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C. M. Johnson
Schnabel Engineering, cjohnson@schnabel-eng.com

R. T. Indri
Schnabel Engineering, rindri@schnabel-eng.com

F. G. Snider
Schnabel Engineering

S. M. Planck
HDR

K. F. De Lapp
HDR

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State-of-the-Practice Review of Maintenance Closure Structures for Large Spillway Gates

C.M. Johnson[1], R.T. Indri[1], F.G. Snider[1], S.M. Planck[2] and K.F. De Lapp[2]
[1]Schnabel Engineering
11A Oak Branch Drive
Greensboro, NC 27407
USA
[2]HDR
2365 Iron Point Road, Suite 300
Folsom, CA 95630
USA
E-mail: cjohnson@schnabel-eng.com

ABSTRACT

Maintenance, remediation, and inspection of large spillway gates are best performed in a dry, dewatered state due to reduced overall cost, worker safety, and improved work quality. Provision for gate dewatering has become a key design consideration for new spillways. Unfortunately, many existing spillways were not originally constructed with gate dewatering capabilities. Therefore, maintenance and inspection work has often been scheduled during planned drawdowns or seasonally low reservoir levels. However, for operators of hydroelectric, flood control, water supply, and multi-purpose dams, artificial drawdowns can significantly impact operations, flood protection, downstream habitat, and revenue generation. Aging gates deteriorate and require significant maintenance, rehabilitation, and increased inspection. As dams age and gates deteriorate and require maintenance and rehabilitation, owners are increasingly seeking methods to dewater gate bays while maintaining operational pool levels using maintenance closure structures, such as bulkheads, stoplogs, cofferdams, and caissons. Designing these structures is challenging.

This paper summarizes the findings from a worldwide review of the current state-of-the-practice for various types of maintenance closure structures in use for dewatering large spillway gates. Examples are provided for each maintenance closure type identified. The information presented in this paper will be of benefit to those involved with spillways and dams, especially owners, engineers, and researchers seeking better, safer, inexpensive, and more durable maintenance closure structures that can be installed quickly.

Keywords: *maintenance closure structure, hydraulic loadings, bulkhead, cofferdam, dewater, gate rehabilitation*

1. INTRODUCTION

Spillway gates are critical components of dams, providing the ability to pass large discharge rates. Spillway gates require routine inspection, maintenance, and periodic remediation to ensure reliable long-term performance. These tasks are usually best performed in the dry due to reduced overall cost, enhanced safety, and improved work quality. Therefore, provision for gate dewatering has become a key design consideration for new spillways. However, many existing spillways were not originally constructed with gate dewatering capabilities. In these cases, inspection and remedial work is often scheduled during planned drawdowns or seasonally low reservoir levels. However, for operators of hydroelectric, flood control, water supply, and multi-purpose dams, artificial drawdowns can significantly impact operations, water supply, downstream habitat, and revenue generation. For large reservoirs, extended reservoir drawdowns may result in millions of dollars (U.S.) annually in lost revenue.

As dams age, gates deteriorate and require maintenance, rehabilitation, and increased inspection. This need, coupled with lost revenue during extended drawdowns, has led many owners to seek methods to dewater gate bays while maintaining operational pool levels. As a result, the industry continues to evolve in response to these needs as engineers develop better, safer, less expensive, and more durable maintenance closure structures (MCS) that can be installed more quickly to dewater a work area upstream of gates needing attention. Designing retrofit systems can be a major challenge for dams not originally designed with a method to dewater the existing gate bays. This paper draws from worldwide experience in presenting a review of the current state-of-the-practice for various types of structures in use for dewatering large spillway gates.

A summary of an international review of MCS is presented herein, including dams with and without existing dewatering capabilities. MCS are not usually intended to be deployed in emergency situations. However, some information is included regarding which MCS are viable for emergency conditions.

The findings regarding MCS are based on inquiries to the following groups: owners of the 99 largest spillways in the world (based on a search of spillway capacities greater than 28,300m^3/s or 1,000,000cfs according to the International Commission on Large Dams [ICOLD] 2011 World Register of Dams), ICOLD national committee chairs, and major international dam agencies. This research plan met with varying degrees of success. Many organizations were very responsive and helpful, while others were unresponsive to our inquiries or unwilling to allow publishing of information, likely due to security concerns.

