GENERALIZED PROGRAMMATIC FRAMEWORK FOR SPILLWAY INSPECTION AND POTENTIAL FAILURE MODES ASSESSMENT

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ABSTRACT

Dam safety risks are increasing for a number of dams as a result of structural aging, deterioration, and downstream floodplain development. Spillways are critical for safe dam operation, responsible for safely passing flood flow without posing danger to the dam structure. An adequately designed and constructed spillway, reliably available, is required to reduce the likelihood of potential failure modes (PFMs) progressing to actual failure. Many spillways are not operated regularly or have never been required to. Often the lack of use is a result of extended drought, water conservation focused reservoir operation or use of other available outlet works. Such infrequent operation has, in some cases, led to false impressions regarding the spillway's purpose and importance, consequently resulting in lack of attention to spillway design and operational adequacy. Regardless of spillway operation frequency, routine inspections and assessment as part of dam safety practice are necessary to identify and remedy deficiencies to lower the likelihood of PFMs developing. The spillway inspection, PFM identification, and assessment can vary depending on the type, structural, geotechnical, drainage, and hydraulic characteristics of the spillway, its age, and historical operation and maintenance. A programmatic and integrated inspection, evaluation, and analysis framework encompassing the variety of spillway types, issues, and PFMs would provide a useful tool for establishing a strategy toward a safer dam infrastructure. This paper emphasizes the importance of spillway assessment as part of dam safety practices and provides a generalized programmatic framework for integrating spillway inspection, PFM identification, assessment, evaluation, and analysis.

INTRODUCTION

Dams are undoubtedly one of the many brilliant innovations of humans, used to harness the flowing energy of Mother Nature and store life-giving water. Dams have played a vital role in providing service (e.g., clean renewable energy, drinking water, irrigation and recreation) and protection (e.g., flood control) to our communities and economy throughout the ages, and their significant role continues in the modern history of the world. The number of dams has rapidly increased with rapid growth of population and

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community development over the past century. When most of the contemporary dams were designed and constructed risk was not considered; instead, conservative design assumptions, criteria and parameters were typically applied to the best of technical knowledge and standard practice at the time. Nowadays, the associated risk can be estimated with the current advancement of risk analysis methods, available rich datasets (e.g., hydrological and geotechnical) and related knowledge (e.g., flood prediction, earthquake analysis, dam failure case histories). With downstream floodplain development, population growth, and considering the estimated risk, numerous dams can be reclassified as high hazard potential, in which the dam failure may result in loss of life and/or significant economic losses. Safe dam operation and appropriate maintenance are vital to sustaining the benefits and mitigating the associated risks. Dam safety is currently receiving more attention because of the increasing overall public awareness about large infrastructure elements (Federal Emergency Management Agency [FEMA] 2013).

Spillways are one of the most critical components of any dam structure, responsible for safely passing flood flow without endangering the dam structure itself. An appropriately designed and constructed spillway structure is required to reduce the likelihood of potential failure modes (PFMs) developing. Unlike outlet works typically used to release service discharges, spillways are generally operated during relatively large hydrologic events. Therefore, many spillways are not operated regularly and in some cases have never been required to. The infrequent operation of spillways in some instances has led to false impressions regarding the importance of the spillway's purpose, sometimes resulting in a lack of enough attention paid to spillway soundness. Most defects and damages to spillway structures develop progressively, leading to incidents with a wide range of hazard potential (i.e., from minor operational issues to dam failure with catastrophic consequences). Therefore, to reduce the risk of PFMs developing, detailed routine inspections and assessment of the spillway, as part of dam safety practices, are necessary to identify existing or potential issues and remedy deficiencies accordingly.

