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Folsom Dam Auxiliary Spillway – Design Innovations and Construction Lessons Learned

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ABSTRACT

The new Folsom Dam Auxiliary Spillway gated Control Structure, part of the overarching Joint Federal Project, was recently completed. To make operation and maintenance activities for this activity more user-friendly, this project implemented innovative designs, and a select few related to the tainter gate (seals, dogging system, and anchor inspection access) are presented in this paper. This project also provided additional monitoring capacity to the trunnion anchors, both during and post-construction, both physical and data, with great results. Furthermore, this paper discusses some lessons learned on tainter gate specifications during gate construction and installation. Building and bridge construction specifications were generally used in project specifications; however, there are components on the tainter gate that require special attention, such as ASME tolerances and high strength bolting in connections with multiple thick plies. Additionally, this paper suggests specification language and practices to better meet the design intent in terms of fabrication and construction tolerances.

Keywords: Tainter Gate, Specification, Slip Critical, Fracture Critical, Dogging, Seal

1. INTRODUCTION

The new Folsom Dam Auxiliary Spillway Control Structure, located 37km (23miles) north east of Sacramento, California, is part of the Joint Federal Project (JFP), which the U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers executed jointly by distributing cost sharing. The non-Federal sponsors for the JFP are the Central Valley Flood Protection Board (CVFPB) and the Sacramento Area Flood Control Agency (SAFCA). The auxiliary spillway is located southeast of the existing main Folsom Dam. Other principal features of the auxiliary spillway include an approximately 335m (1100ft) long approach channel, a 640m (2100ft) long concrete-lined spillway chute, a 208m (682ft) feet stepped concrete chute, and a concrete-lined stilling basin with baffle blocks. See Figure 1. The control structure was completed in the summer of 2015. The entire auxiliary spillway is expected to be finished in 2017.

The Control Structure is a reinforced concrete gravity structure comprised of two 27.4m (89.75ft) wide independent flow-through monoliths flanked by non-flow-through monoliths on each side. Both flow-through monoliths house three submerged tainter gates, each 7m (23ft) feet wide by 10.4m (34ft) high, measured from the soffit of the conduit to the gate sill. See Figure 2. Each of the six tainter gates has its own dedicated upstream bulkhead gate for operation and maintenance (O&M) and security purposes (Figure 3). Each tainter gate is supported by a dedicated built-up box trunnion girder and sixteen 7.62cm (3in) diameter 1034MPa (150 ksi) post-tensioned anchors. Each tainter gate is operated by a pair of hydraulic cylinders.

In this project, the structural and mechanical design team implemented a novel design approach on a number of tainter gate appurtenances. The following section describes these designs, which were intended to provide improvement upon typical tainter gate features. At the end of the paper, lessons learned during gate fabrication and installation on specifications are also presented.
Figure 1. Folsom Dam Auxiliary Spillway, Aerial View

Figure 2. Auxiliary Spillway tainter gate

Figure 3. Auxiliary Spillway Flow-through Monoliths
2. INNOVATIVE DESIGN FEATURES

2.1. Gate Top Seal System

For submerged tainter gates, or tainter valves, a seal is attached to the top of gate and seals against some sort of headwall, or the seal is attached to the headwall and seals against the gate. At JFP, a redundant system was employed, with a seal on the headwall (swipe seal) and a seal on the gate (top seal). The top seal is a rubber J bulb seal with a 1.27cm (0.5in) preset that mates with stainless steel plate embedded in the concrete headwall. The swipe seal is a “top hat” shape with a 0.635cm (0.25in) preset. Adjustability for presets was provided by overslotted bolt holes (top seal) and adjustable anchor bolts and shims (swipe seal). Typically for submerged tainter gates, access to the headwall directly upstream of the skin plate is limited or not available when the gate is opened. However, at JFP, a walkway was provided for safe access in the headwall area during gate operations, enabling O&M staff and engineers to monitor the performance of the seals and the gate itself, with close-up visual monitoring and by directly contacting the skin plate to check for excess gate vibration, etc. Note that the actual sealing performance of the seals will be tested during wet commissioning in 2017.

