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G-2 Failure GATES OTHER THAN RADIAL GATE

G-2.1 Key Concepts

There are multiple gate types used in flood control and navigation dams that could fail and affect the operation of the dam or lead to a dam breach. Failures of the gates could be a result of additional loading for which the gates were not designed (hydrologic, impact or seismic), inadvertently opening of the gate, cyclic loading during normal operation, etc. Example of gates used in flood control dams include Tainter gates, drum gates, roller gates, ring gates, and gates used in the outlet works or penstocks. Failure of these gates could result in increased flow downstream and could lead to loss of life and economic consequences. Tainter gates are evaluated in detail in two other chapters of this manual.

Gates used in navigation locks include miter gates, vertical lift gates, reverse Tainter gates, submergible gates and sector gates. For navigation dams, examples of gates used to control pool include roller gates (submergible and unsubmergible), Tainter gates (submergible and unsubmergible), lift (sluice) gates and wickets. Failure of these could results in loss of navigation and loss of pool leading to economic consequences. In some instances, for high hazard navigation dams, failure of a gate could potentially result in loss of life.

G-2.2 Description of Gate Types and Potential Failure Modes

G-2.2.1 Drum Gates

A drum gate consists of a hollow steel structure, hinged on the upstream side that floats in a bath of water contained within a float chamber bounded by reinforced concrete walls. These gates are unique in that the gates are lowered to release water, with water flowing over the top of the gates. Figure G-2-1 shows a cross section through a drum gate. Water is let into the float chamber to raise the gate (raising the reservoir level and shutting off spillway flow) and water is released from the chamber to lower the gate (initiating spillway flows and lowering the reservoir level). Gate seals prevent water from going around the gates, and gate stops or seats keep the gates from rotating too far up and out of the float chamber. A drain is used in order to keep unwanted water from filling the gate. The drain is usually connected from the interior of the gate by a flexible hose to an outlet through the concrete at some location.

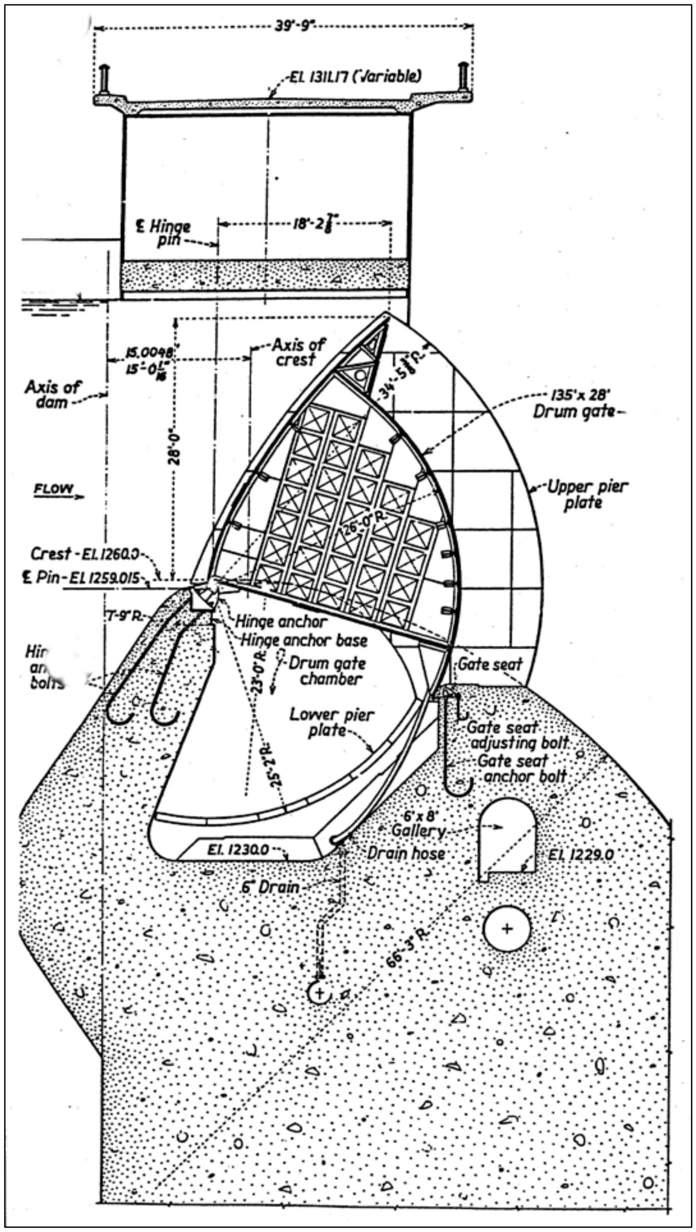

Figure G-2-1.—Cross section through drum gate.

These gates are rather complex, and require maintenance to ensure reliable operation of all the valves, piping, and structural features. Some of the vulnerabilities that should be considered when performing a risk analysis of these types of gates are as follows:

- Inadvertent lowering of a gate (and release of life-threatening flows) can occur under normal operations if water is lost from the float chamber or the gate fills with water (and is no longer buoyant). The ability of the float chamber inlet conduits and valves to supply water to the chamber faster than it is released through the outlet conduits and valves must be assessed.

The size of the conduits and valves is one consideration. The type, robustness, and maintenance of the valves and piping are other considerations. Similarly, the type, robustness, and maintenance of the internal gate drains and hoses must also be considered.

- Puncturing of a gate from rockfall, spalling concrete or other sources could allow the gate to fill with water faster than the drain can release water, causing dropping of the gate and life-threatening downstream flows.

- Seismic loading on the gates can affect several components of a drum gate including:

    - The hinge pins that tie the gate to the float chamber wall

    - The hinge pin anchorage that ties the hinge pins to the float chamber wall

    - The float chamber walls themselves

    - The piping and valves that control the flow into and out of the float chamber and gate drain

    - The gate seats that keep the gates from rotating too far up and out of the float chamber

    - The piers, which if they deflect can cause gate binding between piers making the gates inoperable

Each of these should be evaluated relative to various levels of seismic loading. Drum gates have been filled with Styrofoam to prevent inadvertent lowering. However, this greatly diminishes the ability to inspect and maintain the gates.

The Bureau of Reclamation (Reclamation) has nine dams within its inventory that have drum gates; United States Army Corps of Engineers (USACE) has one project and Pacific Gas & Electric Company (PG&E) has two. There have been two incidents of inadvertent drum gate lowering amongst the Reclamation projects. An evaluation of the data is shown in table G-2-1. A brief description of the two case histories in Reclamation's inventory (Guernsey and Black Canyon Dams) is presented later in this chapter. Two incidents in 4475 gate years of operations results in an annual probability of a gate problem of about 4.4×10^{-4}. This can be used as a base rate, and adjustments made up or down, based on key site-specific adverse and favorable factors (see also "chapter A-10, Building the Case").

Table G-2-1.—Summary of Drum Gates

Dam	Completion Year	Years of Service	No. of Gates	Gate-Years of Operation
Arrowrock	1915	103	6	618
Black Canyon	1924	94	3	282
Tieton	1925	93	6	558
Guernsey	1927	91	2	182
Easton	1929	89	1	89
Hoover	1936	82	8	656
Grand Coulee	1942	76	11	836
Friant[1]	1944	74	3	222
Shasta	1945	73	3	219
Sepulveda[2]	1941	77	7	539
Cresta[3]	1949	69	2	138
Rock Creek[3]	1950	68	2	136
Total			54	4475

NOTES: All are Reclamation projects unless noted otherwise.
[1] Two drum gates replaced.
[2] USACE has drum gates at only Sepulveda Dam.
[3] PG&E has drum gates at two projects (Cresta Dam and Rock Creek Dam).

G-2.2.2 Obermeyer Gates

Obermeyer gates are composed of steel panels supported by inflatable bladders. Elevation of the gate is controlled by the air pressure in the bladders and can be adjusted to control pool. These gates have usually been used under low head conditions. Issues with Obermeyer gates are usually experienced in areas with heavy ice and debris where puncturing of the inflatable bladders could occur.

G-2.2.3 Ring Gates

Ring gates which control morning-glory type spillways can operate according to a similar concept as drum gates. The ring floats in a circular chamber, and valves let water in and out of the chamber. A drain line keeps water from collecting within the gate. Gate stops keep the gate from floating completely out of the chamber. Many of the potential failure mechanisms for drum gates would also apply to ring gates. The exception might be failure of the hinge pins, as there are no hinges or hinge pins associated with this type of ring gate. However, there may be some mechanism whereby the gate could become torqued and stuck in the chamber. This could affect the ability to release water during a large flood.

