AN INTRODUCTION TO STRUCTURAL EVALUATION OF DAM APPURTENANT STRUCTURES: SPILLWAYS AND RADIAL GATES

VEERAJA MALYALA, ADIT JOSHI, BRAD ZELONIS AND TIMOTHY KING
AECOM, USA

1. SPILLWAY BACKGROUND

1.1 What is a Spillway?

A spillway is a hydraulic structure that passes normal (operational) and/or flood flows in a manner that protects the structural integrity of a dam. Spillways are sized hydraulically to safely pass floods equal to or less than the design flood. The design flood is less than or equal to probable maximum flood.

1.2 Importance of a Spillway in Relation to Reservoir Operation and Dam Stability

A spillway is a very critical component of dam operation and stability. Numerous examples exist of dam failures from improperly designed/constructed spillways or insufficient spillway capacity. Sufficient release capacity is of utmost importance for composite or embankment dams because overtopping is often a critical failure mode. Spillway failure severely affects the flood release capacity of the reservoir, which can adversely affect the stability of the dam. The recent incident at Oroville Dam in California has amplified concerns regarding spillway safety. Following the incident, Federal Energy Regulatory Commission (FERC) at national level and Division of Safety od Dams (DSOD) at California level requested that owners of high and significant hazard dams perform detailed spillway assessment and complete a spillway focused potential failure mode analysis (PFMA) (FERC, 2017)

2. CONCRETE SPILLWAY EVALUATIONS

2.1 Concrete Spillway Background

Figure 1 shows the typical components of a concrete spillway structure.

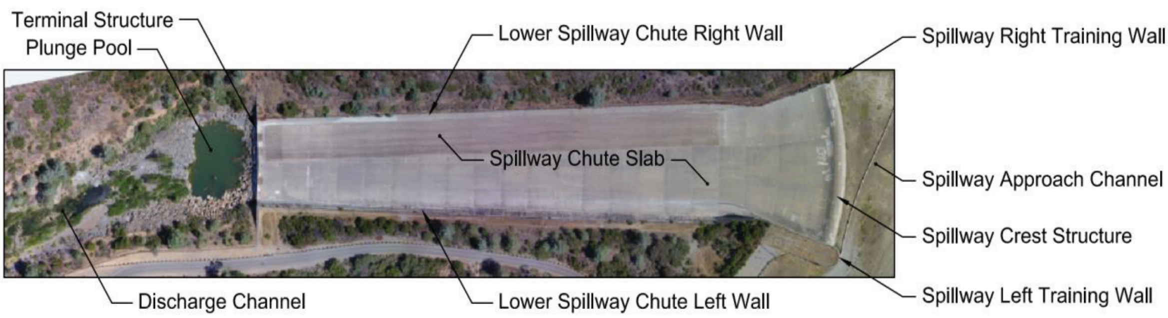


Figure 1 : Typical Concrete Spillway Layout

The primary causes of dam failures are overtopping of embankment dams caused by inadequate spillway capacity, structural defects or deterioration such as erosion of backfill , deformations resulting from settlement due to seismic activity or surface and subsurface problems in spillway structure such as poor drainage, inadequate anchorage, cracking, joint defects, inadequate waterstops in joints and slab reinforcement.

2.2 Concrete Spillway Inspections

A comprehensive evaluation of a spillway per FERC letter (2017) includes the following tasks:

1. Review of existing spillway documentation;
2. Visual inspection of the spillway structure;
3. Nondestructive testing and subsurface investigation; and
4. Stability and hydrologic evaluations.

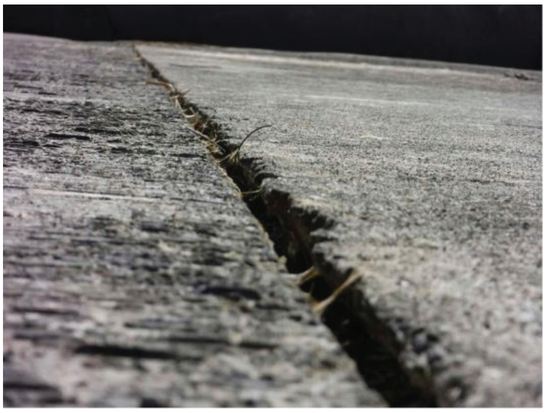
2.2.1 *Review of Existing Spillway Documentation*

This task involves reviewing background data for the spillway, such as record drawings, foundation mapping reports (if available), construction photographs, previous inspection reports and recommendations, the supporting technical document, the most recent instrumentation monitoring reports to understand the vulnerabilities in the spillway structure. The existing design is compared with current, modern spillway design practices based on USBR Design Standards No.14, Chapter 3 and potential failure modes, to identify potential deficiencies of the existing design that can affect spillway safety. The records of any monitoring instrumentation (e.g., survey monuments, seepage weirs, piezometers) are reviewed to determine whether any adverse trends are developing that may lead to spillway instability.

