flows that are out of line with historical behavior, and particularly looking for any evidence of possible material transport by the flow (such as discolored or turbid water, sediment deposits along flow paths, behind weirs, in weir boxes, etc.). • Regularly monitor water pressures from piezometers and observation wells located in the dam embankment and foundation in the vicinity of the outlet works, looking for increasing or decreasing trends, or any otherwise anomalous data. • During a major flood event, when reservoir levels are unusually high, perform frequent visual and instrumented monitoring as described above. • Occasionally perform camera inspections or dive inspections of the interior of the outlet works, looking for evidence of cracks, deterioration, joint openings, settlement/collapse, blockage, etc. and any evidence of seepage water entering or exiting the outlet works conduit.

Table A2.
(Supplements information previously provided in Table 2)

Monitoring Considerations Regarding Earthquake-Related Potential Failure Modes for Embankment Dams	
Potential Failure Mode (PFM)	***Monitoring Considerations***
<u>Seepage-related failure in the aftermath of an earthquake due to any of the potential failure modes identified under normal operating conditions</u>. Seismic shaking may lead to disruption/damage that results in potential failure mode initiation.	• Periodically obtain readings at all seepage and drain flow monitoring locations, and at all piezometers and observation wells, to maintain baseline information to use for comparison purposes in the aftermath of an earthquake. • Periodically perform surveys of the embankment measurement points on the dam, to maintain baseline survey information to use for comparison purposes in the aftermath of an earthquake. • Immediately after significant seismic shaking at the damsite, inspect the dam including: **(1) the downstream slope and toe area of the dam embankment, downstream areas, and abutment areas** looking for signs of sinkholes, depressions, new seepage or wet areas, changes at existing seepage/wet areas, and any evidence that material may be being transported with any seepage flows (such as discolored or turbid water, sediment deposits, etc.); **(2) the downstream channel area** for unusual quantities of flow that may be due to underseepage exiting into the channel, and for evidence of material transport by underseepage that may exit into the channel; **(3) all areas of the dam embankment** for cracks, sinkholes, and areas of unusual or excessive settlements or deformations; **(4) the reservoir water surface** for whirlpools, and **(5) of discharges from the outlet works**, looking for evidence of material transport with the discharges. • Immediately after significant seismic shaking at the damsite, promptly obtain readings at all seepage and drain flow monitoring locations and evaluate the data for changes from normal performance. Obtain water pressure data from piezometers and observation wells, and evaluate the data for changes. It may be appropriate to automate the monitoring of some of the flow and water pressure monitoring instruments, and consideration might be given to employing a seismic trigger that results in frequent readings following significant seismic shaking. Survey the embankment measurement points at the dam. • Consider whether seismic monitoring equipment with telemetry would be appropriate for the damsite.

Table A2.
(Supplements information previously provided in Table 2)

Monitoring Considerations Regarding Earthquake-Related Potential Failure Modes for Embankment Dams	
Potential Failure Mode (PFM)	***Monitoring Considerations***
<u>**Seepage-related failure in the aftermath of an earthquake due damage to the outlet works such that pressurized water escapes**</u>, erodes embankment material along the outlet works, and eventually results in a dam breach	• Periodically obtain readings at all seepage and drain flow monitoring locations located proximate to the outlet works, and at all piezometers and observation wells located proximate to the outlet works, to maintain baseline information to use for comparison purposes in the aftermath of an earthquake. • In the aftermath of significant seismic shaking at the damsite, perform an immediate visual inspection of the dam in the vicinity of the outlet works that includes inspection of: **(1) the downstream slope and toe area of the dam embankment in the vicinity of the outlet works**, looking for signs of new seepage or wet areas, changes at existing seepage/wet areas, and any evidence that material may be being transported with any seepage flows (such as discolored or turbid water, sediment deposits, etc.); **(2) the dam crest**, looking for sinkholes, depressions, longitudinal cracks, and transverse cracks; **(3) the upstream slope** for signs of sinkholes, depressions, and areas of unusual or excessive settlements or deformations; **(4) the reservoir water surface** for whirlpools. • Immediately after significant seismic shaking at the damsite, promptly obtain readings at all seepage and drain flow monitoring locations located proximate to the outlet works, and evaluate the data for changed conditions from normal historical performance. Also, obtain water pressure data from piezometers and observation wells located proximate to the outlet works, and evaluate the data for changed conditions from normal historical performance. [It may be appropriate to automate the monitoring of some of the flow and water pressure monitoring instruments, and consideration might be given to employing a seismic trigger that results in frequent readings following significant seismic shaking.] • Consider whether seismic monitoring equipment with telemetry would be appropriate for the damsite.
<u>**Earthquake-related damage to the outlet works intake structure, and the**</u>	• In the aftermath of significant seismic shaking at the damsite, perform an immediate visual inspection of the outlet works discharge amount, looking for unusually high discharges, and of the outlet works intake structure,

Table A2.