Federal agencies such as the U.S. Army Corps of Engineers (USACE), U.S. Bureau of Reclamation (USBR), Federal Energy Regulatory Commission (FERC) and others have significant roles in the evolving U.S. dam safety practice. The safety guidelines developed by these agencies apply to all major features of dams, including spillways. According to USACE (2014), spillway inspections are generally performed as part of dam inspections. The USACE policy and procedures on the safety of dams are described in detail in *USACE Safety of Dams – Policy and Procedures* (UASCE 2014). Currently, dam inspections are performed in accordance with the dam safety program, which has transitioned or is in the process of transitioning from a standards-based approach to a risk-based or risk-informed approach (USBR-USACE 2015). The USBR dam safety program, Safety Evaluation of Existing Dams (SEED), is intended to identify and evaluate dams which pose an increased threat to the public, and also includes spillway inspections as part of the overall program. Additional guidelines have been developed and issued to support safety and assessment of discharge release structures such as conduits, outlet works, and spillways (USBR 2004, FEMA 2005).

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The general dam safety guidelines and procedures are recommended to be regularly implemented by the owners/operators. However, spillway inspections and review of associated PFMs have not always been fully and regularly integrated into the practice of inspection, particularly those spillways that only receive infrequent or emergency use. The recent incident at the Oroville Dam in California has heightened concerns regarding spillway safety. Following the incident, FERC requested that owners/operators of high and significant hazard dams perform a detailed spillway-focused inspection and assessment and complete a spillway-focused PFM analysis (FERC 2017a).

Spillway inspection, PFM identification, assessment, and remedial actions determined to be necessary can vary depending on the type, structural, geotechnical, drainage and hydraulic characteristics of the spillway, its age and historical operation and maintenance actions. Hence, a spillway-focused generalized programmatic and integrated inspection and assessment framework encompassing the variety of spillway types, issues, PFMs, and potential solutions would provide a useful tool for establishing a strategy toward a safer dam infrastructure. This paper is intended to present such a spillway focused programmatic assessment plan, providing the reader with a guide for preparing and performing a hands-on spillway assessment, determination of the spillway vulnerabilities, and reduce the risk of spillway associated PFMs. This programmatic framework is intended to be used as general guidance; however, each spillway has unique characteristics to which inspection and evaluation efforts need to be tailored, considering project setting, design, construction, historical operation and maintenance, and applicable dam safety requirements.

SPILLWAY ASSESSMENT

Spillways are typically described based on their expected priority and frequency of operation, control condition, and linings. Primary spillways (aka principal or service spillways) are designed to pass most large flood flow releases from the dam, and are often the only spillway provided. They are typically designed to provide what was considered conservative and safe operation at the time of design, and reflect the understanding of hydrologic conditions and construction materials at the time. Conversely, auxiliary or emergency spillways are generally intended to be operated very rarely, only during very large flood events. They are designed to provide additional protection against dam overtopping during extreme conditions if the normal outlet works and/or service spillway cannot provide sufficient capacity (USBR 2004). Spillways can be differentiated into controlled crests, where mechanical equipment such as gates, flashboards or fuse panels are used to manage outflows, and uncontrolled crests, where flow passes voluntarily over the crest with no control. Spillways can be further divided into lined chutes, where concrete slab and side slope or vertical walls contain most or all of the discharge passing through the spillway, and unlined chutes that rely on excavated natural channels to carry the flow. Lined chutes are typically used where the spillway is in regular use or the unit flow capacity requirements are large and the foundation materials are not resistant to erosion. Lined chutes increase the reliability of the structure. Unlined spillways generally rely on the natural foundation material with limited improvement. Often, primary spillways are lined, while emergency spillways may be

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unlined. Since the spillway-associated PFMs differ between lined and unlined spillways, this distinction was utilized in developing the programmatic spillway inspection and assessment procedures presented in this paper.

Generally spillway assessment and inspection efforts include six main steps: 1) initial PFM identification, 2) document review, 3) hands-on condition assessment, 4) data analysis, 5) PFM assessment and development, and 6) action plan development. Each of these steps is vital to the evaluation of the safety of spillway, determine issues and associated risks and develop a plan to remedy deficiencies.