2.2.2 *Visual Inspection of the Spillway Structure*

Visual inspection of the spillway needs to be performed by a licensed engineer who has subject matter knowledge of spillway structures. The inspection team should include engineers who can assess the structural, geotechnical, hydrological, and geological aspects of the spillway. Some spillways can be accessed readily, while others require high-angle descent, using ropes. The different defects that may be observed on a spillway include cracks, spalls, joint offsets, hollow or drummy-sounding concrete, deformations, and plugged drain pipes. Figure 2 shows photographs of typical deformations that can be observed during spillway inspections.

Joint Offsets and Deformations



Negative offset act

Cracking/spalling/joint defects

Drain Pipe Deformations

Corroded transverse drain pipe in chute slab

Terminal Structure Issues

Figure 2 : Example of Spillway Deformations

2.2.3 *Nondestructive Testing and Subsurface Investigation*

A non-destructive survey of a spillway chute and the side walls can be performed in a multi-phase approach. The approach can consist of, in sequence: 1) optical and thermal imaging using drones; 2) Slab impulse response (IR), 3) ground penetrating radar (GPR), and 4) multichannel analysis of surface waves (MASW).

2.2.3.1 *Optical and Thermal Imaging Using Drones*

The optical and thermal imaging survey, as shown in Figure 3, can be performed using a drone equipped with high definition and thermal imaging camera(s). Two surveys need to be performed at different times of day to achieve thermal differentiation. The results of the optical and thermal imaging survey can be used to map cracks, open joints, and other flaws detectable with such methods along the spillway slab and side walls. These results need to be reviewed to identify potential locations of slab defects, for a more detailed evaluation with other nondestructive testing techniques.

Figure 3 : Example of Optical Imaging of a Spillway Using a Drone

2.2.3.2 *Slab Impulse Response (Slab IR)*

The Slab IR method typically is used to assess subgrade conditions beneath slab-on-grade and behind the walls and tunnel liners and delamination or voids with in the slab. Slab IR is generally used in conjunction with GPR or impact echo, to better delineate observed material flaws. An example of Slab IR and GPR inspection results are shown in Figure 4.

The conventional Slab IR methodology consists of striking the concrete surface with a hammer or other impact device to generate compressional waves. These waves propagate through the slab and are reflected at the slab and subgrade interface, or they reveal a discontinuity within the slab. The waves are measured by a receiver that is positioned next to the impact point of the hammer. The measured response at the receiver is routed to a digital recording system and subsequently is analyzed to evaluate the slab and subgrade conditions.

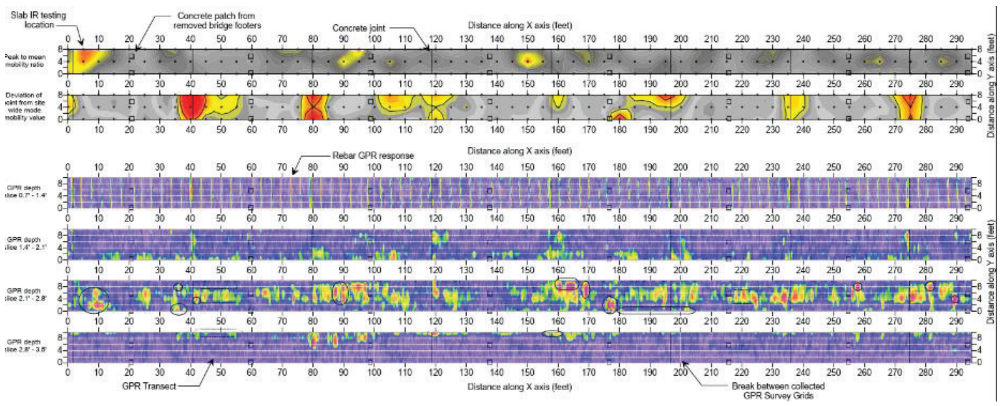


Figure 4 : Slab IR Results (top) and GPR Results (bottom) at Same Location and Depth

2.2.3.3 *Ground Penetrating Radar*

The GPR method involves transmitting electromagnetic pulses into the subsurface and recording the subsequent reflected signal. These electromagnetic pulses are primarily influenced by the dielectric properties of subsurface materials. Contrasts in dielectric properties typically correspond to variations in soil type, rock type, groundwater content, and the presence of voids or buried cultural features (e.g., building foundations, debris, utilities). These variations in subsurface conditions subsequently influence the amount of energy that is reflected to the antenna and the amount of energy lost to attenuation and signal degradation. Figure 5 shows an example of GPR scanning of a concrete slab. The highlighted red circle shows an indication of a void.

