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USACE Portland District Spillway Gate Rehabilitation Program

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ABSTRACT

The U.S. Army Corps of Engineers (USACE) Portland District has 90 spillway radial Tainter gates. There are 42 gates at the 11 Willamette Valley Basin projects, 5 gates at the two Rogue Basin projects, and 43 gates at the two Columbia River projects. Since 2001, there have been various studies, inspections, and incidents that have prompted the Portland District to become concerned about the structural integrity and mechanical and electrical reliability of these gates. In 2008, load induced buckling was observed on three of the four Tainter gate end frames at Foster Dam, which led to emergency repairs. Additional observations of buckled Tainter gate strut arms at Dexter Dam in December 2009 required repairs and created urgency with respect to documenting the risk to the downstream population at all District projects. These events led to a comprehensive assessment of the Tainter gates in the Willamette Valley and Rogue Basin projects, which was implemented in 2010. The comprehensive assessment included a gates specific potential failure modes analysis (PFMA); structural, mechanical, and electrical assessments; identification of interim risk reduction measures (IRRM); and analysis of impacts of the interim risk reduction measures. As part of this assessment, the District developed a tool for prioritizing projects for gate repair based on the results of the assessment. Since identifying the issues with Tainter gates, Portland District has implemented IRRMs, taken a systems-based approach to repairs, and implemented a capitalization program to improve gate reliability. Repairs are complete or underway at 36 of the 42 Tainter gates in the Willamette Valley. A study is underway to address reliability of regulating outlets, and future studies are planned for Columbia River spillway gates.

Keywords: *Spillway, Gates, Risk, Rehabilitation, Tainter, Radial.*

1. INTRODUCTION

The US Army Corps of Engineers (USACE) Portland District has 90 spillway Tainter gates. There are 42 gates at the Willamette Valley projects, 5 gates at the Rogue Valley projects, and 43 gates at the Columbia River projects. Table 1 provides an inventory of Portland District's Tainter Gates. Since 2001, there have been various studies, inspections, and incidents that have prompted the Portland District to become concerned about the structural integrity and mechanical and electrical reliability of these gates. There are several factors that led to this conclusion:

- The consequences, both life safety and economic, of an unreliable spillway Tainter gate system are significant.
 - Life safety consequences are greatest at the Willamette and Rogue River projects where a full pool release through a spillway bay exceeds downstream channel capacity. These projects have large volume reservoirs and little or no other means to evacuate the reservoir.
 - Economic consequences dominate on the Columbia River projects due to lost hydropower and navigation. Life safety consequences are considered minimal on the Columbia River projects.
 - Design criteria have been updated as knowledge expanded due to operational experience. The majority of the District's gates are deficient when evaluated under the current design guidance. New guidance includes effects of loads such as trunnion friction and single sided hoisting. Structural analysis indicates that the gates are overstressed when operated, even under normal pool levels.
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- Spillway Tainter gate trunnions across the US have had issues with seized or “frozen” trunnion bearings. This has also been experienced in the Portland District. Seized trunnion bearings are the result of deferred maintenance and have resulted in sheared keeper plate bolts and increased trunnion friction.
- Fabrication deficiencies have been identified during inspections. The primary fabrication deficiency is poor weld quality, which has resulted in cracked welds.
- Operational use changes have occurred. These operational changes include spilling with small gate openings (1 to 2 foot gate opening of a 30 to 40 foot gate) for improvements to water quality (temperature control), spilling for fish passage, and spilling for power load balancing resulting from wind power generation being added to the grid.
- Inspections have identified numerous deficiencies including: localized buckled members, wire rope failures, seized trunnion pins, cracks in steel in gate members, and deformed members.

Table 1 - Portland District Tainter Gates and Status.