Morning Glory spillways, such as the one shown on figure G-2-2, have other issues related to where the flow is controlled. Although the design would assure that the flow is controlled at the spillway crest, passing more than the design flow can result in control transitioning to the "throat," and extrapolating discharge curves beyond the design value may not be appropriate, unless the shift to throat control is accounted for. In addition, debris may be easily lodged in tunnel type spillways (depending on the diameter) in which case there may be little that can be done to remove the blockage until the flow subsides.

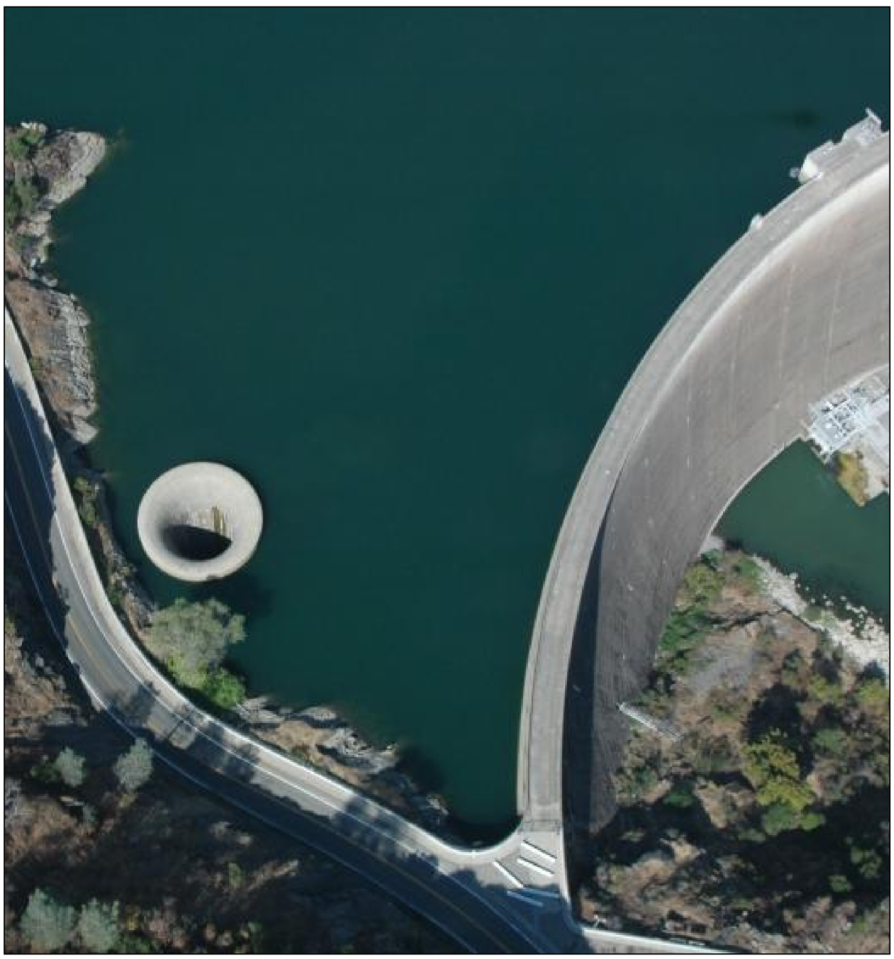

Figure G-2-2.—Morning Glory Spillway, Monticello Dam (California, Reclamation).

G-2.2.4 Roller Gates

This type of gate is more commonly found in older, low head navigation dams with wide pier to pier distance. A roller gate is a horizontal steel cylinder spanning between piers, usually riveted. The cylinder is attached to end disks at each end which bear against inclined racks set into the side of each pier. To control flow, the gates are raised or lowered in the rack by chains powered by electric motors in the piers. The primary structural members of the roller gates are outlined below. Schematic sketches of roller gates are shown on figure G-2-3. Key components of a roller gate include:

- Drum Assembly.—A large cylinder which acts as a beam and torque tube to carry dead and hydrostatic loads. The skin plate of the drum is stiffened by internal ribs and truss-type assembly. All loads on the drum are transferred to the end disks.

- Apron Assembly.—Skin plate and truss assembly used to increase the damming surface of the gate without increasing the diameter of the drum. The drum rotates as the gate is raised or lower and remain in contact with the spillway crest. The apron can be added to the bottom or the top of the gate.

- End Disks.—Drum assembly transfers load to end disks which are truss type configurations.

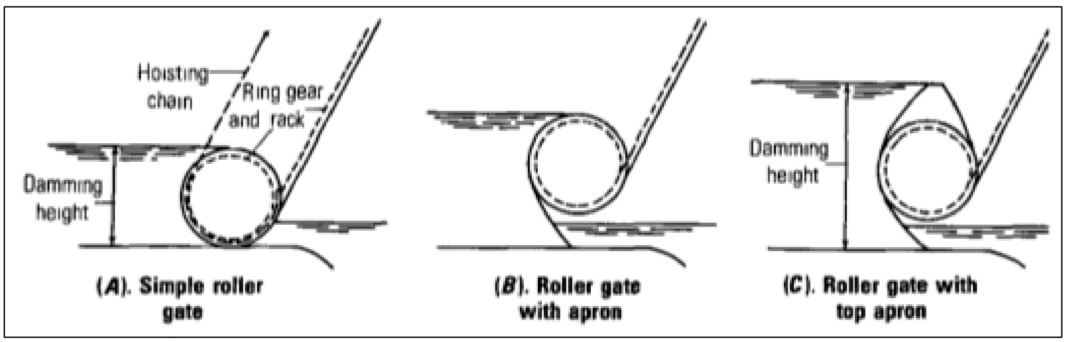

Figure G-2-3.—Sketch of roller gates (Rantz 1982).

Submersible roller gates were designed to facilitate flow of ice and debris. Figure G-2-4 shows a cross section of a submersible roller gate.

When evaluating roller gates for a risk assessment, consideration must be given to the original design and current condition of the gate body. Many gates designed in the 1930's for locks and dams on the Mississippi River did not consider additional loading due to ice (Bower et al. 1994) or seismic events. Excessive corrosion and section loss can lead to overstressing of the members, fatigue cracking and possible unsatisfactory performance of the gate. Fatigue cracking can be caused by stress concentrations due to poor detailing or weld details added to riveted structures for repairs or strengthening and excessive vibration of the gate during operation. Fatigue cracks can usually be found at the location of the repair or at the riveted connections between components such as the drum

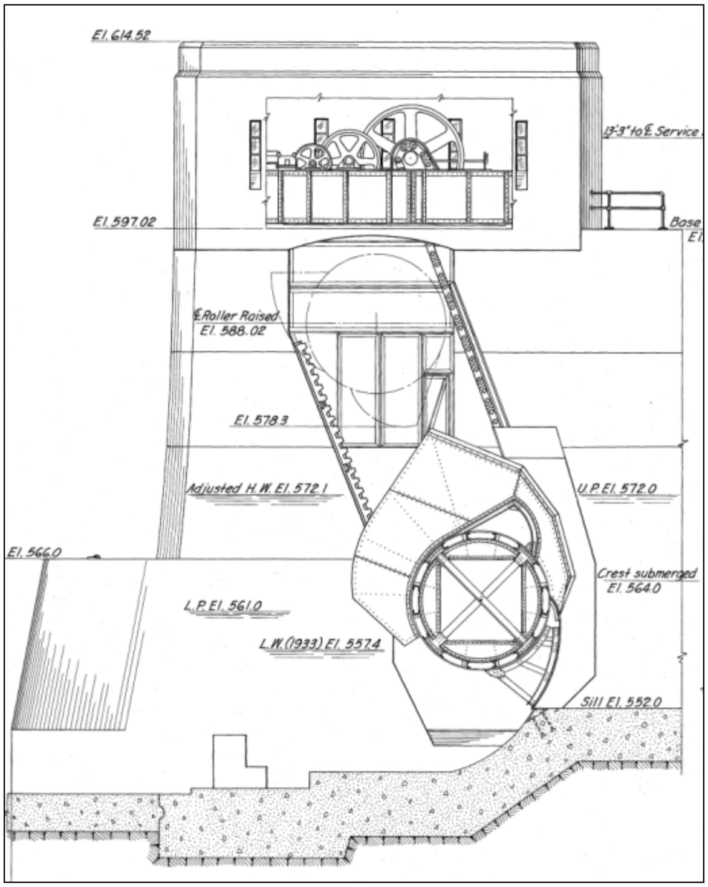

Figure G-2-4.—Cross section of a roller gate, Lock and Dam 14, Iowa (USACE 1936).

cylinder and end shields. The apron is more susceptible to vibration, so fatigue cracking due to vibration could be found at this location (Bower et al. 1994). Roller gates are built with enough redundancy that fatigue cracking will not usually cause unsatisfactory performance of the gate body. Riveted structures are generally less susceptible to fatigue cracking since the components are separated and the cracks will not propagate from one to component to another. Evaluation of less redundant components, such as the lifting chains and apron structure, should be done.