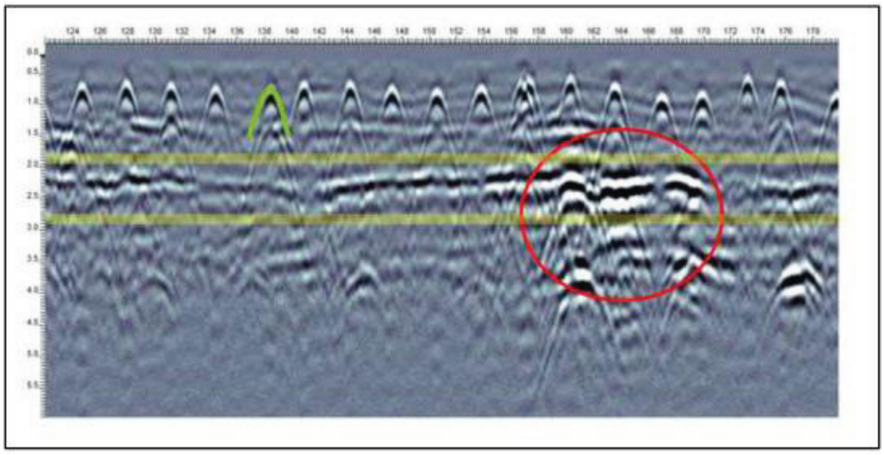


Figure 5 : GPR Result Example

2.2.3.4 *Multichannel Analysis of Surface Waves (MASW)*

The MASW method involves profiling shear wave velocities of subsurface layers. Dispersion refers to the principle that the velocity in a seismic surface wave varies as a function of the frequency of the waveform. The dispersive characteristics of the surface waves are directly related to variations in physical properties of the underlying geologic layers—the higher the shear wave velocity, the denser the rock feature. Figure 6 shows the MASW results for a spillway chute slab. The shear velocities increase from blue to red (the higher the shear velocity, the denser the rock material).

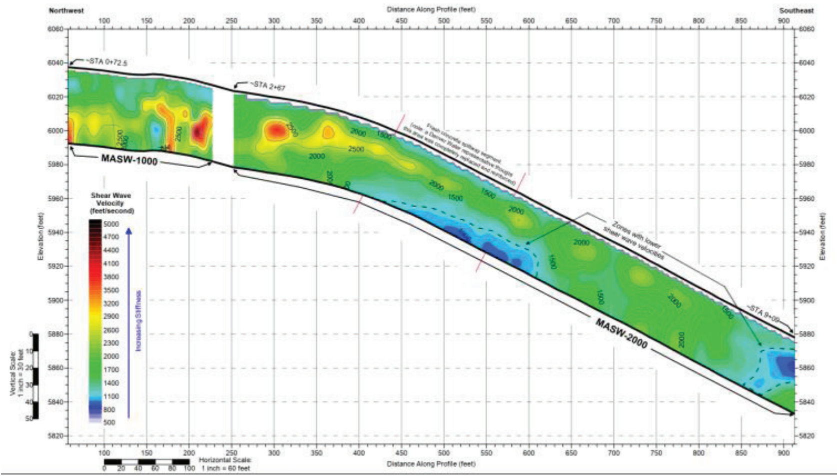


Figure 6 : MASW Result Example

2.2.4 *Stability and Hydraulic Evaluations*

Based on the results obtained from data review, visual inspection, and nondestructive testing, potential spillway failure modes can be identified. A global stability analysis of existing spillway crest and chute structures for flotation (uplift), overturning, sliding, and bearing capacity may be required. The stability analysis needs to follow the procedures of the U.S. Army Corps of Engineers Engineer Manual 1110-2-2100 (USACE 2014) and U.S. Bureau of Reclamation best practices manuals (Chapter F-1,F-2 and F-3) recommendations. The spillway channel and stilling basin alignment can be analyzed hydraulically. The analysis needs to examine the potential for cavitation damage along the spillway chute as well as the potential for chute slab uplift from development of stagnation pressure at transverse joints, cracks, and/or failed repair patches along the chute. Analyses also need to be conducted to assess energy dissipation and uniformity of flow entering the stilling basin. The potential scour and the need for scour protection need to be evaluated based on the stream power and erodibility index theory for the spillway.