Project	Total Number of Gates	Placed In Service	Status
Willamette Valley Basin Projects			
<i>North Santiam Subbasin</i>			
Detroit	6	1950	In Design
Big Cliff	3	1951	Repairs Complete
<i>South Santiam Subbasin</i>			
Green Peter	2	1962	Repairs Complete
Foster	4	1964	Repairs Complete
<i>McKenzie River Subbasin</i>			
Cougar	2	1959	Construction to start in 2016
Blue River	2	1965	In Design
<i>Middle Fork Willamette Subbasin</i>			
Hills Creek	3	1957	In Construction
Lookout Point	5	1951	In Construction
Dexter	7	1953	Repairs Complete
Fall Creek	2	1963	Repairs Complete
<i>Coast Fork Willamette and Long Tom Subbasins</i>			
Fern Ridge	6	1940	Structural Repairs not Required Mechanical and Electrical Repairs are Planned
Rogue Valley Projects			
Applegate	2	1988	Repairs not Required
Lost Creek	3	1976	Structural Repairs not Required Mechanical and Electrical Repairs are Planned
Columbia River Projects			
The Dalles	23	1952	Future Work
John Day	20	1966	Future Work

1.1. Tainter Gate Assessment

In 2010, the current reliability and safety of Portland District Spillway Gate Systems was assessed due to recent events:

2008 – buckled Tainter gate strut arms at three of the four Tainter gates at Foster Dam led to emergency Tainter gate repairs.

2009 – wire rope failure at two of three gates at Big Cliff led to emergency wire rope replacement.

2009 – buckled Tainter gate strut arms at Dexter Dam where emergency Tainter gate repairs were implemented.

The assessment was done using risk-based tools and a risk-informed decision making process. The goal of this analysis was to inform the Portland District about the risk associated with the operability and dependability of spillway Tainter gates. By establishing the relative risk at each of these projects, a prioritization of risk mitigation and IRRMs can be established. IRRMs are a temporary approach to reduce Dam Safety risks while long-term solutions are being pursued. In establishing IRRMs, the prevention of loss of life is the first and foremost objective, followed by prevention of catastrophic economic or environmental losses. A systems-based repair and capitalization program was implemented to improve gate reliability. Repairs are complete or underway at 30 of the 42 Tainter gates in the Willamette Valley.

2. INTERIM RISK REDUCTION MEASURES

To reduce risk associated with failure of the Tainter gates, gate operating restrictions were implemented at 9 projects on an interim basis until the gates could be rehabilitated. Operation of the gates with the pool near the top of the gate can mobilize large friction forces within the trunnion, resulting in additional bending in the struts. If these forces are large enough, the gate structure could catastrophically fail, resulting in a sudden release of water from behind the gate.

Analysis showed that operating the gates at these 9 projects with the pool above the upper girder on the gate could overstress the struts. Gate operating restrictions were implemented that prevented the gate from being operated if the pool was above a certain elevation on the skin plate. Typically, the elevation was at the upper girder. Implementing the gate operating restrictions significantly reduces the likelihood that the Tainter gates would be operated with the pool above the upper girder. However, it is possible to operate at a higher pool elevation than the elevation of the upper girder by raising the gates as the pool rises (the gates would need to track with the pool). Gate operating restrictions remain in place until rehabilitation work on the Tainter gates is completed.

3. GATE REPAIR PROGRAM

Although structural concerns initiated the spillway gate rehabilitation program effort, Portland District realized through the PFMA process that a systems based approach was necessary for spillway gate rehabilitation. Portland District focused on four factors to ensure reliability and safety:

- Structural strengthening
- Improving mechanical reliability
- Improving electrical reliability
- Implementing a regular operational testing, maintenance, and inspection program

3.1. Structural Strengthening

The structural problem encountered was that spillway Tainter gates required strengthening due to unaccounted loads (typically trunnion friction) and new design criteria. The objective of the program was to strengthen the gates to meet the current design criteria. Typically, the overstressed members were the struts, ribs, and horizontal girders. The criteria used to strengthen the gates came from USACE EM 1110-2-2702 and USACE ETL 1110-2-584.

Finite element models (FEM) were built for each gate including separate models for quality control purposes. Load combinations were run from the criteria to determine the worst case loading and to ultimately determine which members were overstressed. At the same time, steel samples were taken from gates in order to verify yield and ultimate strengths as well as chemical composition for weldability determination.

The most significant issue involved in the strengthening program was to address the large machinery load (Q) that occurs in a few of the load combinations as seen in Table 2. The maximum applied machinery load is generally two to five times larger than the required lifting load. This load is a force applied to the gate from the lifting hoists and

occurs when the gate is jammed within its bay in a non-moving, single-sided hoisting event (LC 5) or when the gate is completely open bearing against its gate stops (LC 6) while the hoist is still operating. To overcome this issue, a load limiting device (LLD) was incorporated into the design, which limited the hoisting load to what was required to operate the gate under its worst case loading (LC 3, single-sided hoisting, gate moving) in order to achieve the flood control mission.