Potential Failure Modes Identification

According to FERC (2017b), a PFM is defined as “the chain of events leading to unsatisfactory performance of the dam or a portion thereof.” This includes any events resulting in uncontrolled and/or unintended release of water. However, past events (e.g. Oroville spillway failure) demonstrate that even if an event does not lead to uncontrolled/unintended release of water, the consequences of that event can be significant and should also be considered. Therefore, the first important step in a generalized framework for spillway inspection is to establish a good understanding of spillway vulnerabilities and associated PFMs. This step would identify what deficiencies to look for during a document review and hands-on condition inspection. A list of general considerations that would increase the spillway vulnerability and may lead to PFMs developing is presented in Table 1.

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Table 1. General Considerations Increasing Spillway Vulnerability

Capacity	Inadequate hydraulic capacity of the spillway and/or chute during flood
	Change in understanding of hydrology and larger spillway flood capacity requirements
	Blockage due to debris or landslide
	Inability to operate the gate system (for controlled crest spillways)
Geotechnical	Landslide/rock fall into the spillway area
	Undermining of foundation due to leakage erosion/piping
	Rockslide/landslide and foundation failure
	Seismic consideration (e.g., existence of faults), change in understanding of seismicity
Hydraulic	Cavitation
	Hydraulic stagnation pressure
	Spillway chute and/or stilling basin overtopping due to air bulking or wave action
Structural	Surface deterioration
	Structural gate members inadequacy, deterioration/corrosion
	Slab failure due to deformation, settlement, and excessive net uplift pressures
	Structural failure during seismic event
Erosion and Energy Dissipation	Spillway erosion
	Inadequate energy dissipation and downstream channel erosion and/or head-cutting
	Dam structure undercutting – undermining
Operational	Control system deterioration, malfunction and failure (for controlled crest spillways)
	Underdrain system inadequacy and/or failure
Historical Record	Maintenance records (e.g., repair of damaged areas)
	Project modification

Lined spillways. Concrete-lined chute/tunnel spillways usually consist of a weir to direct reservoir outflows into the chute or tunnel conveying the water to downstream and often some form of energy dissipation to reduce the high energy of the flow before entering the downstream natural flow path. The PFMs to consider when inspecting concrete lined spillways can be summarized in the five main categories below.

- Spillway lining overtopping:
  The spillway walls can be overtopped when the spillway discharge exceeds the design capacity, air bulking increases the volume of mixed flow greater than design capacity, or spillway capacity within the chute is decreased due to blockage (e.g., debris, side slope failure). If this occurs, the materials above and behind the lining that are not

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resistant enough will be eroded by the overtopping high velocity flow. Erosion could potentially progress rapidly beneath the concrete lining and lead to spillway failure.

- Lining deterioration, instability and erosion:
  Significant lining deterioration (e.g., cracks, spalls, and delamination) can result in spillway system failure through different mechanisms such as lining structural failure, foundation exposure, and increased pore pressure under the lining. Unrelieved uplift pressure under the spillway chute lining can also overstress the concrete slab and lead to chute lining failure. The uplift pressure buildup can be caused by hydraulic stagnation at the upstream edge of displaced slabs at joints or increase in pore water pressure due to lack of functional underdrain system. Lining erosion resulting from cavitation or abrasion could also cause lining failure over time. Failure of the chute lining slab or walls and resulting exposure of the foundation material to high velocity flow can quickly worsen the situation.

- Foundation erosion:
  The foundation erosion process is necessary for a number of PFMs to fully develop. If the spillway foundation is vulnerable to erosion, internal seepage through cracks, holes, damaged or deteriorated joint sealant or water stops could introduce erosive flows under the slab and initiate foundation erosion. Failure of, or lack of a functional underdrain system, could also initiate internal seepage erosion beneath the slab. Foundation material erosion can progress under the lining to such an extent that unsupported slab or sidewall lining could crack or collapse, leading to failure of the spillway system.