3 RADIAL GATE EVALUATIONS

3.1 Radial Gate Background

A controlled spillway uses a mechanical structure to control the rate of flow through the spillway. Various mechanical structures may be used, such as radial gates, lift gates, roller gates, stanchions, and rubber dams. Radial gates or tainter gates are often considered to be the most economical and practical structures because of their light weight, fast operation, favorable discharge characteristics, and lower required hoist capacity.

Radial gates primarily are composed of structural steel. Connections vary from rivets to bolts/welds, depending on the age of the gate. As shown in Figure 7, radial gates are generally composed of the following primary components: skin plate assembly, vertical ribs, horizontal girders, bracing, strut arms, trunnion assembly, and hoist mechanism. This general layout can vary, based on the age, size, and loading on the radial gate. For example, older (1930s) riveted gates typically have horizontal and vertical trusses.

Figure 7 :. General Radial Gate Layout

3.2 Radial Gate Inspections

3.2.1 *Purpose*

Radial gates require proper maintenance, inspection, and testing to ensure their safe operation. Being in a wet environment, radial gates are susceptible to corrosion, which may weaken the capacity of a structural member. Maintenance activities, such as lubricating the trunnion, cleaning weep holes, and replacing seals, are required to prevent corrosion and/or displacement of a gate's members. The radial gate also relies on proper maintenance of the hoist mechanism, to ensure that it is working properly and lifting the gate evenly. Improper maintenance and inspection of radial gates can lead to costly repairs and/or catastrophic events, such as the Folsom Dam radial gate failure from excessive trunnion friction.

Visual inspection of radial gates is limited because the only observation point typically is from the top of the spillway piers and/or bridge. At those heights (more than 40 feet), each portion of a radial gate cannot be observed sufficiently to verify its condition. A hands-on "rope access" is the best method to visually inspect each of the gate members and connections.

3.2.2 *Criteria*

In the United States, the Federal Energy Regulatory Commission (FERC) implemented a radial gate initiative in 1998, following the failure of the radial gate at Folsom Dam. The purpose of the radial gate initiative was to ensure a routine review of the design analysis and "hand-on" inspection of the radial gates at each of the FERC-regulated projects. Per Chapter 14, Evaluation of Hydropower Projects, of the FERC Engineering Guidelines (FERC 2017), radial gates are classified as Category 1 or 2. For Category 1 gates, failure or mis-operation will have dam safety or operational consequences, such as endangering downstream life/property and affecting the project's ability to safely pass a flood. For Category 2 gates, failure will have minimal to no consequences. Inspections, tests, and analysis are required, based on the category of the gate. The requirements for Category 1 gates are summarized in Table 1.

Every 10 years, a close-up, detailed inspection is required on each radial gate. This detailed inspection is split into three components: (1) analysis review; (2) full travel inspection; and 3) rope access inspection. Each component of the radial gate inspection works together and is required for a full and thorough understanding of the gate's condition. For example, the observations and as-built dimension from the rope access inspection are used for the analysis review to ensure the design analysis reflects the current condition of the radial gate. The cause of the deflections/deformations observed during the rope access inspection can be determined from observations (i.e., gate binding) during the full travel test.

Table 1 : FERC Gate Category 1 Requirements

Requirement	Required Interval
Close-up Detailed Inspection	10 years (each gate)
Visual Inspection	1 year
Ampere Testing	1 year
Full Height Testing	5 years
Operation Test	1 year
Required Analyses	Static

3.2.3 *Analysis Review*

Before the rope access inspection, the radial gate design analysis is to be reviewed by a qualified engineer and the rope access team. The design assumptions, material properties, member sizes, methods, and results are reviewed for their correspondence with current design standards and the as-built properties of the radial gate. As part of the analysis review, the team also reviews the modifications/repair history, operation sequence, and maintenance procedures of each radial gate.

To help with the rope access inspection, critical and non-critical members/connections are identified. A critical member/connection is a member in which failure would be expected to result in collapse or partial collapse of the radial gate.