Welding and fabrication issues from the 1950s and '60s needed to be addressed. Typically, complete joint penetration welds were not back-gouged, which left a line of indications at the joint's mid-depth and effectively made them partial penetration welds. Back-gouging is a process that removes imperfections from a partially welded joint to assure complete fusion upon subsequent welding. Therefore, a fit-for-service weld analysis was performed to ascertain if the joint had adequate capacity. Intersecting welds that cause restraint within the joint and that can lead to fracture were drilled out to eliminate a brittle failure mode (Figure 1).

Table 2 - Load Factors for Tainter Gates.

Load Cases			Loads/Load Factors							
			D	G	Hs	Hd	Q	EV	IM	EQ
Limit State	Description	Case	γ_D	γ_G	γ_{Hs}	γ_{Hd}	γ_Q	γ_{EV}	γ_{IM}	γ_{EQ}
Strength I	Gate Closed	1	1.2	1.6	1.4Hs2	0	1.2Q1	0	0	0
Strength I	Gate Closed	1	1.2	1.6	1.4Hs2	1.2(1)	1.2Q2	0	1.6(1)	0
Strength II	Usual Operation	2.a	1.2	1.6	1.4Hs3	0	1.4QFs2+ 1.0QFt2	0	0	0
Strength II	Usual Operation	2.b	1.2	1.6	1.4Hs2	1.2(1)	1.4QFs2+ 1.0QFt2	0	1.6(1)	0
Strength II	Unusual Operation	3	1.2	1.6	1.4Hs2	0	1.4QFs2+ 1.0QFt2	0	0	0
Extreme I	Gate Closed	4.a	1.2	1.6	1.4Hs3	0	1.2Q2	0	0	0
Extreme I	Gate Closed	4.b	1.2	1.6	1.4Hs1	0	0	0	0	1.0EQ
Extreme I	Gate Jammed	5	1.2	1.6	1.4Hs2	0	1.2Q3	0	0	0
Extreme I	Gate Opened	6	$\gamma_{D2}(2)$	$\gamma_{G2}(2)$	0	0	1.2Q3(1)	1.3W(1)	0	1.0EQ(1)
Notes: (1) Select one at a time										
(2) Use max or min values, whichever produces maximum effects										
D – dead loads; G – gravity loads (silt, debris, ice); Hs – hydrostatic; Hd – hydrodynamic; Q – machinery load; EV – environmental loads (wind); IM – impact loads; EQ – earthquake load; γ – load factor to be applied to loads as indicated in table.										

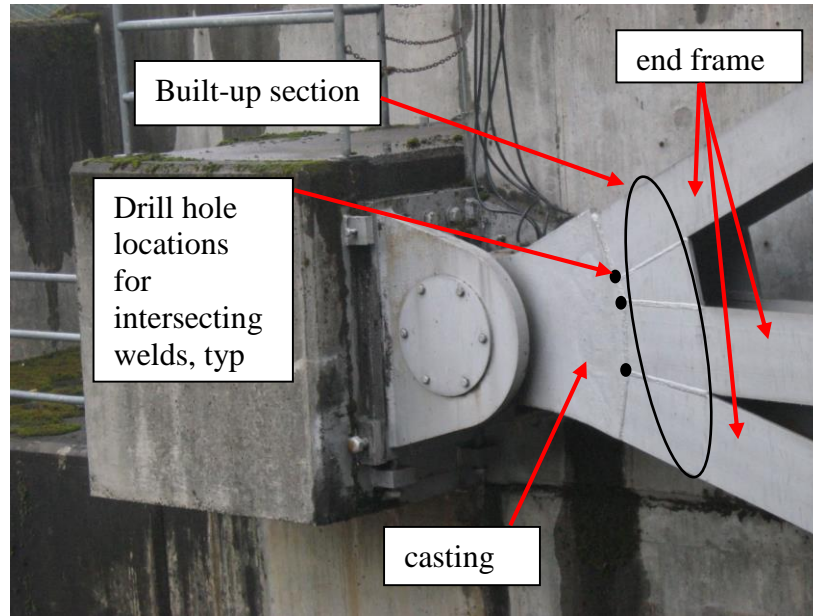


Figure 1. End Frame at Casting Intersecting Welds, Fall Creek Dam, Lowell, Oregon.