- Seismic loading:
  Seismic loading in excess of design consideration could initiate cracking i the spillway structure concrete lining. Significant cracks in the concrete could lead to failure of spillway crest, gates and piers, as well as chute lining. This could result in unintended release of water if the spillway crest fails or expose the foundation to high velocity flow, increasing the risk of foundation erosion if the lining fails. Also, failed/dislodged concrete lining may block the spillway and lead to overtopping of the lining. These failures can be further exacerbated by liquefaction of granular foundation material due to seismic loading.

- Slope instability:
  Increased pore pressures in the chute side slope foundation (e.g., within the spillway side slope foundation or on unprotected slopes above the spillway) can potentially lead to slope failure. Slope failure in the spillway sidewall foundation could result in concrete lining failure and exposure of the embankment to further erosive forces. Slope failure above the spillway chute could result in spillway lining overtopping due to flow restrictions from material blocking the chute. It could also divert water to a new flow route that could threaten the embankment or undermine the dam foundation. This could cause embankment and foundation erosion and threaten the safety of both the spillway and dam. Additionally, increased pore pressure behind spillway walls with blocked drains could potentially overstress the wall reinforcing.

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Unlined Spillways. Since there is no lining in unlined spillways the characteristics of the foundation rock or soils are critical when considering the PFMs. The PFMs to consider when inspecting unlined spillways can be summarized in the following four main categories.

- Open channel erosion:
  Operation of an unlined spillway may initiate open channel erosion/incision at vulnerable locations where the bed material is not strong enough to resist the erosive energy of spill flow. Significant erosion/incision could lead to head-cutting or slope instability processes and threatens the integrity of the structure.
- Seepage/internal erosion:
  Internal erosion would start when the hydraulic gradient of seepage flow through weak areas such as faults reaches the critical gradient. Subsequently, materials will be plucked and transported away, creating an erosion feature. If the material has sufficient cohesion a pipe can form, eroding material progressively further into the foundation. The internal erosion, regardless of simple erosion feature or forming a pipe, would carry the same risk as open channel erosion.
- Headcutting:
  A headcut, sudden change in bed elevation at the upstream edge of a gully, in earthen material progressively moves upstream in the opposite direction of the flow towards the source. Headcutting can be initiated by open-channel erosion .A breach may occur if headcutting reaches the spillway crest, creating the potential for a catastrophic failure in unlined spillways.
- Slope instability:
  Slope stability can be compromised by either toe erosion undermining the slope or increased pore pressure reducing stability. Both spillway toe erosion and an increase in pore pressure within the foundation or on adjacent slopes that could potentially increase the vulnerability of the unlined spillway.

Spillway Flow Control Systems. Often, spillways are equipped with mechanical control systems such as gates and valves. In this case, operational failure of the spillway control system may decrease the spillway outflow capacity and consequently raise the reservoir elevation. If the spillway is the only flood release structure or if alterative reservoir outlet works are not operational and the issue cannot be fixed in a timely manner this could lead to a dam overtopping PFM. Some dams have at least a few different ways of discharging the flow (e.g., emergency spillways, outlet works, low level outlet, and powerhouse). Sometimes, controlled spillways are equipped with multiple independent and redundant controlled outlets (e.g., multiple gates). Therefore, the number, capacity and vulnerability of the all flow release systems should be considered when identifying and developing PFMs.

Document Review

Reviewing the available documents pertaining to a particular dam and spillway provides essential information necessary for a successful spillway assessment, so its importance

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cannot be emphasized enough. The information would guide the inspection effort and prepare the team for the hands-on inspection and testing. This would also allow them to identify any potential problematic areas beforehand, which require more attention during the hands-on inspection. A general list of the type of documents that may provide valuable information for spillway assessment is provided in Table 2.