USACE has 25 dams within its inventory that have roller gates. Although there have been multiple incidents amongst these projects, most have been barge allisions. It is estimated that only four incidents were the result of something other than barge allision. An evaluation of the data is shown in table G-2-2. A brief description of one case history is presented later in this chapter. Four incidents in 9401 gate years of operations results in an annual probability of a gate problem of about 4.2×10^{-4}. This can be used as a base rate, and adjustments made up or down, based on key site-specific adverse and favorable factors (see also “chapter A-10, Building the Case”).

Table G-2-2.—Summary of USACE Roller Gates

Waterway/River	Dam Name	Year Constructed	# Roller Gates	Years of Service	Gate Years	# Recorded Incidents
Kanawha River	Winfield Dam	1937	6	81	486	2
	Marmet Dam	1934	5	84	420	
	London Dam	1934	5	84	420	
Mississippi River	Lock 25 Dam	1939	3	79	237	1
	Lock 22 Dam	1939	3	79	237	
	Lock 21 Dam	1935	3	83	249	
	Lock 20 Dam	1935	3	83	249	
	Lock 18 Dam	1937	3	81	243	
	Lock 17 Dam	1939	3	79	237	
	Lock 16 Dam	1937	4	81	324	
	Lock 15 Dam	1934	11	84	924	
	Lock 14 Dam	1935	4	83	332	1
	Lock 13 Dam	1939	3	79	237	
	Lock 12 Dam	1938	3	80	240	
	Lock 11 Dam	1937	3	81	243	
	Lock 10 Dam	1937	4	81	324	
	Lock 9 Dam	1937	5	81	405	
	Lock 8 Dam	1937	5	81	405	
	Lock 7 Dam	1937	5	81	405	
	Lock 6 Dam	1936	5	82	410	
	Lock 5a Dam	1936	5	82	410	
	Lock 5 Dam	1935	6	83	498	
	Lock 4 Dam	1935	6	83	498	
	Lock 3 Dam	1938	4	80	320	>100
Ohio River	R.C. Byrd	1937	8	81	648	
			115		9401	

G-2.2.5 Submergible Tainter Gates

Submergible Tainter gates have been used as a lock gate or as a spillway gate as part of the moveable damming surface of navigation locks and dams. When used as a lock gate they are typically found at the upstream end of the lock. Submergible gates were used as spillway gates so that the gate could be lowered to pass ice and debris. Several locks and dams on the Ohio and upper Mississippi have these types of gates. Due to excessive vibration when lowered, most of these gates are not operated in this manner. In many cases the sill has been modified such that the gates cannot be submerged. Since these gates are generally not submerged, this gate has similar vulnerabilities as Tainter gates covered in other chapters of this manual. If the gates are submerged during operation, the potential for vibration and fatigue cracking should be considered. Figure G-2-5 shows a general cross section of a submergible Tainter gate. For submergible gates used as lock gates, the gates are typically operated under static head only and not used to pass flow (except when flushing ice), so vibration concerns are not an issue.

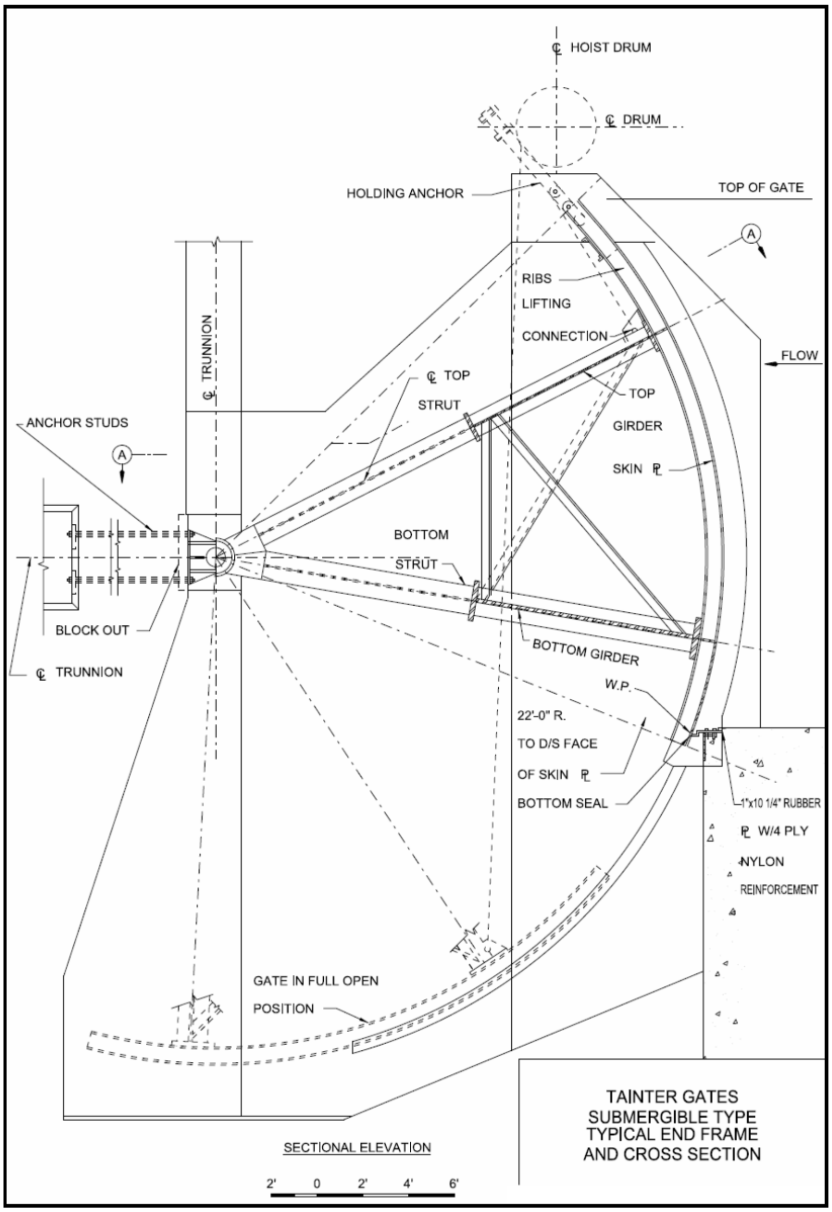

Figure G-2-5.—Typical end frame and cross section, submergible Tainter gate (USACE 2014).

G-2.2.6 Vertical Lift Gates (Navigation Locks and Spillways)

Vertical lift gates have been used to control pool in dams and coastal areas and for lock gates on navigation dams. Some different type of lift gates are large fixed-wheel gates or roller gates, which are raised and lowered with a hoisting mechanism. Failure of one or more of these large gates could release water that exceeds the channel capacity or a sudden surge of water that could surprise recreationists, or in the case of a navigation lock, it could lead to loss of lock service.

For navigation locks, overhead or submergible gates may be used in the lock chambers especially in those with high heads, such as John Day and Ice Harbor Locks and Dam.

Submergible lift gates are usually used as the upstream gate of a lock where the gate rests below the upstream sill, as seen on figure G-2-6. Overhead lift gates, as seen on figure G-2-7, are used as the downstream gate of a lock where the lift is great enough to provide the necessary clearance when the gate is out of the water. This type of gate requires a tower with overhead cables, sheaves, and bull wheels to support the gate during operation and counterweights to assist the hoisting machinery. Vertical gates are commonly used when the space and sufficient support is not available and will not permit the use of miter gates, or as hurricane or tide gates when the gate may be subject to reverse hydrostatic and hydrodynamic loading (USACE 2014b).

Vertical lift gates are used as spillway gates when the amount of head on the gate would require an exceedingly large pier to support a Tainter gate, therefore providing a more economical design.

Vertical lift gates tend to be more robust than radial gates in that there are no compression members subject to potential buckling. The gates carry the load primarily in bending. There have been cases at USACE dams where vertical lift gates have experienced fatigue cracking due to cyclic loading and poor weld details. An example of this (John Day Lock and Dam) is included in the case history section below. Also, as discussed above, there may be a massive gate hoist structure mounted above the gates, with counter-balance weights and hoisting mechanisms. Under seismic loading, excitation of the hoist houses and associated equipment can lead to high stresses and potential shear or moment failure of the supporting structure. If the material falls on the gates, they can be damaged and release water. If damage to the structure prevents operation of the gate for lock, navigation will be lost.