3.2.4 *Full Travel Inspection*

Full travel inspections are important to observe whether each radial gate is capable of operating to the full extent required to safely pass flood flows. A full travel inspection involves observing the gate move through its full range of motions, fully closed to fully open and back. In addition, bump tests with the primary and emergency power sources typically are performed, to measure in-rush currents and test the capability and operation of the emergency power. The full travel team typically includes a mechanical, electrical, and structural engineer, to observe the gate and hoist during the full travel inspection. The mechanical component of the inspection observes the spillway gate machinery, hoist chain, hoist condition, reducers, and gear system. The electrical inspection observes the operation of the hoist motor and testing of any back-up source. Voltage readings are measured for in-rush currents, steady-state currents, and voltages for the full travel inspection, to ensure that they are not exceeding the capacity of the hoist motor. The structural component of the inspection is to observe the gate members (i.e., skin plate, ribs, girders, strut arms, trunnion, and chain) and areas not visible during the rope access inspection (i.e., side seals, side rollers, gate guides).

3.2.5 *Rope Access Inspection*

As shown in Figure 8, a rope access engineer observes each of the radial gate members and connections. The rope access inspection team uses climbing techniques in accordance with the Society of Professional Rope Access Technicians (SPRAT) standards or Industrial Rope Access Trade Association (IRATA) standards. Observed deterioration (e.g., corrosion, pitting, deformations, cracking, deflections) of gate members are photographed and noted. Similarly, observed deficiencies (e.g., missing bolts, bolt prying, corrosion, gaps) in the gate connections are photographed and noted. As-built measurements of the member and connections are collected and compared to the design analysis assumptions.

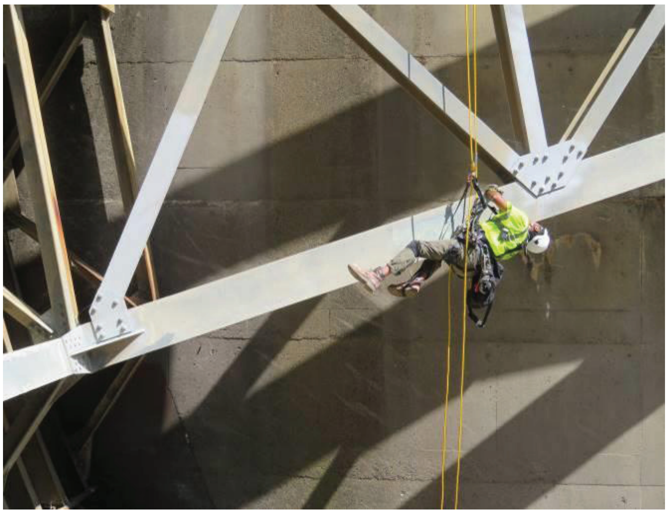


Figure 8 : Rope Access Inspection

3.3 Radial Gate Inspection Advantages

Radial gates are complicated structures that require routine inspection to eliminate the risk of failure. Portions of the gate that are subject to typical corrosion and deflection/deformations are not visible from the spillway bridge deck/pier. Because of the multiple members and tight spaces, a drone cannot get a close-up view of many members. By following the described radial gate inspection program, the full radial gate system is to be observed in detail by engineers with knowledge of the gate's components, critical members/connections, and operation. This knowledge is beneficial because the rope access engineers can inspect critical areas of the gate thoroughly and actively diagnose observed deterioration.

Findings for gate member/connection deficiencies that are observed during the rope access inspection include member corrosion, member deflection, member/connection cracking, trunnion deficiencies, concrete support deterioration, connection failures, seal deficiencies, gate travel deficiencies, and hoist support deflection/cracking. Figure 9 shows examples of these common findings. Each of the deficiencies that are shown were identified during a rope access and full travel inspections. The deficiencies went unnoticed during routine observations from the spillway bridge deck and piers.