The top seal is most effective when the gate is fully closed, and it only remains effective until the seal completely disengages, which occurs after the seal travels upward about 30cm (1ft) during gate opening. Note that top seal friction was included in the tainter gate design, and it mainly increased the trunnion friction moment and hydraulic cylinder force for small gate openings.

Much of the JFP was modeled after Oroville Dam, which included an inflatable seal installed near the top seal region on the headwall. Since this system had minimal success in sealing, the JFP design team selected a rubber swipe seal design (see Figure 4), which will be in contact with the gate skin plate (to some degree) at any opening. The preset is established by compression from the gate skin plate, and, thus, the preset changes with skin plate deflection. To compensate for the skin plate deflection in the downstream direction due to hydrostatic pressure, a series of 10cm (4in) wide “charging gaps” was included in the design to allow water to enter from behind the swipe seal to deflect the seal in the downstream direction (Figure 5). Based on the swipe seal stiffness, it was estimated that pressure provided by the charging gap could deflect the seal in the downstream direction by 0.6cm (0.24in) at maximum pool. Combined with the preset, the swipe seal will remain in contact with the skin plate except for some of the extreme load cases, where some leakage is acceptable. Note that swipe seal compression and its associated seal friction were included in the tainter gate design, and it mainly increased the trunnion friction moment and hydraulic cylinder force.

![Figure 4. (Left) Gate in Fully Opened Position, Exposing Swipe Seal. (Right) Top Seal and Swipe Seal, with Tainter Gate in Closed Position](image-url)
In order to maximize skin to seal contact, tight tolerances were set to establish a smooth, consistent gate radius. First, flatness of the 7m (23ft) by 13.7m (45ft, arc length) skin plate was required to be within 2.54mm (0.10in). In other words, the depth of any dimples on the skin plate needed to be less than 2.54mm deep. In order for the contractor to demonstrate that no tolerance was exceeded, a laser tracking 3D measurement system by FARO was employed, which has accuracy to 0.0254mm (0.001in). The gate radius measured from the center of the trunnion to the upstream face of the skin plate is 12m (39.5ft), with an allowable deviation of only 1.6mm (0.0625in). It was recognized during design that this is a very tight tolerance for such a large surface, causing the fabricator to request a relaxation of the requirement, but the request was denied, and the fabricator, with advanced technologies and excellent planning and workmanship, was able to meet the tolerances with a few tolerable exceptions.

It was observed during tainter gate dry commissioning that the swipe seal induced additional wear and tear on the skin plate paint system during initial operations, but it was limited to a fraction of the top coat, and no further damage was observed after the first operation. It was most likely caused by unevenness of the underlying metalizing. A thicker top coat could have been applied to counteract the initial break in, but the top coat would be more brittle and possibly delaminate. In many ways, a stainless steel overlay would be the best solution since the skin plate would be virtually free of corrosion, eliminating future operational maintenance repainting efforts. The stainless steel surface would also be machined to a very smooth surface compared to a metallized and painted surface, reducing the wear and tear and thereby increasing the life of the swipe seal. However, such a large stainless surface would be very expensive, possibly increasing gate weight. It is suggested, therefore, that future designs consider the two options to determine whether the O&M savings of a stainless steel overlay outweighs the potential added initial costs. A critical factor in such an economic exercise would be whether a smoother skin plate surface would realistically prolong the life of the swipe seal.

2.2. Side Seal Cavity

In typical tainter gates and tainter valves, the embedded stainless steel plates in the piers run the full length of gate travel, such that the side seals are engaged and preset for the full range of motion. While this is simpler for pier construction, this unnecessarily increases the wear and tear on the side seal. Moreover, side seal installation and the eventual replacement are difficult due to limited access with the gate and skin plate in place. Thus, for seal O&M efforts, skin plate modification is not uncommon as means for accessing the side seal. The JFP team determined that a side seal cavity can eliminate these problems and selected it for the design (Figure 6).

For this project, the embedded stainless steel side seal plates extend from the sill to their termination point slightly higher than the soffit of the headwall. Above the termination, a 12.7cm (5in) deep side seal cavity was provided in each pier (see Figure 4). The transition from the open cavity to the side seal plate includes an embedded plate that
angled into the pier, which enables the side seal preset to smoothly reestablish when closing the gate and the preset to slowly disengage when opening the gate.