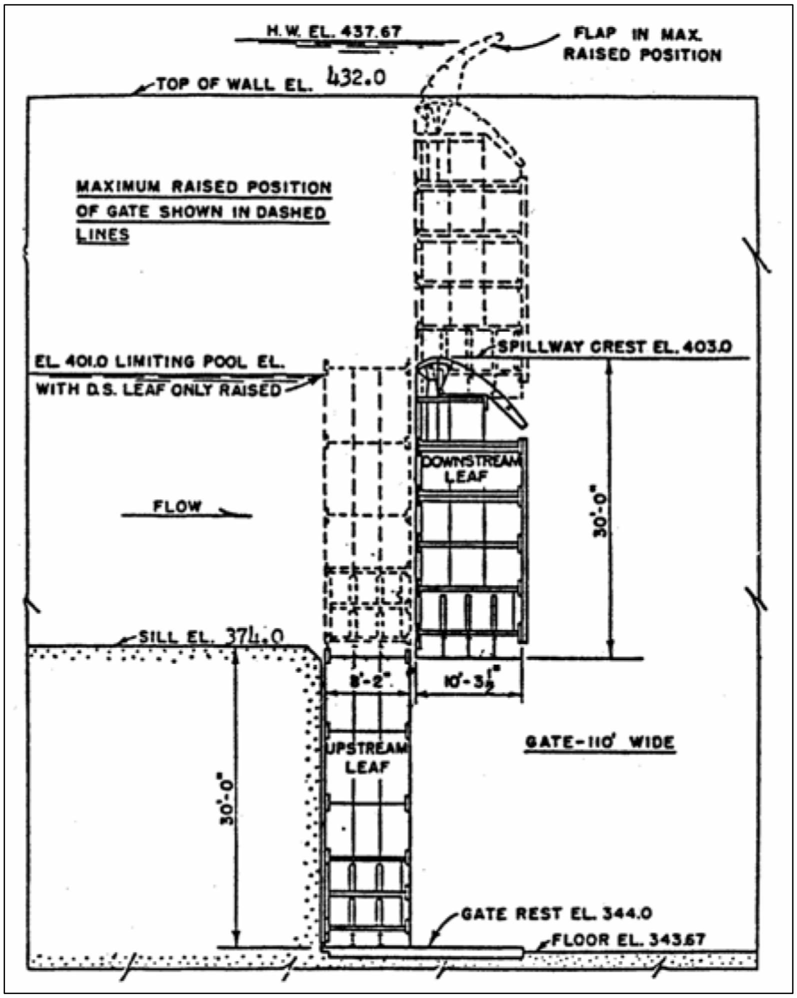

Figure G-2-6.—Submergible vertical lift gate (USACE 2006).

Figure G-2-7.—Overhead vertical lift gate.

G-2.2.7 Miter Gates

Miter gates are the most common gate type used for navigation locks. They consist of a pair of gate leaves mounted on opposing lock walls. When the gates are closed, they are in a mitered position, forming a shallow three hinged arch, with the arch pointing in the upstream direction. When the gates are opened, they are recessed into the lock wall. Miter gates are designed to be vertically or horizontally framed, although horizontally framed gates are more commonly found in the USACE inventory. Horizontally framed gates (figure G-2-8) consist of a series of horizontal girders that are framed together with vertical diaphragms, composed of welded plate sections, with skin plate attached to the upstream flanges. Each horizontal member is supported by the vertical quoin post on one end and the miter post at the other end. Vertical framed gates (figure G-2-9) consist of vertical beams that span from a horizontal girder at the sill to a horizontal girder at the top of the gate. The horizontal girders transfer the load to the miter and the quoin at the top and into the sill at the bottom of the gate. Vertically framed miter gates are usually used in locks with height to width ratio less than 0.5 (USACE 2014a). Since the vertically framed miter gates rely on the concrete sill, the condition of the sill should also be assessed if this type of gate is present.

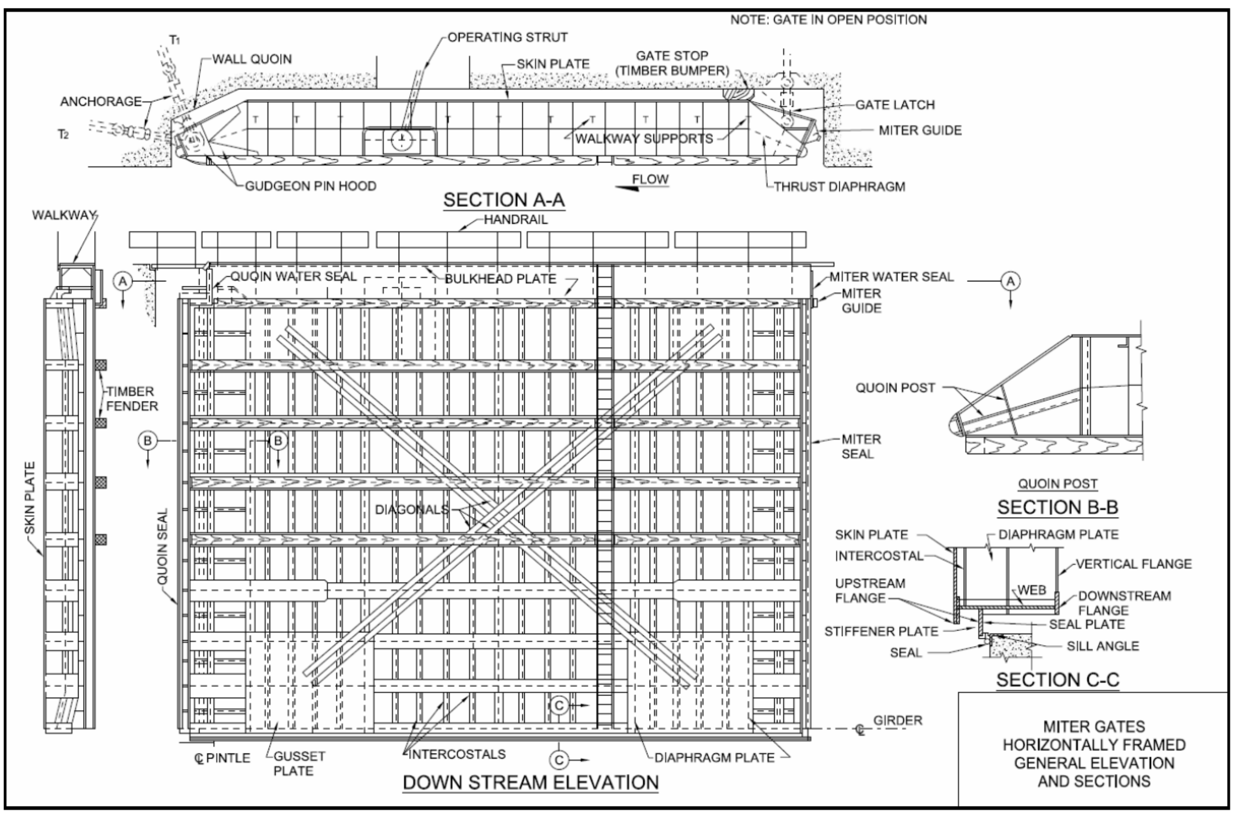

Figure G-2-8.—General elevations and sections, horizontally framed miter gates (USACE 2014a).