For each MCS type identified, key design considerations (including hydraulic loading and overtopping performance), deployment methods (including floating/water ballast bulkheads), installation times, safety considerations, relative costs, and durability concerns are identified. This information, along with recent trends and future design considerations presented in this paper, will be of benefit to those involved with spillways and dams—and, more specifically, to owners and engineers tasked with the selection of an optimal system for their specific site.

2. CURRENT PRACTICE BY SOME MAJOR ORGANIZATIONS AND REGIONS

The type of MCS in use around the world varies based on the specific characteristics of each individual site. However, our research discovered some trends attributable to certain geographical areas or organizations. Several fairly recent publications were found on this topic, including PIANC Working Group 26's Design of Movable Weirs and Storm Surge Barriers (PIANC 2006), Design of Hydraulic Gates (Erbisti 2014), and United States Army Corps of Engineers ERDC/GSL TR-10-44 (Padula 2010) and ERDC/CHL TR-12-8 (USACE 2012). These publications provide an overview of some types of systems employed, case studies, and key design aspects.

Figure 1. Stoplog Install, Itaipu Dam, Brazil/Paraguay (Itaipu Binacional)

For example,

- In Australia and Africa, many areas experience a dry season that lasts about six months. Major gate maintenance is typically scheduled during the dry seasons, in which the reservoir levels are below the bottom of the gates and no MCS is needed.
- For large dams throughout South America, steel stoplogs are very common for dewatering spillway gates and penstocks. For example, on the border of Brazil and Paraguay, upstream stoplogs are used at Itaipu Dam, the second largest hydroelectric production facility in the world. As shown in Figure 1, the stoplog sections are installed using a gantry crane traveling along the spillway crest and lowered vertically into built-in slots in the dam.
- In Russia and other parts of Eastern Europe, it is difficult to schedule major gate maintenance within the short dry season. In such cases, lowering the reservoir by 2-3m (6-9ft) is impractical as it would require operating under the base load curve at most hydropower plants for extended periods of time. Where it is either very difficult to dewater gates using an MCS or difficult to schedule activities during seasonal drawdown, less extensive work is performed underwater by divers. However, the quality and long-term performance of underwater work is often much lower than work performed in the dry. For major gate repairs, a common type of MCS in Russia is steel caissons, which are designed specific to each site. See section 3.2 for a description on steel caissons in Russia.
- In the United States, the U.S. Army Corps of Engineers utilizes a large number of stoplog systems, as well as floating bulkheads and other systems. It is in the process of replacing older, deteriorated maintenance closure systems with safer, more reliable systems. The largest bulkheads identified were approximately 35m wide by 11.6m tall (115-ft wide by 38-ft tall) at the Olmsted Project and 40.5m wide by 8.2m tall (133-ft wide by 27-ft tall) in the Nashville District. The largest bulkheads reported by the Tennessee Valley Authority are 14.6m tall by 14.6m wide by 0.76m thick (48-ft tall by 48-ft wide by 30-in thick) hinged floating bulkheads discussed in section 3.7.
- The U.S. Bureau of Reclamation (Reclamation) has several large dams in the western United States. The largest bulkhead currently in Reclamation's inventory is 16.8m by 16.8m (55-ft by 55-ft). Reclamation's largest circular bulkhead is 6.1m (20-ft) diameter (LaBoon 2014). Other larger dams owned by Reclamation constructed in the early 1900s were not equipped with MCS and have traditionally been serviced during seasonally low reservoir levels or scheduled drawdowns. However, the potential for increased revenue by maintaining high pool levels during maintenance has led to an increased desire for MCS at large dams.

3. MAINTENANCE CLOSURE STRUCTURE TYPES

MCS types found in the research are classified according to the following structure types: historical systems, steel caissons, sheetpile cofferdams, one-piece drop-in bulkheads, operational bulkheads, floating bulkheads, hinged floating bulkheads, stackable blocks, rolling bulkheads, needle and infill systems, arch systems, stoplogs, emergency bulkheads, vertical lift gate bulkheads, and inflatables.