Figure 6. Side Seal Cavity (Left: viewed from upstream. Right: viewed from top)

Though it required more customization on the pier reinforcement, the side seal cavity already paid dividends during gate seal installation. The contractor attached the field-spliced perimeter seal (top J bulb seal, each of the side seals, and the bottom seal) to a segmented steel frame and was able to easily bolt the seal to the skin plate with the gate in the opened position (Figure 7). It is anticipated that future seal removal and replacement will be relatively problem free.

Figure 7. Perimeter Seal Mounted on Steel Frame, and During Installation
2.3. Multi-Elevation Dogging System

During design, the O&M staff at Folsom expressed desire to have a redundant gate support system when the tainter gates were opened during maintenance activities; one example is the aforementioned seal replacement, which can be deployed quickly and readily. There are also maintenance activities for which holding the tainter gate partially opened is advantageous, including gate bottom seal repair, partial gate skin plate repaint, conduit inspection, etc. A typical system to temporarily hold the gate open is called a dogging system, a term originated from historic nautical term “dog,” which meant to secure a movable feature. A cursory search on tainter gate dogging systems did not yield any significant guidance on the design and operation of the dogging system that suited the JFP’s needs or worked for the unique JFP geometry.

Figure 8. Dogging Devices (Circled) - Engaged and Disengaged

Figure 9. Upper and Lower Dogging Devices

Typical dogging systems involve chains that lock the gate in a single position. A variety of concepts were brainstormed and considered for the dogging system. Ultimately, a sleek, simple, multi-elevation system was employed. It features two pairs of dogging devices per gate – upper dogs on Girder 1 and lower dogs on Girder 3 – and three pockets in each pier face, which contain bearing plates. The dogging device includes a steel tube (HSS)
whose load is transmitted through the W27 girder cross section by a series of stiffener plates. The dogging device rotates about a pin, such that it is oriented vertically when disengaged and is angled normal to the embedded bearing plate when engaged. The dogging device rotates manually (eliminating risks of potential equipment breakdown) with a lever that is accessible from platforms on the gate. See Figures 8 and 9 for device. The dogging device was designed to bear in compression, transmitting the weight of the gate and the potential pushing force from the hydraulic cylinder. An ultra-high molecular weight, plastic bearing pad was attached to the ends of the dogging device to protect the surfaces and improve grip on the engaged dogging device.

With this simple system, the gate can safely maintain 6 different positions, from approximately 1.2m (4ft) to fully open. The added benefit of a multi-elevation dogging system was realized during erection of the tainter gate and subsequent construction activities. By having a redundant support system, safe access and working conditions were provided under the tainter gate, eliminating the need for scaffolding or other means of temporary supports. The ability to lock the gate in multiple elevations also helped the contractor save time from locking the gate completely opened or partially opened whenever long-term access through the conduit was needed.

2.4. Trunnion Anchorage

Each tainter gate is anchored to the concrete control structure by sixteen 7.62cm (3in) diameter 1034MPa (150 ksi) post-tensioned trunnion anchors. For any tainter gate, trunnion anchors are vulnerable to failure due to corrosion. Especially when constantly loaded from the post-tensioning, its failure can happen very quickly and often without warning signs. Thus, double corrosion protection was included in the JFP anchors, provided by HDPE ducts (which extend full length through the piers) and grout. Visual inspection of the full length of embedded anchors is not possible. Typically, anchors are only accessible on the live end, and the ends are covered by a protective steel box, which can be removed to facilitate inspection. Innovations on the JFP design include extending the anchors deep into the structure, adding an inspection gallery (See Figure 10), and installing Plexiglass protection boxes on both the dead ends and the live ends. The ability to visually inspect the anchor ends increases the chances of seeing any potential signs of anchor failure, such as rust, water coming out from the anchor ducts, signs of movement, etc. Note that Plexiglass was used instead of steel as an anchor end enclosure to provide improved inspectability, taken as a lesson learned from Oroville Dam, where plexiglass enclosure provided excellent visibility to the anchor live end.
3. CONSTRUCTION ACTIVITIES

3.1. Overview

Besides the aforementioned features that are primarily for permanent O&M purposes, this project includes noteworthy features and specification requirements that affected construction and performance. Associated lessons learned are presented in this section.