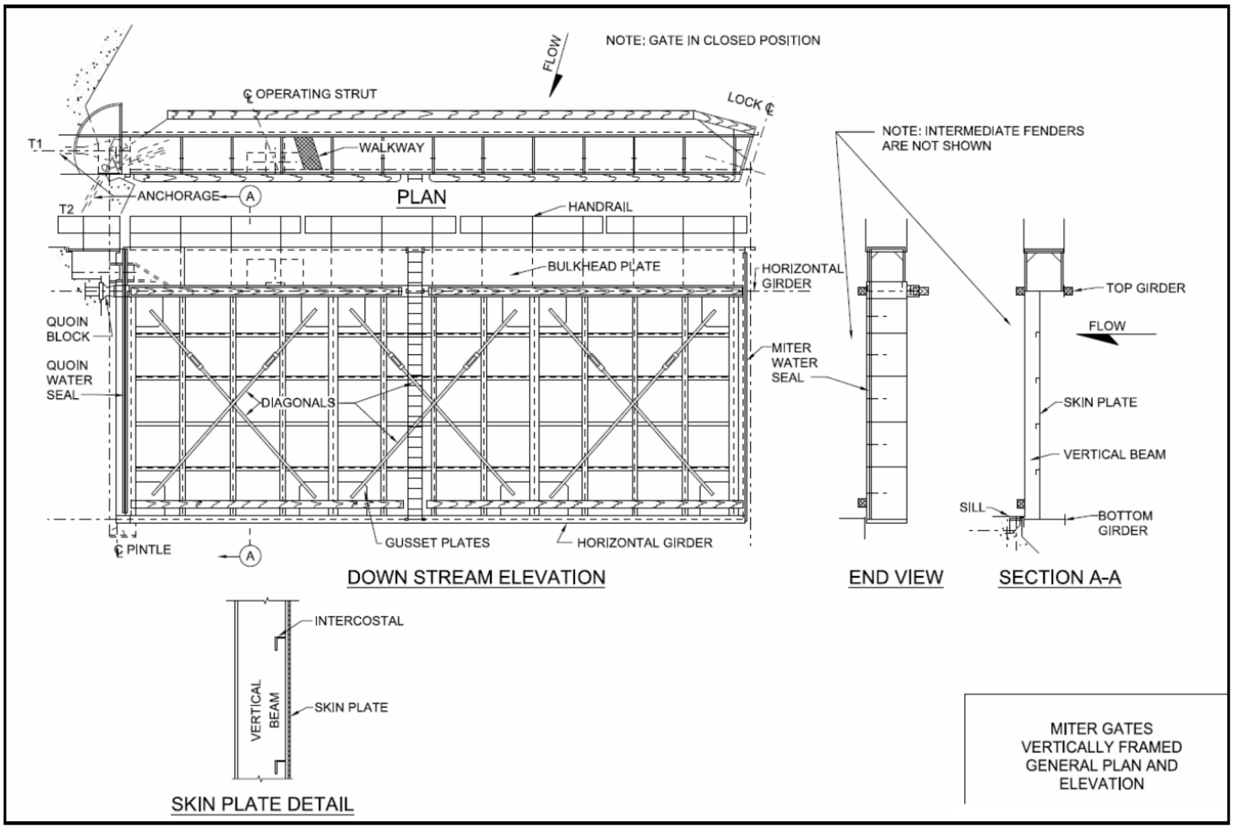

Figure G-2-9.—General plan and elevation, vertically framed miter gates (USACE 2014).

The main structural issues encountered in miter gates are due to the cyclic loading it experiences during lock operation. Fatigue cracking on horizontally framed miter gates has been experienced at a number of dams within USACE. Fatigue cracking occurs due to the stress reversal occurring at the welded connections where stress concentrations and/or residual tensile stresses are present. During operation, loads on the gates are carried through compression, creating a load reversal at these locations, which are exacerbated by the geometric configuration of the welds. In many cases, it has been found that the cracking extends well beyond the weld zone into the base metal of the flanges. This type of cracking is often wide spread since the gate is designed to carry the load through the entire gate structure but is most commonly found near the lower girders near the quoin and miter ends (USACE 2014). Although miter gates are redundant structures, if the cracks are not repaired, they could lead to structural failure of the gate due to buckling or excessive gate movement during mitering. These issues can be worsened by excessive corrosion of the girders. The most severe corrosion generally occurs between upper and lower pool and near the water line where galvanic protection has limited effect and the paint system is damaged by debris and barge impact. There have been numerous examples of unscheduled and extended lock closures for emergency repairs of the miter gates due to fatigue cracking.

Other components of the gate are also subject to cyclic loading and have experienced fatigue cracking as well. Failure of the gudgeon anchor arm has occurred due to fatigue cracking. Since the miter gates are designed to transfer load to the quoin blocks on the wall, the anchor arms are generally only designed to take the operating load of the gate weight as it is opened or closed. As the quoin blocks are worn down over time, more load is transferred to the pintle and anchor arms, increasing the stress range of the anchor arms. Cracks usually start at welded connections due to weld discontinuity and poor weld details. Failure of the embedded anchorage can also occur due to poor weld details and extensive corrosion of the members and the inability to detect corrosion and cracking or access them for repair or replacement.

Cracking has also been found in the flanges where the pintle casting is connected or in the pintle socket casting itself. Cracking in the flanges can cause excessive movement of the pintle, which could result in problems during operation of the gates. Cracking of the pintle socket casting is usually caused by worn or improper adjustment of quoin blocks resulting in loss of contact with the wall quoin. This results in additional load on the pintle, which can lead to cracking of the pintle or failure of the bolts at the girder connection (USACE 2010b). Figure G-2-10 shows cracking around the pintle casting discovered at Greenup Locks and Dam in September 2003.

Figure G-2-10.—Cracking in main chamber miter gates, Greenup Lock and Dam (USACE 2010a).

Since miter gates are designed to take all differential hydrostatic loading through arching action, it is critical that the gates are properly mitered before the chamber is filled. Additionally, the anchor arms are only designed for the weight of the gates leaves, and the operating machinery is only designed to move the gates through static water. Therefore, there should be very limited flow through the chamber when the gates are operated. This means that miter gates are particularly susceptible to operational failures. Miter gates are also susceptible to failure from modes.

Evaluation of the miter gates under seismic loading should also be considered if seismic loading is considered during the risk assessment. A brief description of the two case histories in the USACE' inventory (Markland and Greenup Locks and Dams) is presented later in this chapter.

USACE has over 150 navigation locks within its inventory that have miter gates. There have been many hundreds of incidents amongst these projects, most being the result of barge allisions. Because data has never been summarized for all projects, there is no reliable base incident rate available.

G-2.2.8 Sector Gates

Sector gates are used in coastal areas, where the lock or canal may be subjected to head reversal due to tidal range or storm surge. The gate consists of two leaves that join at the center to create the damming surface and recess into the lock wall when open. The advantage of using sector gates is that they can be loaded from either direction and can be opened and closed under small differential heads, or with flow through the lock. Additionally lock structures with sector gates do not need culverts or culvert valves, as the lock chamber is raised or lowered by simply cracking open the sector gates. Sector gates are generally used for locks with differential head of 15 feet or less. Figure G-2-11 shows a general plan and cross section of a sector gate.

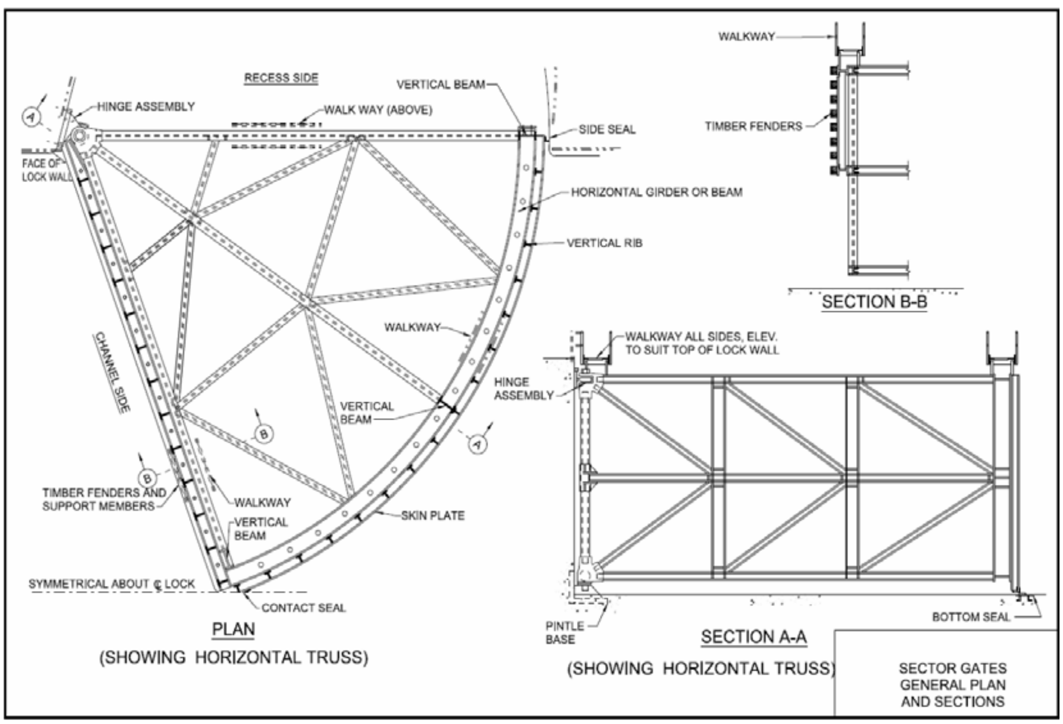

Figure G-2-11.—General plan and section of a sector gate (USACE 2014a).

As in the evaluation of other gates types, vulnerabilities include overstressing due to additional loading than what the gate was designed for, including hydrologic and seismic loads. Evaluation of the anchorage into the lock wall shall also be assessed for movement, section loss, cracks at welded connections, etc. Many sector gates cannot be easily dewatered due to the configuration of their lock chambers (i.e. no bulkhead slots) in conjunction with the high traffic demand associated with them. Because sector gates are typically so large, special high capacity cranes are generally required to remove them from their recesses to permit detailed inspections and repair. Thus corrosion of submerged structural members can be a typical problem.