(Supplements information previously provided in Table 2)

Monitoring Considerations Regarding Earthquake-Related Potential Failure Modes for Embankment Dams	
Potential Failure Mode (PFM)	***Monitoring Considerations***
control gates located there, such that uncontrolled reservoir releases occur through the damaged outlet works	looking for evidence of dam to the structure. Consider whether providing telemetered downstream discharge information and/or video camera feeds from the damsite are appropriate. • Consider whether seismic monitoring equipment with telemetry would be appropriate for the damsite. • In the aftermath of significant seismic shaking at the damsite, test operate the outlet works to determine if they have been damaged. • In the aftermath of significant seismic shaking at the damsite, perform a survey of structural measurement points on the outlet works intake structure to assess deformations/damage.
Earthquake-induced liquefaction of foundation and/or embankment materials, that results in dam instability, and consequent overtopping and breaching OR **Earthquake-caused dam deformations resulting in overtopping of the dam embankment**, and consequent erosion and breaching of the dam embankment	• All that can be done relative to this failure mechanism, that involves essentially "immediate" dam failure in the aftermath of an earthquake, is to promptly detect failure of the dam, and immediately proceed with downstream evacuations in accordance with the Emergency Action Plan. If significant dam deformations have occurred, but little or no dam overtopping is currently occurring, efforts can be made to quickly evacuate the reservoir (to the extent possible), as well as proceeding with downstream evacuations. • Consider whether seismic monitoring equipment with telemetry would be appropriate for the damsite. • In the aftermath of significant seismic shaking at the damsite, if no reservoir overtopping is evident, an evaluation should be made to determine if the reservoir is being released through foundation discontinuities, seepage paths through partially liquefied strata, damaged outlet works structures, etc. • In the aftermath of significant seismic shaking at the damsite, seepage and flow measurements and visual observations along the downstream toe and downstream area should be performed to assess possible changes due to the seismic shaking.

Table A3.
(Supplements information previously provided in Table 3)

Monitoring Considerations for Concrete Dam Potential Failure Modes Under Normal, Flood, and Earthquake Loading Conditions	
Potential Failure Mode (PFM)	***Monitoring Considerations***
<u>Blockage of foundation drain holes due to calcite or iron sludge buildup leads to an increase in uplift pressures in the foundation, that ultimately leads to sliding</u> failure in the foundation or at the dam/foundation contact. Alternatively, the situation may be marginally stable under normal operating conditions, but seismic shaking or additional reservoir loads in a flood lead to sliding failure in the foundation or at the dam/foundation contact.	• Regularly monitor foundation drain flows, looking for unusual increases or decreases in flows. • Regularly monitor foundation uplift pressures to make sure that pressures are within expected performance limits. • Provide scribe marks (or employ other methods) in gallery wall and floor locations at each joint between blocks in the dam that can be visually inspected for evidence of relative offsets. Regularly inspect scribe marks for such offsets. • Inspect foundation drain outfalls, looking for visual evidence of clogging, blockage, sludge buildup, etc. that needs to be addressed. • Survey structural measurement points on the dam, looking for evidence of unusual downstream deflections and to maintain baseline survey information to use for comparison purposes after an earthquake or major flood event. • Institute and maintain a regular foundation drain cleaning program to prevent clogging or blockage of foundation drains. • In the aftermath of significant seismic shaking at the damsite, perform an immediate visual inspection of the scribe marks (looking for new offsets), and promptly obtain readings of the foundation drain flows and foundation uplift pressures. Perform a survey of the structural measurement points. • During a major flood event, perform frequent instrumented monitoring of foundation drain flows and foundation uplift pressures, and frequent visual monitoring for possible scribe mark offsets. Perform a survey of the structural measurement points at the conclusion of the flood event.
<u>Sliding failure at the dam/foundation contact due to poor bonding of the dam's concrete to the foundation rock, and insufficient keying at</u>	• Regularly visually inspect the downstream face of the dam and the gallery walls, floors, and ceilings for evidence of new cracks or significant changes at existing cracks. • Provide scribe marks in gallery wall and floor locations at each contraction joint that can be visually inspected for evidence of relative offsets. Regularly inspect the scribe

Table A3.