3.2. Trunnion Anchor Monitoring

Vibrating wire load cells were installed on 25% of the anchors at the dead end to provide a means to monitor residual prestress in the anchor during construction and for future operations. (See Figure 10.) The load cells were useful during construction in providing quality assurance of the prestress level during the sequenced stressing operation over a period of months and in providing real-time post-tensioning losses once stressing and grouting were completed. These large diameter anchors are cold-rolled, which translates to atypical and somewhat uncertain relaxation characteristics. Ultimately, the AASHO-calculated relaxation losses proved conservative.

The load cells will continue to help monitor the long-term integrity of the anchor and preempt sudden failures, though in a more limited capacity. Since the anchors are fully threaded, the grout re-characterizes the length of anchors between the ends from “free stressing” to “grouted,” preventing free movement of the anchors. Thus, the presence of grout hinders the ability of the load cells to detect losses some distance away from the load cell location. As a result, in order to provide the O&M staff a complete picture to assess the condition of the trunnion anchors, a second method was used. The dispersive wave method, patented by the company FDH Velocitel, records the frequency response of an anchor when it is subjected to different kinds of light tapping at both ends of the anchor. Since the anchor’s frequency response is a function of anchor tension, by comparing the frequency response to the response when the anchor was first tensioned, a quantitative sense of the remaining anchor prestress can be determined (See Figure 11). The dispersive wave technology has advanced since it was utilized at JFP, and, currently, the Corps has an ID/IQ contract for the acquisition of dispersive wave testing to determine the amount of post-tension force in existing tainter gate trunnion anchors (USACE, 2015).

Based on the positive experiences of inspecting and testing both anchor ends, and of gathering tension data on anchor during and after construction, it is recommended that future designers also consider incorporating accessibility to both ends of the anchors, consider installing load cells, and definitely utilize state of the art monitoring technology such as the dispersive wave method to monitor the trunnion anchors.

Figure 11. Dispersive Wave Example (FDH Velocitel, Trunnion Anchorage Road Analysis at Folsom Dam, Final Report, 2015)
3.3. Fracture Critical Designation

A tainter gate is a unique structure, so even though Corps guide specifications are available, the project specification has to be tailored for the specific project, and caution must be taken when importing requirements from multiple sources (specifications and codes), which can be contradictory. In addition, specifications and codes might not be up to date with current technology or may have other limitations. One such conflict is the concept of fracture critical members, which was borrowed from the bridge industry to address fatigue failure due to repetitive bridge loading. For a tainter gate, even though hydrodynamic loading differs with earthquake loading in terms of the length of sustained loading, the determinacy of the number of cycles, and the load magnitude, applying analyses and detailing employed for earthquake loading on tainter gate design would still yield a design that is resilient to repeated vibration cycles from hydrodynamic forces.

Designers would generally specify the fracture critical requirement for welds and steel material and then rely on requirements in established specifications and codes such as AASHTO-LRFD and AWS D1.5. Designers would also generally aim to design connections with fatigue stress category C or better because of the fatigue design parameters in the AISC Steel Construction Manual. Since those specifications and codes are inherently created for buildings and bridges, they do not always cover concerns that a tainter gate designer would face. For example, in this project, the tainter gate strut arms were identified as fracture critical members. The designer determined that even though the strut arms were compression members, the fracture critical designation was prudent because of the potential range of stresses in loading cycles and because failure of these critical members could lead to loss of life. This application of the fracture critical member call-out differs from AASHTO, which defined it as a component in tension whose failure is expected to result in the collapse of the bridge or the inability of the bridge to perform its function (AASHTO, 2014). The fracture critical call-out is a good short-handed way for designers to require increased material hardness, additional material testing, material traceability, rigorous weld testing requirement, etc. that would ensure better material quality and workmanship. For this project, which included a fabricator who knew the code well enough to attempt to reinterpret the contract requirements regarding the struts, this issue was resolved with constant dialogue with the fabricator, as well as in person pre-construction conference and periodic quality-assurance visits. However, a better solution to avoid contractual confusion is for the designer to redefine fracture critical members as those identified on drawings, not allowing deference to the definition from codes.