Various repair options were considered for each individual project, taking into account scheduling, cost, constructability, and the risk of unknown field conditions that have been experienced on similar jobs performed in the past. Generally, the strut arms, ribs, and horizontal girders required strengthening. The ribs and girders were reinforced by either additional bracing or increasing the section. Repair options considered for strengthening of the strut arms included cover plates, complete end frame replacement (struts and strut bracing), and additional bracing. The addition of bracing (to decrease the effective length of the strut arms) was typically not a viable option. The strut arms see significant axial and weak axis bending forces and relatively small strong axis bending forces. Therefore, even if the strong axis of the strut arms could be effectively braced, the additional capacity gained would not do very much to bring down the stress level in the section. Bracing would be required to cross the width of the spillway to the gate's adjacent end frame or attach to the horizontal girders, making strong axis bracing impractical. The location of the existing weak axis bracing from the original design is typically at its optimal location. Therefore, the strut arm section's axial capacity is 'capped off' and any additional bracing that would decrease the strut's effective length would not increase section axial capacity.

There are numerous benefits associated with a repair that reinforces the strut arms with cover plates. This lessens work scope, saves time and cost, and lessens the impact on other disciplines as opposed to a greater work scope such as replacing end frames. Cover plates have been implemented at Willamette Valley projects such as Fall Creek and Lookout Point Dams outside of Lowell, Oregon, and Foster Dam outside Sweet Home, Oregon. The strengthening of the Fall Creek Dam spillway gates may be seen in Figure 2. However, there are issues that need to be evaluated if this option is to be implemented. For instance, cover plate termination before the casting was required for the Fall Creek project. It is not desirable to weld to the castings due to potential cracking concerns and melting of the trunnion bushing from welding heat. An analysis was performed in order to determine if the built-up section immediately upstream of the steel casting (not reinforced with a cover plate) had adequate strength (Figure 1 and Figure 2). Fatigue is an issue that needs to be addressed for cover plates. Welded cover plate terminations have an undesirable fatigue category associated with them, which can ultimately lead to fracture of the base metal member.

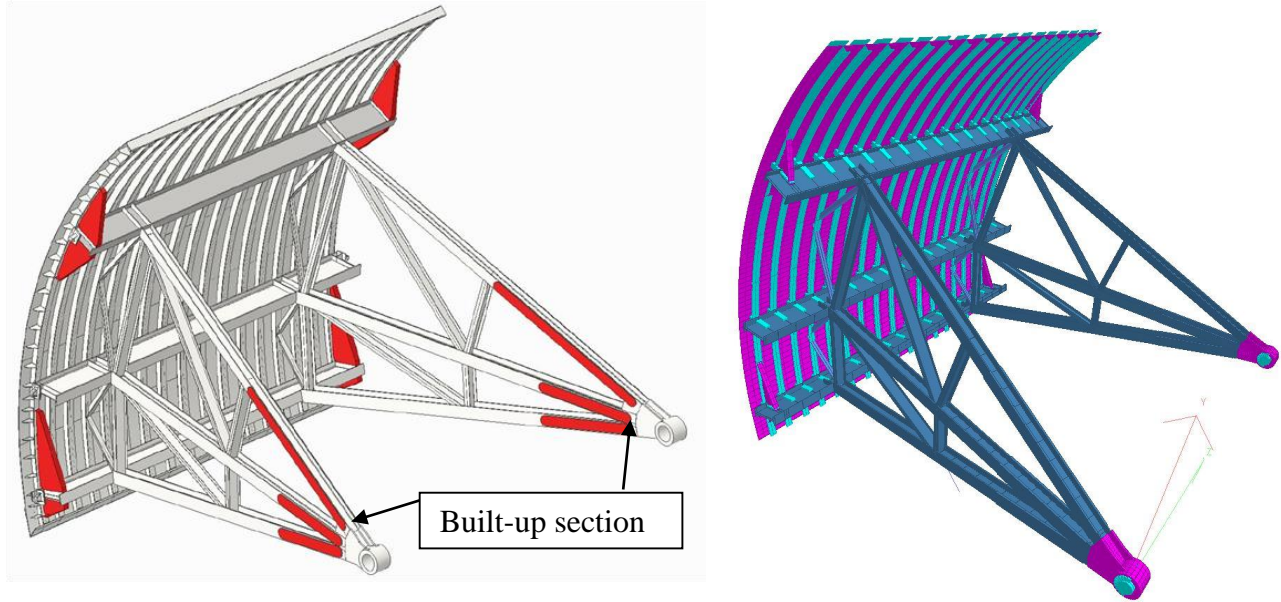


Figure 2. Strengthening (Red Highlights) of Fall Creek Dam Spillway Gates. Drawing Isometric Left and FEM Isometric Right.