3.1. Historical Systems

MCS designs evolved from concepts of early movable dams. The earliest movable dams were constructed to retain water at canals in China around the year 983 AD (Erbisti 2014). These movable dams consisted of tree trunks, which were raised and lowered into slots cut into opposite sides of the banks using ropes. Movable wood dams evolved into horizontal swinging gates and, later, to metal gates and needle dams (such as Poirée needle dams) around 1830. Early Poirée dams were trapezoidal-framed iron bar structures permanently mounted to the crest of a dam. The frames were raised or lowered by means of chains. Poirée dams rely on interlock with adjacent Poirée dam sections for stability (see Figure 2). Loss of one frame destabilizes all other frames. These types of systems evolved into other similar systems, such as Boulé dams, Parker gates, and bear-trap gates. Bear-trap gates consist of two flat leaves that are hinged horizontally at their lower ends. The two leaves form a chamber that can be filled with water, raising the leaves and forming an inverted v-structure. Water is subsequently drained from the chamber to lower the Bear-trap gate. These systems were well documented by Wegmann (1918). Although these types of MCS are still in use at some dams around the world, many of them are being replaced by more substantial, durable, and reliable systems. They are not typically considered for new designs, but some of the principles are manifested in modern MCS.

Figure 2. Poirée Needle Dam, Dardanelle Lock and Dam, USA (USACE Little Rock District)

3.2. Steel Caissons

Steel caisson systems consist of steel frames with cladding and watertight chambers filled with air, which are placed against the face of a dam to allow worker access to perform work underwater. One such caisson system was used at Bhakra Dam in India in the 1980s. Two vertical steel columns were installed on the downstream channel. A fully enclosed, multi-level working platform was built to travel vertically on the steel columns to service the full height of the dam. Crews worked within the enclosure while the enclosure was submerged underwater. The face of the enclosure nearest the dam was left open to allow workers access to the face of the dam to make needed concrete repairs. The enclosed chamber required strict pressure and air quality monitoring for worker safety (McDonald 1999).

Steel caissons are commonly used in Russia to perform concrete and gate repairs on the upstream face of a dam, such as Nizhny Novgorod HPP (see Figure 3). The caisson is towed by boat in a horizontal position, using floats for buoyancy, and ballasted to an upright position against the face of the dam. Water is pumped out of the caisson, sealing the caisson against the concrete using hydrostatic pressure and creating an underwater enclosure to make concrete repairs in the dry. A steel caisson, approximately 6m (19.7 ft) tall, was used at the Saratov HPP in Russia. It was towed into place and anchored by divers (see Figure 4). Although other caisson systems have been used against more complex sealing surfaces (e.g., repairing sheetpile with the Acotec DZI Limpet Cofferdam [Acotec 2015]), use of caissons to seal directly against portions of large, irregular-shaped spillway gates presents design and worker safety challenges.

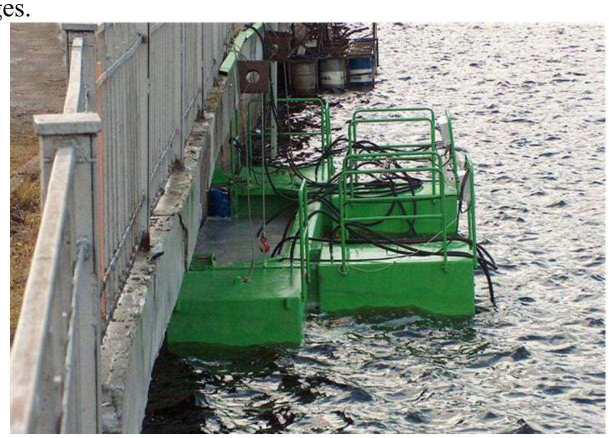

Figure 3. Nizhny Novgorod HPP Caisson, Russia (Hydroproject Institute)

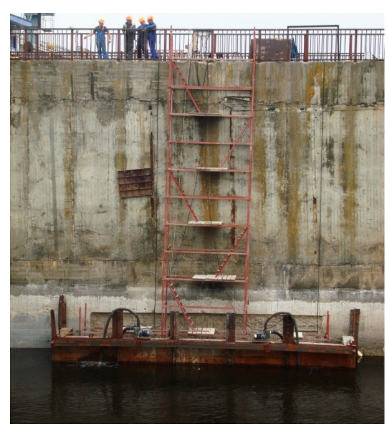

Figure 4. Saratov HPP Caisson, Russia (Hydroproject Institute)