G-2.2.9 Outlet Works and Penstocks

Outlet works and penstocks tend to generally be operated frequently to release water, and failure of the conduits or gates would typically not release enough water to result in life-threatening flows. However, there may be a case where the outlet works or penstocks have enough capacity to release life-threatening flows. In these cases the gate mechanisms should be reviewed for vulnerabilities. In addition, exposed penstocks or conduits can be subject to high bending stresses during earthquake loading, especially when full of water, potentially resulting in pipe rupture. However, in many cases, the outflows could be limited by the size of the rupture.

G-2.2.10 Culvert Valves – Lock Filling/Emptying System

Reverse Tainter valves are the most common valve type in USACE navigation locks. Reverse Tainter valves differ from Tainter gates in that the trunnion is located upstream of the gate and the skin plate faces the downstream direction. The gate has a “reverse” orientation from the Tainter gates used in dam spillways. Cracks in the reverse Tainter gates have been found in the radial ribs and welds due to vibration caused by high velocity water flow and cyclic loading due to normal operation of the lock. Depending on the design of the filling and emptying system, a failure of this valve may not cause a loss of service. If there are two filling and emptying systems, the damaged gate can be placed out of service without losing the capacity to operate. If there is no redundancy in the system, then a loss of service of the lock will need to be evaluated. A brief description of the USACE Cannelton Lock and Dam valves is presented later in this chapter.

G-2.3 Event Trees

For other types of potential failure modes (PFM) related to gates, the development of event trees follows the same procedure as previously described in this manual. First, the PFMs are identified and described fully from initiation, through step by step progression, to the breach mechanism for uncontrolled release of reservoir water or loss of service. Then, based on this description, an event tree is developed (see "chapter A-5, Event Trees"). It is not possible to show examples for every type of potential failure mechanism associated with gates or valves, and it is incumbent on the risk estimating team to look at each case and determine if there are potentially significant risk contributors. An example event tree is included on figure G-2-12. If there are, the PFMs and event trees should be developed for these cases.

The following are examples of PFM descriptions:

- **Failure of a Drum Gate under Seismic Loading**

  With the reservoir high on the drum gates, a large earthquake occurs at the site that causes large seismic response and cracking through the unreinforced concrete near the base of the upstream float chamber walls. Additional cracking separates the upstream walls from the side walls. The upstream walls with gates still attached at the hinge pin, move into the float chambers. Buoyant forces are sufficient to displace the gates and attached concrete to the point where the gate is no longer effectively retaining water. Failure of one or more gates exceeds the safe downstream channel capacity.

  The event tree developed from this description is shown on figure G-2-12. Only one branch has been fully developed for illustration purposes.

  Structural evaluation of reinforced concrete supporting structure for gates is similar to that already described (refer to the section on Reinforced Concrete Fragility). Hydrodynamic loading must consider the structural response if the gates sit atop a tall concrete structure. Estimating the chance that a gate and the attached concrete would be displaced enough to render the gate ineffective would consider the buoyant forces and likely flow velocity through the damaged gate opening, and the geometry of the opening relative to the gate geometry, but ultimately would be a judgment call (see "chapter A-6, Subjective Probability and Expert Elicitation"). Each branch of the tree can be estimated for a single gate failure, and then the likelihood of multiple gates failing can be estimated using Pascal's Triangle, as described in "chapter G-3, Seismic Failure of Spillway Radial (Tainter) Gates.

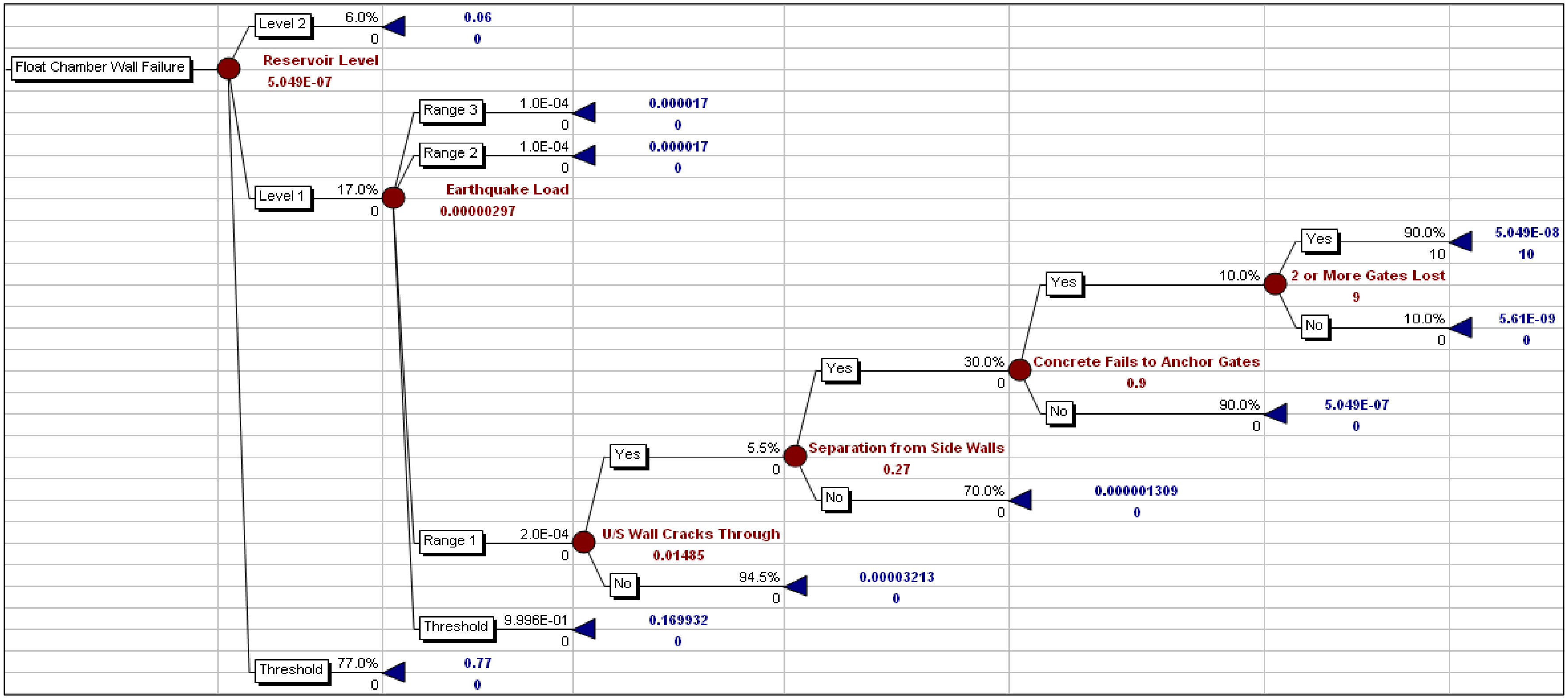

Figure G-2-12.—Example event tree for seismic failure of drum gate wall

- **Miter Gate Failure Due to Fatigue Cracking**

  The main and secondary members of the downstream miter gate have section loss due to corrosion and experienced fatigue cracks. Fatigue cracks continue to form at the welded joints between the horizontal girders and the quoin or miter posts or the welded joints of the diagonal gusset plates. The fatigue cracks are caused by the lock cycles, cycling of residual stresses in the welds, temporal loads, loss of diagonal stress, and impact loadings from tows. The fatigue cracks form and are undetected due to their small size, infrequent inspections, or being hidden by water, corrosion, silt, or debris; therefore, intervention is unsuccessful. The fatigue cracks propagate through one or more main structural members and cause localized failure of the main structural member(s). Failure of a main structural member (horizontal girder, quoin post, miter post, or diagonal gusset plate) renders the miter gate inoperable and results in a lock closure and disruption to navigation traffic.

G-2.4 Consequences

For flood control dams, consequences are evaluated by estimating incremental life loss due to the dam breach. Consequences will be a function of the reservoir level at the time of failure (which determines the breach outflow). Loss of life can be estimated from these breach outflows and the estimated population at risk that would be exposed to the breach outflows, using the procedures outlined in "chapter C-1, Consequences of Dam or Levee Failure" and "chapter G-3, Seismic Failure of Spillway Radial (Tainter) Gates."