Complete end frame replacement, including the trunnion hub, is another strengthening option which was implemented at Dexter Dam Spillway gates outside of Lowell, Oregon (Figure 3), Big Cliff Dam outside of Detroit, Oregon, and Green Peter and Foster Dams outside of Sweet Home, Oregon. This option is obviously more expensive than cover plates and also requires additional work and schedule considerations since the gate will be taken off seal. However, this option minimizes the risk of unexpected field conditions and results in a new end frame that utilizes modern steel and welding techniques, increasing long term reliability.



Figure 3. New End Frame at Dexter Dam Spillway Gates, Lowell, Oregon.

3.2. Electrical Modifications for Reliability

The electrical assessment was conducted to establish a probability of failure for the electrical components associated with the operation of spillway Tainter gates at Portland District projects. For the purposes of the electrical assessment, the probability of failure is defined as the probability that an individual gate will not operate the next time operation is attempted. It does not take into account the reasons behind the necessity for operation, the consequences of inoperability, or the timeframe required to troubleshoot and repair the failed component. The goal is to obtain a probability of failure below 1.0E-04 for each gate individually and also for the gate system at each project. This reliability metric was developed by Jack Lewin in the evaluation “Reliability Assessment of Spillway Gate Installations” written in November 2001.

At each project, the electrical equipment was subdivided into three primary categories: (1) power sources; (2) power distribution; and (3) control equipment. A probability of failure for each category was derived by developing a fault tree based on the project’s electrical configuration and distribution system, as well as its local control equipment. The three individual values were then summed to provide an overall project spillway electrical probability of failure.

From the results of the Portland District reliability study, it was observed that the dominant probability of failure lies with the local control equipment, which is also the easiest and least expensive to repair or replace. The second most likely to cause a failure of the gate to operate is the loss of distribution equipment due to the lack of redundancy in dam power feeders at most of Portland District sites. The least likely to cause a failure to operate is the loss of all power sources, which includes utility power, loss of medium voltage switchgear in the powerhouse, and emergency backup generators.

In order to increase the reliability of the Portland District spillway gate electrical systems, the following modifications have been made to the gate systems as part of the gate rehab projects:

Controls: Replace entire control systems for all spillway gates, which were all original and at or nearing the end of their 50yr design life. Convert all local spillway gate control systems to deadman style pendant controls and provide multiple pendants for each site that can be used on all new gate systems across Portland District’s sites. This pendant style system provides redundant pushbutton controls and thus increases reliability. Also, by converting to the deadman style controls, the controls were simplified and the number of components used in the control systems was reduced by eliminating incremental limit switches and timing relays, which reduces the overall probability of failure. Deadman controls, as implemented on Portland District spillway gates, are defined as controls designed to return the system to a safe or neutral state in the absence of continuous input from a human operator, i.e. the operator must press and hold the raise or lower button during the entire gate operation; if released, the operation stops.

Power Distribution: Replace existing dam feeder and install/replace redundant dam feeder. It is also important to ensure each dam feeder is physically separated from one another, i.e. each feeder either takes different route to the dam or is in a separate raceway. For example, two feeders fed from the same distribution panel with a single bus are not considered to be redundant. The goal is to ensure that a single fault in a piece of distribution equipment or physical damage to a single raceway will not cause a loss of both feeders.

Power Supply: Replace switchgear and/or associated feeder breakers for main and redundant dam feeders. Replacing or rehabilitating the emergency backup generators is also considered on each of the rehab projects. In addition to these changes, adding a portable generator supply receptacle at the spillway decks, which allows the ability to utilize trailer mounted generators for emergency spillway operation, has also been done, thus adding a fourth available source of power.

One other recommendation to come out of the electrical reliability assessment, which has not been addressed due to operational constraints at a majority of the Portland District’s sites, is increasing the frequency of operations. An increase in operations would improve the reliability of the gate systems, but there are operational constraints that do not enable the gates to operate except when the reservoir levels are down below spillway crest, which is typically only during flood season.