Hands-on Assessment

Prior to scheduling a date for the hands-on assessment, enough time must be allowed for preparation and to perform a preliminary PFM identification and review available documents. The inspection planning should also take into account the operational, seasonal, and environmental considerations pertaining to the spillway. The inspection team must work closely with other groups such as dam operation staff and technicians, and consider access difficulties that may require specialists such as rope access engineers and/or divers for safe access to parts of the facility. Also, the team may need to attend special training sessions such as confined space training, depending on the project specifications. The hands-on assessment encompasses different techniques, including visual inspection, non-destructive, and destructive testings to assess the spillway condition.

Visual Inspection. The visual inspection must be performed by individuals with adequate training and background familiar with dam and hydraulic structures. If engineering evaluations are included, a professional engineer, licensed in the appropriate jurisdiction is also required. The experience and knowledge level of the inspection team, with regards to operation, safety, structural, geotechnical and hydraulic aspects of dams, is a key factor to a successful assessment effort. The visual inspection must be conducted by carefully observing the spillway condition and looking for abnormal features and possible deficiencies. This encompasses a wide range of features and deficiencies related to hydraulic, structural, geotechnical, and operational characteristics of the system. A general list of features to look for during visual inspection of spillways is presented in Table 3. It is necessary to accurately document and record the observed features during visual inspection. Documenting spillway condition and observed features with photographs taken from similar vantage point provides a baseline for future inspections. A general list of equipment that may be needed to efficiently perform the inspection is provided in Table 4.

It should be noted that the condition of energy dissipation structures such as stilling basins, plunge pools, and downstream channel is crucial to the overall functionality of the spillway and should be inspected along with the spillway structure.

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Table 2. Useful Documents and Information for Spillway Assessment and Inspection

Document Type	Information to look for	Lined Spillways	Unlined Spillways
Design/ construction drawings	Geotechnical exploration program	x	x
	Construction details (compare with as-built to examine differences between original design and as-built)	x	x
As-built drawings	Foundation characterization	x	x
	Excavation objectives	x	x
	Connection between slabs, expansion joints, water stops	x	---
	Anchors, reinforcing	x	---
	Drains, weepholes (materials, location, accessibility, outlets)	x	x
	Project modifications	x	x
Construction records	Spillway work design changes	x	x
	Issues with lining materials	x	---
	Concrete mix design and testing, placement tolerances and curing	x	---
	Foundation issues	x	x
	Observations	x	x
Construction photos	Foundation preparation	x	x
	Anchors	x	x
	Lining reinforcement	x	---
Geotechnical/ geology studies	Seismicity assessment	x	x
	Characterization of geotechnical setting relevant to spillway foundation and surrounding slopes	x	x
	Earthen material erodibility	x	x
	Faults and discontinuities	x	x
Hydrological studies	PMP*, PMF**	x	x
	Flood analysis (duration, magnitude, frequency)	x	x
	Flood routing	x	x
Hydraulic design	Spillway design capacity	x	x
	Hydraulic characteristics for a range of flows (e.g., depth, velocity, stream power, cavitation index)	x	x
	Energy dissipation	x	x
	Tailrace channel	x	x
Operational and historical records	Operational plan	x	x
	Past spill events (spill flow discharge and duration)	x	x
	Inspection and maintenance records	x	x
	Project modifications	x	x

***P**robable **M**aximum **P**recipitation
****P**robable **M**aximum **F**lood

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Table 3. General List of Features to Look for During Visual Inspection