3.3. Sheetpile Cofferdams

Interlocking steel sheetpile has been used for dewatering upstream of spillway gates. Sheetpile works well for low-head facilities where sheetpile can be driven into a soil foundation to form a temporary wall. Other modular or repeating systems consist of built-up sections of vertical tubes and plates that seal together. The sheetpile is driven into the soil so that it acts as a vertically cantilevered system. The material cost for sheetpile systems is relatively low, and its use is fairly common for a wide range of applications. For installations at taller dams, where driving into the upstream channel is impractical, sheetpile may be used on the walls of other structures offering a top support, such as a vertical needle system as described in section 3.10.

3.4. One-Piece Drop-In Bulkheads

One-piece drop-in bulkheads are fabricated and deployed as a single, full-size structure. No field assembly is required. One-piece bulkheads typically consist of one large steel space frame truss, which is lifted by a large crane (or two), with the crane(s) often mounted on a barge. Bulkhead load bearing, similar to a stoplog system, usually transfers hydrostatic load to the piers. The steel framework consists of interconnected horizontal spanning trusses with a steel skin plate on either the upstream or downstream face. Bulkheads tend to be more robust towards the middle (horizontally) to resist maximum bending moments and less so at the supports where moments are small. Bulkheads often bear in slots in the concrete piers. The primary advantage of this type of structure is that it may be installed within a few hours because it is a single unit. However, it may require large cranes for installation. The largest one-piece drop-in bulkhead discovered in our research was at Olmsted Locks and Dam Project in the USACE Louisville District, which is 35.1m long by 11.6m tall (115-feet long by 38-feet tall) and is shown in Figure 5.

Figure 5. Bulkhead Installation at Olmsted Locks and Dam Project, USA (USACE Louisville District)

3.5. Operational Bulkheads

Operational bulkheads are similar to overhead garage doors and are stored in the horizontal position above the bulkheads slots when not in use. The bulkheads can be lowered into slots. For example, the Olmsted Locks and Dam Project in the USACE Louisville District has an operational bulkhead at each of its two lock chambers. The bulkheads allow each lock to go back and forth relatively quickly between “open river” conditions and normal locking conditions. In open river condition, the miter gates are pinned back to the lock walls, and the river flows unimpeded through the locks. The operational bulkheads can be lowered into flowing water typical of open river conditions. Once these bulkheads are set, they can be raised during differential head conditions. Each structure is a massive bulkhead consisting of nine horizontal trusses and an upstream skin plate. Figure 6 (photo courtesy USACE) shows both bulkheads; the bulkhead at the right is in the lowered vertical position and the bulkhead on the left is in the horizontal open position. Each bulkhead is 34.7m long by 15.2m tall (114-feet long by 50-feet tall). The hoisting equipment is located in machine houses cantilevered out over the lock chambers approximately 27.4m (90 feet) below.

Figure 6. Operational Bulkheads at Olmsted Locks and Dam Project, USA (USACE Louisville District)

3.6. Floating Bulkheads

Floating bulkheads are somewhat similar to docking a ship against the upstream face of the dam. The large steel structures contain internal ballast chambers, which are filled with water to adjust buoyancy. The bulkheads are ballasted to remain partially exposed above the maximum design water level. These structures typically consist of an internal steel framework clad with steel skin plates on all sides. The geometry of the bulkhead is designed to mate with the spillway structure and, typically, seals against the sides and bottom edge of the gate bay. The hydrostatic load is transferred to the skin plates, to the internal steel framing, and then to the concrete piers. Bulkheads are typically towed in a horizontal position using one or two small boats. When the bulkhead arrives near the point of installation, it is partially filled with water to rotate it into a vertical position. Rotation of the bulkhead to vertical typically requires a water depth of at least half the height of the floating bulkhead, which is not possible at many locks. It is then slowly maneuvered into contact with the upstream face of the dam and often tied off to the dam with chains to minimize small movements of the bulkhead. Next, the water downstream of the bulkhead is drained out. As the water drains, the net unbalanced hydrostatic pressure on the bulkheads presses the bulkhead against the dam and provides a seal. The frictional forces on the seals, along with the chains, are usually sufficient to limit movement of the bulkheads to less than one inch under most reservoir conditions. Many of the floating bulkheads discovered in our research were designed for pool fluctuations during installation of less than 1.5m (5 feet). Slightly larger pool fluctuations may be accommodated by operating valves to adjust the amount of internal ballast to keep the bulkhead at a constant elevation. Floating bulkheads are not usually capable of remaining stable in a fully drained condition.