3.4. Slip Critical Bolting

Another code issue experienced for the JFP was related to high-strength bolting. For the structural bolting on the tainter gate, all bolts were specified to be tightened to the prescribed slip critical pre-tension in RCSC (and to have a slip coefficient of 0.35 on the faying surfaces) to improve their fatigue behavior. According to RCSC, all bolts were required to be tightened to snug tight before continue tightening to the target pretension. However, the definition of snug tight was vague and evolved over time. In the 2004 RCSC Specification, “The snug-tightened condition is the tightness that is attained with a few impacts of an impact wrench or the full effort of an ironworker using an ordinary spud wrench to bring the connected plies into firm contact,” while in the 2009 Specification, “Snug tight is the condition that exists when all of the plies in a connection have been pulled into firm contact by the bolts in the joint and all of the bolts in the joint have been tightened sufficiently to prevent the removal of the nuts without the use of a wrench.” While the 2009 Specification added language to further define the snug tight condition, it remains vague on the definition of “firm contact.” In this project, most connections either had typical plate thickness and/or number of plies, and few challenges arose during bolting. However, at the tainter gate strut arm to trunnion hub connection, due to difference in web plate thickness of these two features, the web bolted splice was approximately 7.62cm (3in) thick with a total of 5 plies, including shims. During routine QA inspection, it was discovered that bolts that were previously snug tightened had become loose, despite following RCSC’s requirement. Through trial and error, and after examination per the arbitration clause in RCSC, it was discovered that due to the unusual plate thicknesses, the number of plies, the typical plate unevenness, and the size and spacing of the bolts, the typical snug tight procedure prescribed by RCSC was not enough to truly bring bolts into snug tight. The consequence of bolts not being snug-tight before tensioning is that bolts do not achieve their required pre-tension force, and then the connection is subject to slippage or improper transmission of loads. Ultimately, in the aforementioned web connection, the contractor used an impact wrench to snug-tighten the bolts and proactively performed 100% pretension QC on all slip critical bolts on the tainter gate.
For future projects, particularly for unusually thick connections, it is recommended that mockup (to prove the bolting procedure) and bolt tension QC/QA (at least initially) be required in the specifications to supplement the RCSC specification. A multiple stepped snug tightening sequencing, written by the contractor and approved by the Engineer, requiring workers to check the snug-tightness of all bolts in a connection immediately after snug-tightening the last bolt may also be justified for unusually thick connections.

3.5. Steel Erection

In typical building design, steel erection has the benefit of compression members in bearing due to gravity. Conversely, for erection of tainter gates, whose geometry and orientation are variable, such benefit does not exist, and special attention is often needed. An applicable example for the JFP gates is the bolted connection where the strut arm connects to the trunnion hub assembly. The orientation of this connection is such that gravity tends to increase a gap between the two plies. If a specific bearing tolerance is not specified (e.g. mill to bear according to AWS), the fabricator would be permitted per code to leave a gap between the two members, putting the bolts in unintended shear and possibly creating a compromised connection unknowingly. It is recommended that the work plan require an explicit description of the fit up process to assure that it is well-planned and successful. A specific means of checking the fit up (e.g., an X inch thick feeler gauge shall not fill Y% of the contact area) should also be provided by the designer, determined with consideration of limitations of such requirements due to inaccessibility of the contact area (behind splice plates).

4. CONCLUSION

Brand new dams and gates are fairly rare nowadays, so the engineering community can all benefit from sharing fresh ideas and lessons learned. The design, fabrication, and construction of the Folsom JFP tainter gates included a few novel design features that were intended to provide safe access to O&M staffs, convenient means for seal installation and removal, and reliable means (both visual and non-destructive technology) to monitor the health of the trunnion anchor post-tensioning system. With this paper, it is hoped that engineers designing or studying similar systems may be inspired to find creative solutions or improve the quality and ease of the construction processes.

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6. REFERENCES