In addition to increasing the reliability of the spillway gate systems, the modifications that have been made greatly increase the operability and maintenance of the systems. The reduced hardware and simplified controls systems have

decreased the time it takes for operators to be trained on these systems. Additionally, troubleshooting these systems is simplified as a result of the reduced amount of hardware.

3.3. Mechanical Modifications for Reliability

The mechanical objective of each gate rehab project has been ensuring the hoist and trunnion bearing systems are in a condition that will result in safe and reliable gate operation for the next 50 years of service. To obtain this objective, each system has been evaluated for compliance with current design criteria and the potential for continued reliable operation. The scope required to obtain this objective at each site has been full replacement of the mechanical hoisting and trunnion bearing systems.

Replacement of some hoist systems has been necessitated by gate weight increases from the structural retrofit. However, even locations with negligible weight increase have required replacement to ensure compliance with more conservative, updated mechanical criteria. In addition, most original hoist systems have met or exceeded their intended service life, are starting to show signs of degraded reliability, and are not expected to provide continued reliable service for a 50 year lifecycle. Full system replacements have dramatically increased the reliability of Portland District spillway gate systems. In addition, other improvements, such as designing to more conservative criteria, improved material selections, and design simplifications have also resulted in reliability improvements.

The main design criteria changes that have occurred since original Portland District gate systems were installed have been the assumptions of how overload hoisting forces are distributed between sides of a gate. Original systems were designed assuming that a maximum overload condition would result in a 50/50 load split between sides of the gate. Gate operating experiences have shown this assumption is not valid. When gates are jammed between piers, they tend to flex and skew, resulting in differential hoisting loads between sides of the gate. Current USACE criteria requires designing for overloads with a 70/30 load split between sides of a gate. Portland District designers have gone a step further and have been designing Portland District hoist systems for a 100/0 load split to match the structural design criteria. Designing to this more conservative overload assumption has been made feasible with the use of load limiting devices, which are discussed below.

Other design changes have helped to improve assembly, alignment, and installation of the new hoist systems. This includes C-face mounting of drive system components and skid mounting hoist assemblies with electrical controls. Both of these changes have helped facilitate shop assembly/alignment and have minimized the onsite installation time where the gate is out of service, Figure 4.



Figure 4. Shop Assembly and Testing of Skid Mounted Hoists.

The largest change in material selections have been on trunnion bearing systems. Portland District has utilized fabric, reinforced, composite, self-lubricated trunnion bearing materials to improve the reliability of the trunnion bearing lubrication. Spillway Tainter gate trunnions across the US have had issues with seized or “frozen” trunnion bearings.

This often results from insufficient grease being pumped across the full running surface of the bearing. Self-lubricated materials have the primary lubricant (solid lubricants) incorporated into the parent bearing material. The lubrication is always present on the bearing running surface and does not rely on grease pumps, grease lines, maintenance funding, and other external factors for successful performance. PTFE seals have been utilized with the self-lubricated materials to exclude water and contaminants and ensure low coefficients of friction, Figure 5.

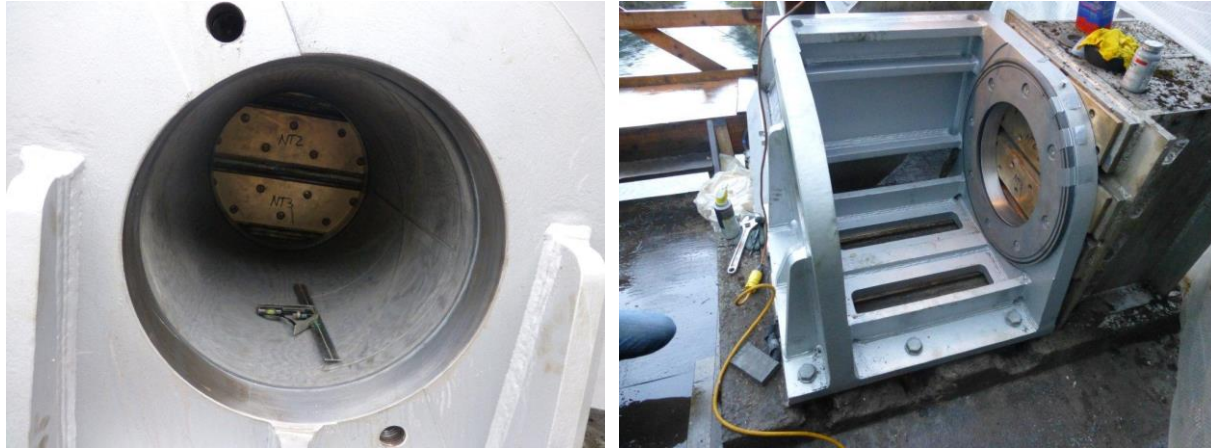


Figure 5. Self-Lubricated Trunnion Bearing and Thrust Washer.