Failure of a navigation dam can be defined as breach of the damming surface or artificial raising of pool due to spillway blockage. This could lead to inundation of individuals downstream (high hazard dams only); overtopping of upstream control structures such as levees due to the artificial raise of pool, leading to inundation; or loss of pool leading to loss of navigation, hydropower generation, municipal/industrial water intakes, etc. Life loss consequences due to downstream inundation shall be evaluated for high hazard locks and dams or when the failure modes lead to life loss in all navigation dams (i.e., upstream inundation or project/navigation industry personnel). Economic consequences due to failure of a navigation lock and dam shall be evaluated when the failure mode does not lead to life loss. Some of the economic damages to consider include:

- Impacts due to loss of service/navigation, including the navigation industry when the lock(s) is out of service or municipal/industrial water intakes when pool is lost

- Downstream property flood damage when releases due to a dam breach exceed downstream channel capacity

- Upstream property flood damage when there is an artificial rise or lowering of the pool
- Loss of hydropower generation
- Emergency repairs to get the project back in service

Navigation Transit Delay Cost tables are available through the Navigation Planning Center of Expertise to estimate economic damages due to loss of service. The table includes navigation delay costs for consecutive number of days that all lock projects in the USACE inventory are unavailable for service. Economic impacts due to loss of navigation should only consider unscheduled closures of the lock(s). The Navigation Transit Delay Cost tables assume all closures are unscheduled and are available for both full and partial closures; where a full closure includes both lock chambers, and a partial closure only considers closure of the main chamber. If a failure mode only affects the auxiliary chamber, economic impacts are generally assumed to be minimal. When using these tables, consideration should be given to the date of publication and what potential changes may have occurred since publication (e.g., change in local industry, inflation, etc.).

When evaluating consequences due to a gate failure at a project, consideration should be given to the availability of stop logs that can be set under flowing conditions. These could have significant affects in consequence estimates.

G-2.5 Accounting for Uncertainty

The method of accounting for uncertainty in seismic loading is described in "chapter A-5, Event Trees." Typically, the reservoir elevation exceedance probabilities are taken directly from the historical reservoir operations data, which do not account for uncertainty. Uncertainty in the failure probability and consequences are accounted for by entering the estimates as distributions (as describe above) rather than single point values. A Monte Carlo simulation is then run to display the uncertainty in the estimates, as described in "chapter A-8, Combining and Portraying Risks." As with all PFMs, parametric or sensitivity studies are key to understanding the risk uncertainty. The rank sensitivity coefficients from @Risk can be used to get a handle on which parameters affect the risk the most. Varying the distributions associated with these parameters within reasonable possibilities can provide insight as to how the risks might change with different input. The possible need for additional information to tighten the estimates for critical parameters can then be evaluated.

G-2.6 Relevant Case Histories

G-2.6.1 Guernsey Dam Drum Gates

One of two drum gates at the south (right) spillway of Guernsey Dam, Wyoming. inadvertently opened in 1986. A painting contractor left trash within the gate which eventually plugged the drain line. The interior of the gate filled with water and the gate lost buoyancy. The gate lowered about half way in seven hours before the problem was recognized and the trash cleared from the drain line. Although the downstream discharge increased significantly, the downstream channel capacity was never exceeded and there were no injuries or fatalities (Graham and Hilldale 2001).

G-2.6.2 Black Canyon Diversion Dam Drum Gates

Extension plates were added to the Black Canyon Diversion Dam drum gates to raise the lake level twice (in 1952 and 1998). During the week of December 15, 1998 during routine exercising of the drum gates, Gate No. 3 was lowered about 1.5 feet, but attempts to raise the gate failed. The gate was lowered another 6 inches, but again could not be raised from that position. The reservoir was lowered and it was found that drain line nipple had come unthreaded from the swivel joint. The gate did not sink entirely because a check valve closed or the drain line on the other end of the gate passed enough water to maintain equilibrium. In 2001, it was discovered that 13 of the 17 hinge pins in Gate No. 3 were fractured. (Only one hinge pin in each of the other two gates was found to be fractured.) The bushings were re-bored, re-aligned and the pins were replaced.

G-2.6.3 Cresta Dam Drum Gates, California

Cresta Dam, California, is located on the North Fork of the Feather River, and is a key feature in PG&E’s Feather River hydroelectric system. The dam forms the forebay for Cresta Powerhouse and was constructed in 1949. There are two 124-foot long by 28-foot high drum gates at the top of Cresta Dam. Drum gates at Cresta Dam are raised to maintain the reservoir level for electric power generation at the Cresta Powerhouse under normal operations and operated to regulate spills during high river flow conditions. On July 5, 1997, the left drum gate at Cresta Dam began to drop uncontrollably. The gate took about 20 to 30 minutes to completely lower. The downstream water level rose from 1.59 feet to 15 feet in approximately 40 minutes. The maximum recorded downstream discharge was 15,140 ft^3/s. No injuries or fatalities occurred as a result of the gate failure.

The left drum gate at Cresta Dam dropped primarily due to a combination of failure of the drum gate drain line and leakage into the drum gate. Failure of the drum gate drain line was likely caused by crimping of the drain line at the downstream stop seal. Water accumulated in the drum gate due to leakage through the check valves as a result of failure of the drum gate drain lines and normal leakage into the drum gate through connections, hatches and the gate skin (Pacific Gas & Electric Company 1997).

G-2.6.4 Markland Lock and Dam Miter Gate Fatigue Cracking

A dewatering was scheduled for the main chamber at Markland Locks and Dam, Pennsylvania, in 1994 to perform major maintenance including jacking the miter gates and replacing the pintle and seals. Once the lock was dewatered and the gates were inspected, severe cracking was found in some of the welds of the horizontal girders as shown on figure G-2-13. In particular, the heaviest cracking occurred near the pintle area on the lower girders. It was determined that the extensive cracking was fatigue-related and additional finite element analysis was done to help determine the cause for the extensive cracking. Through the additional analysis, it was determined that the cracking was due to residual tensile stresses present near the girder welds. When welding occurs during original construction, large stresses are developed in the members near the weld joints. During operation of the gate, the members are subjected to compression loads, causing a stress reversal at these locations. Since the gates were considered to be in critical condition, immediate repairs were made to the gate during the dewatering. This included gouging out the cracks and rewelding. To evaluate the performance of the repairs, another dewatering was scheduled in 1996 It was found that the cracks had re-initiated at the same locations where they had been repaired during the 1994 dewatering. Other modifications were made to the gate during the dewatering of 1996 including adding structural plates, etc., but the condition of the gate was still considered critical. Louisville District Operations and Engineering Divisions instituted a 2-3 year dewatering interval to continue to monitor the gates until the gates were replaced (USACE 1999a).

Figure G-2-13.—Fatigue cracking in girder flange at diagonal anchor plate, Markland Lock and Dam (USACE 2010b).

G-2.6.5 Greenup Locks and Dam Anchor Arm Failure

The emergency closure of Greenup Locks and Dam, Kentucky, main chamber took place from Wednesday, January 27 through Monday, February 22, 2010. The closure resulted from a sudden fatigue failure of the miter anchor arm on the main chamber downstream middle wall gate leaf as shown on figure G-2-14. The gate was being properly operated during a routine up bound lockage. No operator error occurred. The failure initiated at the root of a fillet weld connecting the miter anchor arm to the top connecting link and propagated through the entire cross section of the miter anchor arm. The weld was shown on the original contract drawings and had been identified during Periodic Inspection No. 8 performed in July 2008 as a poor weld detail for a tension member. Visual inspection of the root of the weld and base material subsequent to failure indicates the crack had initiated prior to the failure as evidenced by corrosion in the crack. The crack was not visible during prior inspections due to limited accessibility, paint and over spill of lubricating grease for the gudgeon pin.

Figure G-2-14.—Failed Anchor Arm, Greenup Lock and Dam (USACE 2010a).

The gate came to rest on the concrete sill in a near vertical position supported by the pintle, strut arm and the remaining non fractured but damaged recess anchor arm. Emergency repairs were performed on January 29, 2010 by welding a splice plate to the fractured anchor arm and other gate stabilization efforts were completed to prevent more damage to the gate. The miter gate was removed and a detailed structural inspection was performed on the gate and anchorage. Dive inspections were performed on the gate sill and pintle. Anchor wedge assemblies, anchor arms, connector plates, gudgeon and link pins were replaced and the gate was reinstalled on February 21, 2010. A final inspection was done on February 22, 2010 and the main lock chamber was reopened for traffic (USACE 2010a).