In cases where large pool variations exceed the tolerances of the internal ballast chambers, bulkheads may require provisions for repositioning or mechanical support. Bulkheads are removed by reversing the installation process. Some bulkheads are moved laterally from bay to bay using a truck on the abutments rather than redeploying boats. When the bulkheads are ready to be placed in dry storage, they are usually towed near shore and rolled out of the reservoir. Rollers allow for movement of the massive structures without the need for large cranes (Steve Sembritzky, personal communication, December 31, 2014). Due to the extreme hydrostatic forces and friction caused by small reservoir fluctuations, the seals on these bulkheads wear and may need to be replaced after a few years. Floating bulkheads are typically installed within a few hours and require relatively small boats or crews. Some of the largest floating bulkheads found were the USACE Nashville District's floating bulkhead (or caisson), which is 34.5m-wide by 8.8m-tall (113ft-wide by 29ft-tall) and is shown in Figure 7; at Rocky Reach Dam in Chelan County, WA, USA, which is 18.3m-wide by 21.3m-tall (60 ft-wide by 70ft-tall); and at USACE Portland District's John Day Navigation Lock in Sherman County, OR, USA, which is 30.5m-wide by 9.1m-tall (100ft-wide by 30ft-tall).

Figure 7. Floating Caisson Being Ballasted, USA (USACE Nashville District, ERDC/GSL TR-10-44)

3.7. Hinged Floating Bulkheads

Hinged floating bulkheads operate like an overhead garage door. They consist of parallel steel tubes or built-up sections that have internal ballast chambers and are hinged together between each segment. Bulkheads are foated to the gates from upstream while in the horizontal position. Ballast chambers are filled with water one by one, sinking the individual segments into place against the upstream face of the structure (Lux 1995). Installation of these bulkheads usually requires towing by a small boat (or two). Reservoir levels must be high enough to allow proper placement of the bulkhead after ballasting to the upright position. Expected range of reservoir levels should be accounted for in design of the ballast to ensure placement. Bulkheads are often anchored only at the two top corners with hanger brackets mounted to the face of the spillway to secure the bulkhead in the event the pool is lowered. One advantage of a hinged floating bulkhead over a rigid floating bulkhead is that the individual sections can be designed to be detachable. This allows the number of sections to be tailored to each dam. Also, the small sections are more easily lifted and handled with the use of smaller equipment. The Tennessee Valley Authority in the United States has hinged floating bulkheads for use at twelve of its sites. The floating bulkheads consist of caissons with ballast chambers that may be combined as needed for use at different sites with various gate sizes as shown in Figure 8.

Figure 8. Hinged Floating Bulkhead, USA (Tennessee Valley Authority)

3.8. Stackable Blocks

Stackable concrete blocks have been used to dewater Locks and Dam No. 52 by the U.S. Army Corps of Engineers Louisville District as shown in Figure 9. The blocks are stabilized against overturning by self-weight and against sliding by the horizontal interface friction between blocks. If the weight of the blocks is insufficient for stability, the blocks can be strapped down using vertical pre-stressing straps threaded through the blocks and attached to the top of the dam. All loads are transferred vertically, so the gate width is not a limiting factor on the structural design of the blocks. The blocks are often precast, which allows a high level of construction precision. Uplift pressures on the bottom of the blocks can be reduced by providing open slots in the bottom of each block, effectively eliminating the uplift pressures downstream of the notch. Anchor plates and lifting rods are embedded into the bottom of the base blocks. The blocks are installed with gaps of approximately 51mm (2 inches) between stacks. The gaps are then sealed by using T-shaped vertical seals inserted on the upstream face. The number of required blocks varies based on the height and width of the opening. The downside of dealing with heavy concrete blocks is handling due to their immense weight. For example, one normal-weight concrete cube measuring 2.4m (8-feet) per side weighs nearly 356kN (40 tons). If weight is a design limitation, other materials, such as lightweight concrete, steel boxes with ballast chambers, and fiber reinforced polymer (FRP) composites may be considered. Lighter-weight modular systems, such as Super Sacks® and BoxBarrier® (50 cm height), are options for very low head barriers, but similar technology could be scaled up for taller applications.