Features	Lined Spillways	Unlined Spillways
Reservoir condition in the spillway approach (e.g., vortices and waves)	x	x
Debris condition and debris management system	x	x
Slope stability (e.g., steep slopes, evidence of movement, drainage concerns on side slope and at toe)	x	x
Erosion in spillway approach and/or tailrace channel	x	x
Crest displacement	x	x
Lining damages and deficiencies (e.g., transverse and longitudinal cracks, delamination, spalling, scaling, pop-outs, abrasion and exposed rebar)	x	---
Cavitation damage	x	---
Slab condition (e.g., deformation, distortion, and displacement)	x	---
Reinforcement corrosion or damage	x	---
Joint condition (e.g., gap, offset, and filler material)	x	----
Rock condition (e.g., cracking, joint set, and weathering)	---	x
Chute scour/erosion/incision	---	x
Wall condition (e.g., displacement, tilting, and alignment)	x	x
Efflorescence (with or without staining)	x	x
Seepage	x	x
Sidewall and under- drains condition	x	---
Control structures and operation (e.g., valves and gate leaf, frame, lifting assembly)	x	x
Vegetation	x	x
Animal activities	x	x
Previously repaired areas	x	x
As-built conformity	x	x

Non-destructive Testing. Non-Destructive Testing (NDT) methods are used to evaluate structures without causing damage. They are becoming more popular in different fields of science and engineering because of relatively low cost and high data-gathering efficiency. They can provide valuable information about the properties and condition of spillway lining, foundation, and structural members which cannot be achieved during visual inspection. They use different scientific theories to indirectly evaluate the spillway condition. The tests must be conducted by a team of professionals because the quality of evaluation greatly depends on the experience and knowledge level of operators. The results should be analyzed and interpreted by the NDT team in conjunction with the inspection team to achieve reliable evaluation. The limitations of NDT methods should be evaluated when planning the inspections. Table 5 presents a list of some of common NDT methods that can be used in spillway evaluation.

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Table 4. List of Useful Equipment for Visual Inspection

Equipment	Purpose
Notebook and pen/pencil	Documenting observations
Site specific inspection checklist	Helping with consistency and completeness of inspection effort
Prepared inspection notes	Documenting all joints, slab numbering/lettering for easy tracking
As-built drawing set	Reference for documentation
Heavy-duty brush	Small debris and vegetation removal
Tape measure	Determine size, geometry and location of observed features
Laser measure	Quick measuring from wall to observed features
Survey wheel/tape	Determine location of observed features
Crack gage	Determine size of cracks
Waders/boots	For access to wet areas
Flashlight	Light source for dark areas
Spray paint	Mark observed features for better visibility and future reference
Survey flags	Mark location of observed features
Camera	Take photos and videos of the observed features
Drone	Overhead photo/video of the spillway and its surroundings
GoPro/push cameras/ROV*	Monitoring underdrain system
Hammer	Debris removal, manual hammer impact testing for qualitative identification of material strength and voids under concrete lining
Metal rods	Probing joint gaps
Heavy chain	Chain drag testing for identifying voids under concrete lining
Plumb bob/level	Check deflections of walls or slabs
Borescope	Investigate drains for potential blockage
Access equipment	To access difficult accessible areas (e.g., fall protection, rope access, diving equipment)

***R**emotely **O**perated **V**ehicle

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Table 5. Some of Common Non-destructive Testing Methods for Spillway Evaluation

Non-destructive Testing	Technology	Purpose
Photographic Records	Digital Photography	Take numerous photographs of the structure and compare with as-built drawing for conformity and with previous or future photographs to determine any changing condition
LiDAR	Laser light	Scan the structure and compare with as-built drawing for conformity and with previous or future scans to determine any changing condition
Sonar Scan	Sound wave	Perform underwater scan of approach channel or stilling basin
Ground Penetrating Radar (GPR)	Electromagnetic waves	Determine/locate the depth of materials within a material (e.g., rebar within concrete)
		Measure existing thicknesses of members (slabs)
		Determine voids within or behind/below structural members such as walls/slabs
Schmidt Hammer	Spring rebound	Measure strength of rock/concrete
Impact Echo (IE)	Sound waves	Determine thickness and location of deficiencies within structures (e.g., cracks, honeycombing, voids, delamination and debonding of reinforcement and to the foundation)
Slab Impulse Response (SIR)	Sound waves	Determine the support conditions of slabs-on-grade pre- and post-repair and, in particular, determining subgrade voids
		Locate areas of delamination or voids within concrete slabs within shallow depths
Half Cell Corrosion Mapping*	Electrical resistance	Determine the corrosion potential of a reinforced concrete member
		Map areas with high probability of corrosion potentially before major corrosion damage occurs
Thermal Imaging	Infrared radiation	Map potential areas of deficiencies within the structure (e.g., large air voids, cracks, and delamination)
Ultrasonic Pulse Velocity (UPV)	Ultrasound waves	Determine potential defects in structure (e.g., delamination, honeycombing, cracks and voids)
Seismic Reflection and Refraction	Geophysics	Determine physical properties of subsurface geologic materials (e.g., degree of weathering, density, quality of rock)
		Determine faulting and shear zones
		Map depth to bedrock and bedrock topography
		Map landslides