(Supplements information previously provided in Table 3)

Monitoring Considerations for Concrete Dam Potential Failure Modes Under Normal, Flood, and Earthquake Loading Conditions	
Potential Failure Mode (PFM)	***Monitoring Considerations***
<u>this contact</u>. This potential failure mode could conceivably initiate under normal operating conditions, but the greatest concerns exist in the event of seismic shaking or additional reservoir loads in a flood, that may be sufficient to lead to slide initiation and consequent dam failure.	marks for such offsets. • Periodically perform surveys of structural measurement points on the dam, looking for evidence of unusual downstream deflections and to maintain baseline survey information to use for comparison purposes in the aftermath of an earthquake or major flood event. • In the aftermath of significant seismic shaking at the damsite, perform an immediate visual inspection of the scribe marks (looking for new offsets), perform a prompt inspection of the galleries and downstream face of the dam (looking for changed cracking conditions), and promptly obtain readings of the foundation drain flows and foundation uplift pressures. Perform a survey of the structural measurement points. • During a major flood event, perform frequent visual monitoring for possible scribe mark offsets, and for evidence of changed crack conditions in the galleries and at the downstream face of the dam. Perform a survey of the structural measurement points at the conclusion of the flood event.
<u>Sliding failure between lift lines in the dam due to disbonded lift lines, and insufficient keying between lift lines</u>. This potential failure mode could conceivably initiate under normal operating conditions, but the greatest concerns exist in the event of seismic shaking or additional reservoir loads in a flood, that may be sufficient to lead to slide initiation and consequent dam failure.	• Regularly visually inspect the downstream face of the dam and the gallery walls, floors, and ceilings for evidence of new cracks or significant changes at existing cracks. • Regularly visually inspect the downstream face of the dam for significant changes in historic patterns of lift line seepage. • Provide scribe marks in gallery wall and floor locations at each contraction joint that can be visually inspected for evidence of relative offsets. Regularly inspect the scribe marks for such offsets. • Periodically perform surveys of structural measurement points on the dam, looking for evidence of unusual downstream deflections and to maintain baseline survey information to use for comparison purposes in the aftermath of an earthquake or major flood event. • Periodically inspect galleries, where possible, for signs of cracking, wetness, flow, displacement, etc. • In the aftermath of significant seismic shaking at the damsite, perform an immediate visual inspection of the

Table A3.

(Supplements information previously provided in Table 3)

Monitoring Considerations for Concrete Dam Potential Failure Modes Under Normal, Flood, and Earthquake Loading Conditions	
Potential Failure Mode (PFM)	***Monitoring Considerations***
	scribe marks, and perform a prompt inspection of the galleries and downstream face of the dam (looking for changed cracking conditions). Perform a survey of the structural measurement points if appropriate. • During a major flood event, perform frequent visual monitoring for possible scribe mark offsets, and for evidence of changed crack conditions in the galleries and at the downstream face of the dam. Perform a survey of the structural measurement points at the conclusion of the flood event, as appropriate.
Loss of foundation support and overstressing of the dam's concrete, leading to sudden dam failure, due to **offsets occurring along a fault in the dam foundation**	• Periodically perform surveys of structural measurement points on the dam to maintain baseline survey information to use for comparison purposes in the aftermath of an earthquake. • Periodically perform dive inspections of the upstream and downstream faces to observe and document the condition of the foundation to structure interface. • In the aftermath of significant seismic shaking at the damsite, perform an immediate visual inspection of the dam (looking for changed cracking conditions) and scribe marks (looking for offsets), and promptly obtain regarding all seepage and drain flows, and all water pressure monitoring instruments at the damsite. Perform a survey of the structural measurement points if appropriate.
Corrosion of upstream foundation anchor tendons leads to loss of pre-stress force. Sliding instability results under normal, flood or earthquake loading conditions.	• Regularly visually inspect portions of the tendon anchor system that can be viewed. • Regularly visually inspect the downstream face of the dam and the gallery walls, floors, and ceilings for evidence of new cracks or significant changes at existing cracks. • Provide scribe marks in gallery wall and floor locations at each contraction joint that can be visually inspected for evidence of relative offsets. Regularly inspect the scribe marks for such offsets. • Periodically perform surveys of structural measurement points on the dam, looking for evidence of unusual downstream deflections and to maintain baseline survey information to use for comparison purposes in the