Figure 9. Stackable Precast Concrete Blocks, Locks and Dam No. 52, USA
(USACE Louisville District)

3.9. Rolling Bulkheads

Rolling bulkheads are similar to sliding barn doors. They consist of a steel bulkhead mounted to permanent horizontal rails on the upstream face of the spillway. At the push of a button, the bulkheads are rolled along the horizontal rails to any position along the length of the rails. Wheels at the top and bottom of the bulkhead allow the large door to roll horizontally along the length of the rail. When the bulkhead is in place, the wheels retract and the rubber seals placed along the perimeter of the bulkhead seal against the concrete. The bulkhead transfers hydrostatic load horizontally to the piers, minimizing the load requirements on the monorail. The monorail supports the weight of the bulkhead. When the bulkhead is not used, it is rolled and stored past the end gate bay. The concept of rolling systems has been utilized at several lock gates but has been applied recently on a larger scale at the Panama Canal expansion project, which features gates that can be retracted into slots in the lock walls for maintenance. There are a total of 16 steel gates, which were fabricated in Italy, transported to Panama by ship, and offloaded into recesses constructed in the lock walls. The tallest of the gates is 33.04m-high by 57.6m-wide by 10m-deep (108.4ft-high by 189ft-wide by 32.8ft-deep) and weighs 4,234 tons (Panama Canal Authority 2015).

Figure 10. Norfork Dam Rolling Bulkhead, USA (USACE Little Rock District)

Norfork Dam in Arkansas, USA, an example of a rolling bulkhead, is shown in Figure 10. The 578kN (65 ton) maintenance bulkhead runs along a 203.3m (667-foot) long steel monorail beam attached to the dam. The bulkhead was shipped to the site in two halves, which were assembled on site, transported along the length of the dam in the upright position using two trucks travelling parallel (one to each side of a median), and lifted onto the monorail using two cranes placed on top of the dam. Motorized trolleys slide the 7.3m-high by 14.6m-wide (24-foot high by 48-foot wide) bulkhead in front of individual gate bays. As the bay is dewatered, unbalanced pressure pushes the bulkhead against the structure and holds it in place. Bolted connection brackets were fastened to the existing dam pier caps using high-capacity, deep-embedment post-installed concrete anchors (Garver 2012). Within approximately 5 minutes, the bulkhead can be moved from one gate bay to the next.

3.10. Needle and Infill Systems

Needle and infill systems consist of vertical "needle" beams that are supported at the bottom sill by the spillway structure and at the top by a horizontal spanning girder or truss. The needles may be floated in from the upstream in a horizontal position, fastened to the top horizontal beam, and sunk into vertical position or lifted using a crane. Depending on the space available for the working platform between the gates and the needles, the needles may be installed either bearing against the upstream face of the horizontal beam in a seated condition or anchored to the downstream face in an unseated condition (also called a "reverse" needle system). Floating needles may consist of parallel steel tubes or built-up sections that have internal ballast chambers and are hinged together between segments. Other systems use H-shaped steel needles with horizontal wood infill beams placed within the flanges. These systems are common in France and well-suited for low-head, wide-open channels because load is distributed to the structure through each individual needle. These systems consist of many relatively small pieces (except the top horizontal beam), thus requiring minimal equipment. Infill systems are sometimes carried and installed by hand and consist of wood or steel. Other material that may be considered is fiber reinforced polymer composites, which have been commercialized in other applications, such as bridge decks, due to their high strength-to-weight ratios and enhanced corrosion resistance. Needle and infill systems consist of many small pieces and are appealing for lightweight installations where pieces may be installed in a matter of days or weeks.