3.4. Load Limiting Devices

Changes to more conservative structural and mechanical design criteria have driven a need to optimize how the hoist system is controlled in overload cases. The purpose of a spillway gate is to control flow. When an overload condition is experienced, a gate is still capable of performing the function of controlling flow until it becomes jammed between piers. When a gate jams, there is no value added in subjecting the gate to additional load. Portland District has been able to optimize hoist and gate sizing by utilizing load limiting devices (LLD) to prevent unnecessary load after a gate becomes jammed.

To determine appropriate load limits for a hoist system, Portland District has investigated each gate being rehabbed with a 3D FEM of the gate. Gates are modeled under single sided lifting to quantify deflections. The reaction forces to keep the gate deflection constrained within the pier widths are then quantified. Next, a coefficient of friction is applied to the pier reaction forces, resulting in a drag force that is used to solve the theoretical maximum single-sided hoisting load required to operate the gate. An uncertainty factor is then applied to the theoretical hoist load to account for efficiencies of the mechanical system as well considering the accuracy range of the LLD.

Portland District has performed this analysis on many gate systems and found that most require a motor overload limit between 130%-140% of the motor full load torque (FLT) to prevent unnecessary hoist loads. Motors used for hoisting application are typically selected as a NEMA design B or D. Per NEMA MG-1, design D motors are required to have a max torque no less than 275% of the full load torque with actual values commonly between 300%-350% of FLT. Design B motors are required to have a max torque no less than 205%-225% of the FLT (depending on hp rating and RPM for sizes common to spillway gates) with actual values commonly between 250% - 275% of FLT. These common hoist motor designs have a tremendous amount of overload potential. Portland District has started utilizing LLDs to lower the max torque the system can deliver and keep designs feasible and economical.

Portland District has investigated various LLDs for spillway Tainter gate hoist systems and has authored a White Paper on this subject. Key features of these devices include:

- Reliable operation

- Overload protection for 100% of the operating time (no protection at inrush is unacceptable)
- No disengagement of the load (devices are load holding and never disconnect the motor or brake from the load which could potentially drop the gate)
- Fast reaction time (time between sensing overload and system shut down are minimal)

After evaluating LLDs against a typical spillway gate application, there were three devices that had clear advantages over others:

- Custom wound motors – A motor with a custom winding design that meets the normal operating and overload characteristics specific to the application. The motor is designed with a reduced overload value that prevents overload of the system.
- Torque Transducers – A device that measures drive train torque and triggers a relay to shut the hoist system down when allowable values are exceeded.
- Torque Switch – A shaft coupling with a ball detent system calibrated to move a coupling plate axially when a critical torque value is reached (without disengagement of power-train load). The axial movement of the plate can be used to activate a switch or proximity sensor to shut the hoist system down when allowable values are exceeded.

Portland District has successfully installed custom wound motors and is evaluating them for long term use. In addition, Portland District is also in the process of installing and evaluating torque transducers for successful performance.

4. OPERATION AND MAINTENANCE CHANGES

USACE Northwest Division introduced a policy (Corps of Engineers, Northwestern Division, Operational Testing and Inspections, Periodic Inspections, and Evaluations of CENWP Spillway Gates) in 2012. This policy requires regular trunnion bushing lubrication, full cycle open/close tests, full mechanical/electrical component inspections, and hands-on structural inspections. This has been fully implemented across Portland District to ensure gate reliability and safe operation. Results of the testing and inspection are included in project Periodic Inspection reports.