*May require exposing the rebar, causing some damage to the structure.

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Destructive Testing. Unlike the NDTs, the Destructive Testing (DT) methods require destruction of a portion of spillway to evaluate the structure. The DT methods are usually less complex and easier to interpret but will provide more information compared to NDTs. Because of their destructive nature, they are usually performed only when additional information is required for justification and future repair planning. Table 6 presents a list of some of common DTs that can be used in spillway evaluation.

Table 6. Some of Common Destructive Testing Methods for Spillway Evaluation

Destructive testing	Purpose
Boring	Allows for investigation into subsurface conditions, verification of slab depth, creating a path for borescopes to be inserted beneath the slab in order to determine the size of voids
Coring	Verification of slab depth, creating a path for cameras to be inserted beneath the slab to determine the size of voids, can be used to determine in-place concrete properties and reinforcement size
Geotechnical testing (e.g., drilling, rock coring, Becker hammer, cone penetration testing)	Determine geotechnical properties of the foundation material
Petrographic Analysis	Comprehensive evaluation of concrete to determine potential issues (e.g., durability, low strength, surface distress, etc.)

Data Analysis and Assessment

Following the completion of hands-on assessment, the collected data, information and observations must be analyzed and interpreted. Effective data compilation and presentation is the critical path to accurate analysis and interpretation. The compilation of data is crucial in developing a baseline that can be used for future inspections to measure against and identify changing conditions. The observed features and testing results must be looked at both as a whole and individually to determine their potential source and the spillway vulnerability. Integrated presentation of various observed features would help to readily identify any existing pattern important to assessment. Developing a map of the spillway and presenting observed features is an effective approach to integrate and analyze the observations. For example, a concrete deficiency map of a lined spillway is a useful tool to identify pattern of cracks and areas of concern that indicate the existence of a systematic problem with the structure.

Often, analytical analysis or modeling simulation based on the hands-on assessment information would be required to support the observation and help with the PFM analysis and future planning. This could include hydrologic, hydraulic, structural, and geotechnical analysis. For example, if evidence of cavitation is observed in the spillway

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chute, hydraulic analysis of the flow must be performed to support the observation and determine the risk of cavitation leading to a PFM. Currently, there are number of available software and modeling tools which can be used to perform the supporting analysis, a list of which is presented in Table 7.

Table 7. Some of Common Supporting Analysis and Example of Candidate Tools for Spillway Evaluation

Type	Analysis	Candidate tools
Hydrologic	PMP and PMF re-evaluation	HEC Series (e.g., HEC1, HEC-HMS)
Hydraulic	Capacity, flow, cavitation, uplift and scour, erosion, and headcutting analysis	Capacity and flow (e.g., HEC-RAS, CFD modeling), cavitation and uplift (e.g., analytical spreadsheet), erosion and head-cutting (e.g., SITE, WinDam, Erodibility Index method)
Structural	Structural stability analysis	SAP2000, ANSYS, LS-DYNA
Geotechnical	Slope stability, rock/foundation erodibility and seepage analysis	GeoStudios – Slope W, SEEP W, FLAC