Table A3.
(Supplements information previously provided in Table 3)

Monitoring Considerations for Concrete Dam Potential Failure Modes Under Normal, Flood, and Earthquake Loading Conditions	
Potential Failure Mode (PFM)	***Monitoring Considerations***
	aftermath of an earthquake or major flood event. • In the aftermath of significant seismic shaking at the damsite, perform an immediate visual inspection of the scribe marks (looking for new offsets), and perform a prompt inspection of the galleries and downstream face of the dam (looking for changed cracking conditions). Perform a survey of the structural measurement points. • During a major flood event, perform frequent visual monitoring for possible scribe mark offsets, and for evidence of changed crack conditions in the galleries and at the downstream face of the dam. Perform a survey of the structural measurement points at the conclusion of the flood event.

Table A4.

(Supplements information previously provided in Table 4)

Monitoring Considerations Regarding Flood-Related Potential Failure Modes Associated with Spillway Failure	
Potential Failure Mode (PFM)	***Monitoring Considerations***
Erosion of the downstream channel that leads to undermining of the foundation of the spillway crest structure, which results in its failure and uncontrolled reservoir releases	• Perform close surveillance during spillway discharges for evidence of significant (unexpected) erosion of the downstream channel (such as turbid water, unusual flow patterns, etc.) to: **(1)** document performance for future analysis of this PFM, and **(2)** detect indications that spillway failure may be imminent (for dam failure warning reasons). Surveillance efforts should include photographs and videos. • Perform a careful post-flood inspection to assess the amount of erosion that actually occurred in the downstream channel, and allow comparison with what was expected (to determine if a re-evaluation of the risks associated with this PFM is warranted).
Overtopping of spillway walls that results in erosion of material along the walls, loss of wall stability, and headward erosion along the spillway alignment until the reservoir is reached and uncontrolled reservoir releases occur	• Perform close surveillance during spillway discharges for evidence of flows overtopping the spillway walls to: **(1)** document performance for future analysis of this PFM, and **(2)** detect indications that spillway failure may be imminent (for dam failure warning reasons). Surveillance efforts should include photographs and videos. • Perform a careful post-flood inspection to assess the amount of erosion that actually occurred due to flows overtopping the walls (to determine if a re-evaluation of the risks associated with this PFM is warranted).
Spillway discharges come in contact of the toe of the dam, cause erosion of the dam, eventually leading to a dam breach	• Perform close surveillance during spillway discharges for evidence of possible development of this PFM (such as flow coming in contact with the toe of the dam, turbid water, evidence of oversteepened and/or eroded embankment material, etc.) to **(1)** document performance for future analysis of this PFM, and **(2)** detect indications that dam failure due to breaching may be imminent (for dam failure warning reasons). Surveillance efforts should include photographs and videos. • Perform a careful post-flood inspection to assess the amount of erosion that actually occurred at the toe of the dam (to determine if a re-evaluation of the risks associated with this PFM is warranted).

Table A4.

(Supplements information previously provided in Table 4)

Monitoring Considerations Regarding Flood-Related Potential Failure Modes Associated with Spillway Failure	
Potential Failure Mode (PFM)	***Monitoring Considerations***
Material is eroded from beneath a spillway floor slab by seepage flow such that when large spillway flows occur, the floor slab fails due to inadequate foundation support and initiates a headward erosion process along the spillway alignment that eventually reaches the reservoir and results in uncontrolled reservoir releases	• Perform routine visual inspections of spillway underdrain flows, foundation drain flows from areas beneath the spillway, and other seepage flows occurring proximate to the spillway for evidence of material transport by the flow. • Perform periodic sounding of spillway floor slabs to check for hollow or drummy sounds that could indicate voids beneath the floor slabs. • Perform periodic dive inspections in the spillway stilling basin, looking for evidence of erosion beneath the spillway floor slabs. • Periodically use ground penetrating radar to check for voids beneath the floor slabs. • Perform close surveillance during spillway discharges for evidence of unusual flow patterns (such as rooster tails, obvious flow irregularities at joints, etc.) that could indicate problems with flow surfaces (possibly due to structural failure of floor slabs) to detect indications that this PFM may have initiated and could develop to the point that spillway failure is possible (for dam failure warning reasons). Surveillance should include photographs and videos. • Perform a careful post-flood inspection to look for evidence of structural distress/failure of flood slabs (such as cracks that appear to be structural in nature) that may be due to inadequate foundation support, to determine if further investigation for possible voids beneath the floor slabs is warranted.

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