G-2.6.6 Cannelton Locks and Dam Culvert Valve Failure

The lower river wall emptying culvert valve for the main chamber at Cannelton Locks and Dam, Indiana and Kentucky, was reported to be inoperable on September 10, 1999. The valve emergency bulkheads were set by lock personnel, but extensive leakage prohibited immediate dewatering of the valve chamber. The Louisville Repair Station arrived at the site early in the week of October 4 and were able to get the bulkheads set and the chamber pumped down so that the valve could be inspected and removed for repairs. The initial inspection was performed on Wednesday, October 6, 1999. The valve was inspected in-situ in the valve chamber. The valve was bound against the sidewalls and had a slight twist in a clockwise direction as viewed facing downstream. The skin plate and vertical rib beams were torn away from the lower girder as shown on figure G-2-15. The fillet welds that attached the rib beams to the lower girder had failed. The second and third vertical rib beams were fractured completely through the flange and extended through the web, and proceeded to tear the stem of the T-beam away from the skin plate. These beams had also broken loose from the upper girder. The end vertical rib beam nearest the Kentucky side suffered a fractured web. The downstream flanges of both of these girders experienced warping when the rib beams tore away. The culvert valve was removed and inspected more closely and it was found that the main valve body was considered structurally sound and deemed capable of service. The failure of the valve may be attributed to fatigue of the welds which connect the rib T-beams to the lower girder beam of the main valve frame. Cannelton's 1,200 foot chamber has experienced a significant number of open/close cycles in its 30 year career; this is categorized as low cycle fatigue loading. In addition to the low cycle static loading imparted by differential hydraulic head, the valve also experienced high cycle fatigue due to turbulent flow conditions (USACE 1999b).

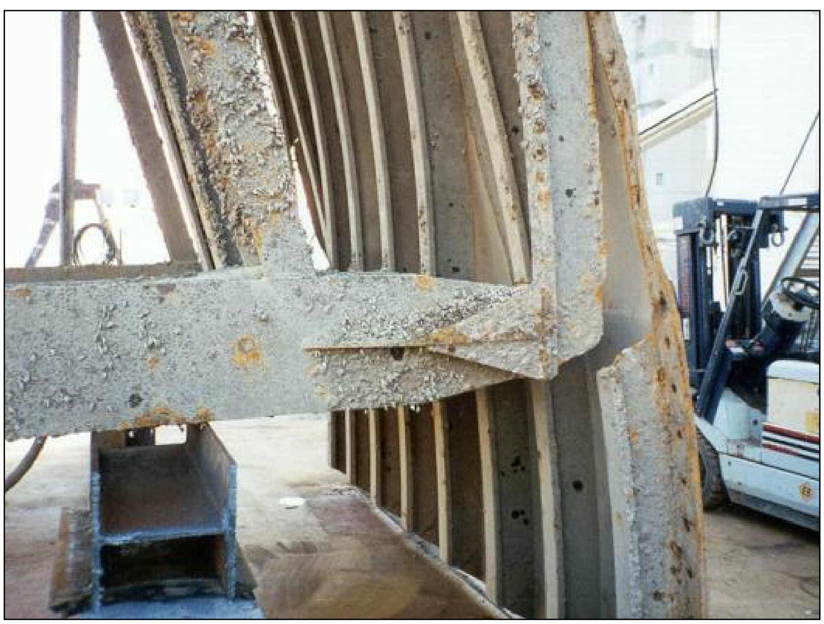

Figure G-2-15.—Failed culvert valve, Cannelton Locks and Dam.

G-2.6.7 John Day Lock and Dam Vertical Lift Gate Fatigue Cracking

The downstream lock gate at John Day Lock and Dam, Oregon, is a vertical lift gate 88 feet wide and 113 feet high. The gate was placed in service in 1963 and was exposed to full pool starting in 1968. A vertical section of the lift gate at the arch frame is shown on figure G-2-16. The gate has exhibited cracking problems of welds and members since 1982. Maintenance of the gate and crack repair has been ongoing at periodic intervals since cracking was first observed. In the periodic inspection conducted in 1994 a significant number of large cracks were noticed at locations where welds were placed in the tension tie, in particular at the welded connections between the bracing and the tension tie and in the tension tie connection to the compression member at the vee joint as shown on figure G-2-17. Because of the concern generated by the reemergence of the cracks, additional analysis was performed using finite element analysis, calibrated with strain gauges on the gate. The contractor was asked to evaluate the condition of the gate, estimate the remaining service life and develop possible modifications to extend the life of the gate. Based on the finite element analysis results it was determined that the cracking in the steel tension ties was caused by cyclic stress which exceeded the fatigue limit of the steel material at the welded connections. Fatigue sensitive weld details and poor weld quality contributed to failures early in the expected life of the lift gate (USACE 1995) . The gate remained in service through maintenance and repairs until 2011 when the gate was replaced at a cost of $12 million. The gate at John Day was modeled after the gate design for the vertical lift gate at Ice Harbor Locks and Dam. The gate at Ice Harbor was placed in service in 1962 and cracking was first discovered in 1980. Fatigue cracking at Ice Harbor lead to gate replacement in 1996 with a 2 month construction outage and a cost of 6.5 million dollars (Hanson and Chambers 2001).

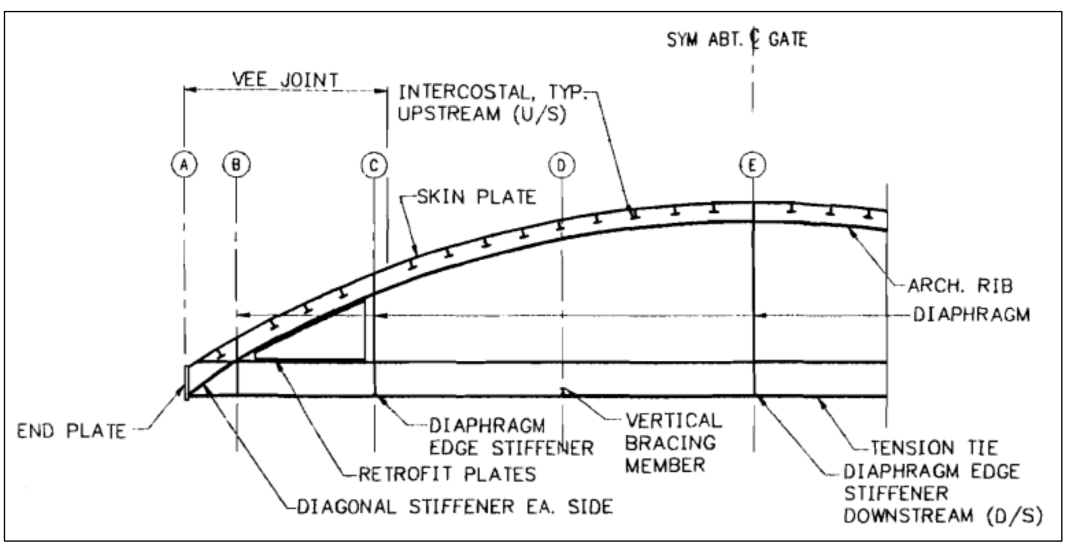

Figure G-2-16.—Vertical lift gate section at the arch frame, John Day Lock and Dam (USACE 1995).

Figure G-2-17.—Fatigue cracking in the tension tie, vertical lift gate, John Day Locks and Dam (Hanson and Chambers 2001).

G-2.6.8 Mississippi River L&D 25 Roller Gate Incident

The emergency repair of a roller gate at Mississippi River Dam 25, Missouri, took place as a result of an incident in April 2010. The incident resulted from a limit switch failure. During a routine gate raising operation as the river was rising to a level in which all gates were being fully raised, the upper limit switch gear of one of the project's three 109-foot-long roller gates moved out of its shaft, which prevented it from turning. As a result, the chain hoisted the gate all the way up to the point at which the hoist chain connection was ripped out of the gate, resulting in heavy damage to no fewer than five chain lug plates. It was believed that no operator error occurred.

The gate came to rest at an angle with the cog/hoist end up into the bottom of the machinery house as shown on figure G-2-18. Emergency repairs began immediately by installing emergency stoplogs to stop flow. Damage was severe enough that engineers decided the gate had to be completely removed in order to implement complete repairs. Removing the gate required multiple attempts with various rigging arrangements. The clear distance from pier to pier is 100 feet; with a gate length of 109 feet, the gate would not clear the pier house. This was the first time a roller gate had ever been removed from a USACE dam. The gate was repaired on a special work barge. During repairs it was discovered that over six feet of mud had accumulated inside the roller gate body; this was removed. Because both side shields were damaged during the failure, each had to be removed and replaced with new custom fabricated replacements, as well as the chain lug plates. To facilitate re-installation, approximately 30 feet of the apron had to be temporarily removed. The fully repaired gate was successfully reinstalled by the summer of 2010 (USACE 2011).

Figure G-2-18.—Damaged roller gate, Mississippi River Lock and Dam 25 (USACE 2011).

G-2.7 References

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