Figure 11. Needle and Infill Cofferdam, Myllykoski Hydropower Plant, Finland
(Pato Osakeyhtiö)

Myllykoski Hydropower Plant in Finland utilized wide flange steel needles and stacked infill beams (webs horizontal in “H”-orientation). Vertical needles were installed from a small mobile crane 445kN (50-ton) from atop the original bridge completed in 1929. Needles were braced at the top by the bridge. Stacked infill beams were placed within the webs of the needle beams as shown in Figure 11. The system closed a gate bay approximately 5.4m-high by 18m-wide (18ft-high by 59ft-wide). Nearly all material was taken from the owner’s storage materials, and the layout of the needles was such that the infill beams did not require cutting. Rubber ribbons were used as seals between the stacked beams at the vertical needles and at the contact with the concrete at the base, resulting in almost no leakage. Despite stringent Finnish safety laws requiring a minimum of three divers working simultaneously, a two-week erection process limited the owner’s construction cost to roughly 25,000 to 30,000€.

3.11. Stoplogs or Stacked Horizontal Trusses

Stoplogs are logs, planks, cut timbers, steel, or concrete beams stacked on top of each other with their ends secured in guides between walls or piers. The logs are usually installed one at a time using a crane with a lifting truss under balanced hydrostatic pressures. Stoplog systems can typically be placed in non-flowing water as they typically have no roller wheels at their ends. The benefits of using this system rather than a large single-piece bulkhead include: increased economic benefit from handling smaller pieces, reduced cranes lifting capacity requirements, increased storage flexibility, and improved transport efficiency. Steel stoplogs utilize a steel skin plate on either the downstream or upstream face to seal water. Rubber seals are placed between each stoplog and at the guide supports. Stoplogs are common at large spillway gates and locks. There are some cases in which stoplogs have been retrofitted to a site and in which slots are cut into the piers. However, new slots require structural analysis of the reduced pier sections, adequate space upstream of the gates for the slots, and sufficient clearance from any overhead bridges. Such modifications are costly. Temporary center posts have been installed at shallow upstream channels to reduce the span and size of the stoplogs, although a more complicated center post installation is required. The largest stoplog project (by orifice size) found was 44.34m-high by 12m-wide (145ft-high by 39ft-wide) for the Runilamu Killam Hydropower Station in Pakistan. It is currently being manufactured by Sinohydro Jiajiang Hydraulic Machinery Company Ltd. in China (JHMW 2015).

The set of six stoplogs at Flix Dam are one of the earliest installations of metal stoplogs found in our research and are still in use today. The stoplogs were fabricated between 1943 and 1948, constructed of iron and rivet materials, and stored in sections above each gate when not in use (ssee Figure 12). The full set of stoplogs measures 12.5m-high by 25.9m-wide (41ft-high by 85-ft wide) and weighs 448kN (100.8 kips). Stoplog systems are used at virtually every inland navigation District of the USACE. For example, Winfield Locks and Dam in the U.S. Army Corps of Engineers Huntington District has a stoplog system on the Kanawha River in Eleanor, West Virginia, USA. The set of six steel trusses was fabricated in Oregon, shipped cross country by train, and offloaded by crane directly from the train to a storage barge on the Kanawha River. The trusses were fabricated from plate sections, which allowed for cutouts for web openings to be reused as gusset plates. After installation, there was some leakage at the seals (see Figure 13), presumably due to storage directly on their seals, causing permanent compression. In some cases, leaks may be reduced using straw, horse manure, oakum, granite dust, sawdust mixed with oil, or blast furnace slag (Softley 2008). In other cases, repairs or new seals are needed. Leakage at seals should be expected, and tolerable limits should be established depending on the type of work. Environmental regulations should be considered when selecting a method for sealing leaks.

Figure 12. Flix Dam Stoplogs, Spain (Endesa)

Figure 13. Stoplogs at Winfield Locks and Dam, USA (USACE Huntington District)

3.12. Emergency Bulkheads

Emergency bulkheads have a top and bottom truss, a pair of rollers on each end, and a skin plate (typically on the upstream side). These systems are similar to stoplog systems, but unlike most stoplog systems, emergency bulkheads are designed to be placed in flowing water. In addition, these bulkheads are also used for maintenance activities.

Emergency bulkheads are commonly used by the U.S. Army Corps of Engineers at almost every high lift navigation dam on the Ohio River at tainter gate bays. Each dam typically has four or so (the number varies), and they are typically stored on the tops of the tainter gate piers. Figure 14 (photo courtesy USACE) shows an emergency bulkhead at Cannelton Locks and Dam on the Ohio River, on the border between Indiana and Kentucky. A traveling crane picks each individual bulkhead section up and lowers it into place in the upstream bulkhead slots, one at a time. The lifting beam and hoist cables are visible at the top of the figure on top of the stacked, lowered bulkhead sections. One of the tainter gates, painted white, is shown at the bottom of the figure.