<table>
<tr><th>Member Corrosion</th><th>Member Deflection</th></tr>
<tr><td>
Heavy corrosion (section loss) and pitting of skin plate assembly bottom member</td><td>
End bracing diagonal member horizontal deflection.</td></tr>
<tr><th colspan="2">Trunnion Deficiencies</th></tr>
<tr><td>
Movement/missing bolt of keeper plate; keeper plate prevents movement of the trunnion pin</td><td>
Debris and abrasion marks on trunnion pin</td></tr>
<tr><th>Concrete Support Deterioration</th><th>Seal Deficiencies</th></tr>
<tr><td>
Heavy concrete spalling at bottom of trunnion support concrete beam</td><td>
Failure of bottom seal</td></tr>
<tr><th colspan="2">Connection Failures</th></tr>
<tr><td>
Prying and deflection of the double-angle end brace connection</td><td>

Horizontal crack at double-angle connection of end brace</td></tr>
</table>

Figure 9 : Findings during Rope Access/Full Travel Inspections

3.4 Radial Gate Inspection Conclusions

On completion of the radial gate evaluation, a gate inspection report is developed to document the inspection findings. Based on the observations in the field and analysis review, recommendations for repair and/or maintenance are provided under the following categories: 1) critical dam safety-related (addressed in 1 year); 2) potential dam safety issue (addressed in 2 years); and 3) general maintenance (addressed in the next maintenance cycle).

A common recommendation of the hands-on radial gate inspections is to analyze the radial gate based on the observed deterioration or gate modification. For example analysis is updated to account for as-built conditions (notches, holes, and correct member sizes), observed member/connection corrosion, and include additional load cases (i.e., gate operating with one hoist). As shown in Figure 10, radial gate analyses are complex and require the use of a finite element model to fully understand the gates behavior and capacity during each loading.

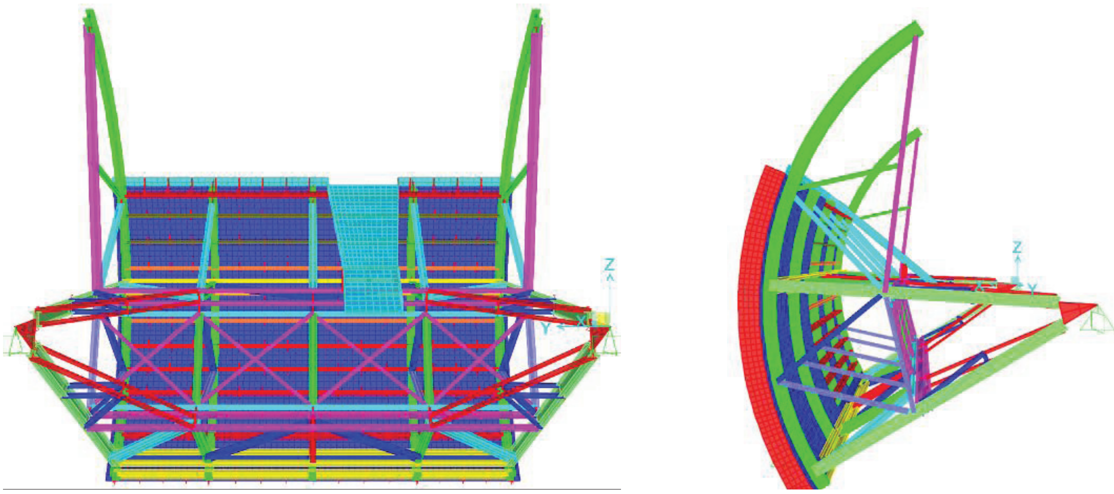


Figure 10 : Fully Assembled Radial Gate Finite Element Model

4. CONCLUSIONS

Spillway structures are critical for safe operation and stability of a dam. Failure of the spillway and/or gates can lead to an uncontrolled release of the reservoir. Because of the risk involved with failure, proper maintenance and inspection of these structures is critically important. Concrete spillways need to be evaluated on a periodic basis, to verify their condition and make any necessary repairs. A typical concrete spillway evaluation includes a review of existing information, a visual inspection, a non-destructive testing/inspection, and stability/hydraulic evaluations. Similarly, spillway radial gates are in a wet environment with limited access to observe the condition of each gate member/connection. Therefore, periodic inspection of the radial gates also is critical, to verify their condition, ability to travel, and to complete a proper analysis. A radial gate evaluation typically includes an analysis review, a rope access inspection, and a full travel inspection. With proper inspection, testing, and analysis of concrete spillway and radial gates, deterioration and/or deficiencies can be identified, and the appropriate risk reduction measures can be performed timely.

REFERENCES

Federal Energy Regulatory Commission (FERC). 2017 (May). FERC Engineering Guidelines. Dam Safety Performance Monitoring Program.

U.S. Army Corps of Engineers (USACE). 2014. Design of Hydraulic Steel Structures. ETL 1110 2 584.

U.S. Army Corps of Engineers (USACE). Jan. 2000. Design of Spillway Tainter Gates. ETL 1110-2-2702