Potential Failure Mode Analysis and Development

After all the information about the spillway is gathered, analyzed and interpreted, only then should the analysis and development of spillway-related PFMs proceed. The PFM analysis and development entails rationalizing the potential processes and sequence of events leading to unsatisfactory performance of spillway, including uncontrolled and/or unintended release of water from the reservoir. Typically, PFM analysis (PFMA) sessions are performed as part of the FERC Part 12 Dam Safety process for FERC-regulated dams, and similar processes are used for other federal projects. For projects that are not subject to federal regulations, PFM analysis and development would provide greater understanding of the spillway and the potential for associated failure modes. The PFMA is conducted by a team of qualified (by experience and/or education) participants and usually includes representatives from the inspection team, dam owner's personnel, and related regulatory agencies. During a FERC spillway-focused PFMA session, the general potential failure modes previously identified will be reconsidered in more depth. The gathered information and analysis will help to classify the PFMs into different categories, based on the probability of occurrence and associated risk. It should be noted that the PFM classification is based on the engineering judgment of PFMA session participants. The PFMs classification is intended to help with future inspection effort and prioritizing actions needed to be taken to lower the vulnerability of project in the future. The outcome of the PFMA session must be accurately documented for future reference. Detailed information about the PFMA procedure and consideration for FERC-regulated dams is presented in FERC (2017b).

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Action Plan

Upon completion of the PFMA session, development of a surveillance and monitoring program is recommended for high risk and probable PFMs. The program should identify the type and frequency of future inspections, evaluate the current instrumentation and visual surveillance program, and discuss priorities to lower the vulnerability of the dam and the risk of PFMs and appropriate recommendations (FERC 2017b). To lower the risk of spillway-related PFMs, several actions (major or minor) may be recommended, depending on the nature and level of the deficiencies. Table 8 presents some of common actions to improve the spillway deficiencies.

Table 8. Some of Common Actions to Remedy Spillway Deficiencies

Capacity	Increase flow capacity (spillway modification or addition of discharge outflow routes)
	Improve debris management protocols
Geotechnical	Improve slope/foundation stability (e.g., anchors, grouting, retaining walls)
	Reduce pore pressure and seepage flow (e.g., seal the joints, improve drain efficiency)
Hydraulic	Increase cavitation index (e.g., reduce velocity and/or increase pressure (if possible), remove surface irregularities, introduce air)
Structural	Repair joints (e.g., eliminate significant joint offsets and large gaps, install water stops)
	Repair surface and structural damage/deterioration (e.g., patching the surface, crack injection, filling voids)
	Replace lining
	Improve structural stability
Erosion and Energy Dissipation	Improve erosional resistance of spillway (e.g., resistant lining, riprap, grouted riprap)
	Improve energy dissipation (e.g., stilling basin, flip bucket)
Operational	Improve physical and operational state of the control system
	Improve physical and operational state of the underdrain system

SUMMARY

This programmatic inspection and assessment plan is intended as a guide for inspection of spillways and a tool which can be adopted for individual projects as appropriate. This framework is intended to provide general information and a road map on how to assess a spillway structure. A brief review of existing dam safety programs and a brief explanation of spillway types and associated risk factors that could lead to failure modes were provided herein to inform the reader and furnish relevant reference. Various means and methods of inspection were described and referenced, along with typical or necessary supporting analysis, potential failure mode analysis and common action plan items to remedy existing deficiencies and lower the risk of PFMs developing. A recommended framework for periodic spillway inspection and assessment to identify changing conditions and spillway vulnerability is presented.

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The programmatic spillway assessment and PFM analysis and development presented herein follows after the typical procedure below:

1. Initial consideration and identification of PFMs
2. Review of existing documents
3. Selecting the most appropriate assessment methods to acquire the most information, plan and execute the inspection and assessment
4. Synthesize the collected data and perform supporting analysis if needed
5. Conduct a PFM analysis and development
6. Develop an action plan

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