5. PRIORITIZATION OF REHABILITATION WORK

In order to develop a long-term plan for repairing the Portland District's spillway gates, a process to prioritize gate repair at the project level was developed. A matrix was developed to consider the various criteria that would be used to prioritize repairs and provided a tool to rank the projects based on these criteria. Each criterion had a metric defined for it, and a score was given for each project. It was decided that the various criteria should not all have the same weight in terms of determining the priority of repair; sensitivity analyses were performed to assess the impact of varying the weight of each of the factors. The criteria for prioritization included:

Engineering Reliability: these criteria were based on the results of structural, mechanical, and electrical reliability assessments. Rehabilitation of projects with lower reliability systems were prioritized over higher reliability projects.

Economic Impacts: these criteria were based on the economic impacts of the gate operating restrictions to the project missions (flood damage reduction, hydropower and recreation). Rehabilitation of projects with high economic impacts were prioritized over those with lower impacts.

Operations Impacts: these criteria were based on the operation's manpower impacts of existing mechanical and electrical reliability deficiencies and from the gate operating restrictions. Rehabilitation of projects with larger operation impacts were prioritized over those with lower impacts.

Environmental Impacts: these criteria were based on the impacts of the gate operating restrictions on the ability to refill the reservoirs in the spring, fish and wildlife habitat, and water quality. Rehabilitation of projects with larger environmental impacts were prioritized over those with lower impacts.

Weights were assigned to the various criteria used to prioritize gate repair to reflect this. The criteria that were linked to life safety issues were given highest weights. Gate reliability (structural, mechanical and electrical) has life loss consequences; therefore, these criteria were given large weights. Flood damage reduction is a primary authorized purpose for these dams, and reduction in this capability due to gate operating restrictions may result in economic consequences; therefore, this criterion was weighted relatively high. The weights of the remaining criteria were smaller and tended to be grouped within a relatively small range. The relative magnitude of the weights of these criteria was debated, and it was found that small changes to these weights do not result in dramatically different project priorities.

6. REHABILITATION PROGRAM

Portland District initiated a capitalization program to rehabilitate all spillway gates in the Willamette Valley in 2009. Table 1 provides the progress to date of Portland District's rehabilitation program.

7. FUTURE WORK

7.1. Columbia River Spillway Gates

Once the Willamette and Rogue projects are complete, the effort will be expanded to include the Columbia River projects. Although potential life safety consequences at these projects are unlikely since the instantaneous change in discharge would not be significant, the potential economic consequences are greatest at the Columbia River projects, where hydropower and navigation capabilities could be impacted in the event of Tainter gate failure.

7.2. Regulating Outlets Reliability

There are 34 reservoir regulating outlets (ROs) in the Willamette and Rogue Basin Projects. The regulating outlets, just as the spillway gates, are integral to the flood damage risk reduction mission. Recent work on ROs within the Portland District revealed a high likelihood of systemic reliability issues. Inability for the gates to function as designed could lead to dam safety, and consequently, life safety issues for downstream stakeholders. The regulating outlets are operated under hydraulic pressure. Any oil leaks could have significant environmental impacts. Additionally, the ROs may be used for downstream temperature control as an interim measure as part of the fish passage improvement plan. Loss of use would severely impact fish listed under the Endangered Species Act in the Willamette and Rogue River Basins. Effort has just begun to assess the condition of each RO and provide a comprehensive evaluation and report on their condition.

7.3. Trunnion Anchors

The trunnion is often anchored to the concrete through steel anchor rods. USACE is currently researching and developing means to test the integrity of these anchors.

8. CONCLUSIONS

Significant conclusions as a result of the CENWP spillway gate program are as follows:

- Although the program initiated out of structural concerns and local buckling at Foster Dam, the potential failure modes analysis and comprehensive inspections indicated a holistic approach was needed. Mechanical and electrical reliability, as well as regular operational testing and inspections, needed to be addressed to minimize risk.

- The initial assessment of CENWP spillway gates that documented findings, the PFMA, inspections, prioritization, reliability, and risk, served as an excellent account and vision and led to a successful and well-funded program.
- The initial spillway gate assessment did not address planning of construction at the 11 projects within the Willamette Valley. Emergency and routine vehicular use of the spillway deck, lack of bulkheads at some projects, and confined construction windows challenged the ability to schedule implementation. A systems approach was developed to coordinate the construction over the entire Willamette River system.
- Extreme machinery loads are challenging to implement structurally, and this led to the investigation of load limiting devices.
- The program needed to be broadened to include other water discharge structures such as regulating outlets.

9. REFERENCES

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