Figure 14. Emergency Bulkhead at Cannelton Locks and Dam, USA (USACE Louisville District)

3.13. Vertical Lift Gate Bulkheads

These bulkheads are often stored in vertical slots in the spillway located upstream of the spillway gates and lowered into place to isolate the spillway gates when needed. In some cases, the bulkhead is a spare gate identical to the permanently installed spillway gates. In other cases, a separate bulkhead is installed upstream of each spillway gate so that each gate may be isolated individually. In cases where the bulkhead is not permanently installed in slots upstream of each gate, the bulkhead is transported using a movable crane that travels along the top of the spillway capable of transporting the bulkhead between bays and lowering it into the vertical slots. These bulkheads are usually part of the original design and construction of the spillway. The bulkheads have a large initial cost and are difficult to retrofit, but they are easily deployed, reliable, and capable of being deployed in emergency situations. Vertical lift gate bulkheads are being used at many new, large spillways, including Folsom Dam Auxiliary Spillway project in California, USA (see Figure 15).

Figure 15. Folsom Spillway Bulkhead, USA (U.S. Bureau of Reclamation/USACE [Frank 2015])

3.14. Arch Systems

Arch systems are commonly used for the closure of locks. Miter gates are fabricated as two separate doors mounted to the lock sidewalls with hinges on the vertical faces. The gates swing open in the middle like saloon doors. The steel doors are often fabricated with diagonal steel cross-bracing that helps keep the gates from in-plane racking due to self-weight. The vertical edge of the gates is mitered along the vertical face at the middle of the channel. The mitered edge forms a large contact surface that remains in compression due to unbalanced hydrostatic pressure when the downstream is dewatered. This surface seals under hydrostatic pressure without having to swing a full 90 degrees such that the gates are never coplanar. This configuration allows for arching action with a hinge between the two gates, reducing the bending moment in each gate compared to a simple span structure across the entire bay. The hydrostatic pressure is transferred to the gate through bending and in-plane axial force to the hinges and into the concrete sidewalls or piers. This type of system is best suited for bays with a flat upstream channel bottom in order to provide a suitable seal because the sealing plane is V-shaped and not a single plane. USACE proposed a hybrid stoplog and miter gate MCS, which consists of stacked horizontal arches, utilizing the cost savings afforded by arching action while allowing the MCS to be installed in smaller stackable sections. Flow-through baffles would be used to facilitate installation in moving water and would be closed off after the arches are installed (Padula 2010).

3.15. Inflatables

Inflatable rubber fabric dams consist of rubberized fabrics, often with steel reinforcement, inflated with water and/or air to create a cylindrical dam. The dams are anchored to the bottom of the channel and deflated during normal service. The potential advantages of this type of dam are the low material costs and the suitability to very wide channels. The cylindrical nature of these systems makes use impractical for tall channels or channels with very limited space upstream of the gates because the drape of the fabric may encroach on the working area. The drape can be reduced by using an intermediate bracing system, such as steel beams, trusses, or tension cables to essentially reduce the span of the fabric. Puncture resistance of inflatable systems may be enhanced by using steel plates, such as with the Obermeyer gate systems, or by combining multiple layers of fabric to provide an optimal balance of water tightness, strength, ductility, durability, and puncture resistance. Other fabric systems, such as Portadam™ systems, consist of a rubber fabric membrane that conforms to irregular shapes but requires closely-spaced steel backup supports and are limited to hydrostatic heads of approximately 3m (10 feet) (Portadam 2015). Invention of inflatable dams is credited to Prof. Mesnager in France in 1955. In recent years, this technology has been advanced in Japan, the Netherlands, and the United States (Erbisti 2014) and is primarily used for flood control applications.

The Balgstuw bij Ramspol in the Netherlands is, in many ways, a modernized version of a bear-trap gate and resembles a large inner tube of a bicycle tire. A flat membrane dam is inflated with air and water to create a half-round dam (see Figure 16). Obermeyer inflatable dams in the United States may contain multiple air bladders with programmable controllers to facilitate precise flow control, which can be varied along the length.

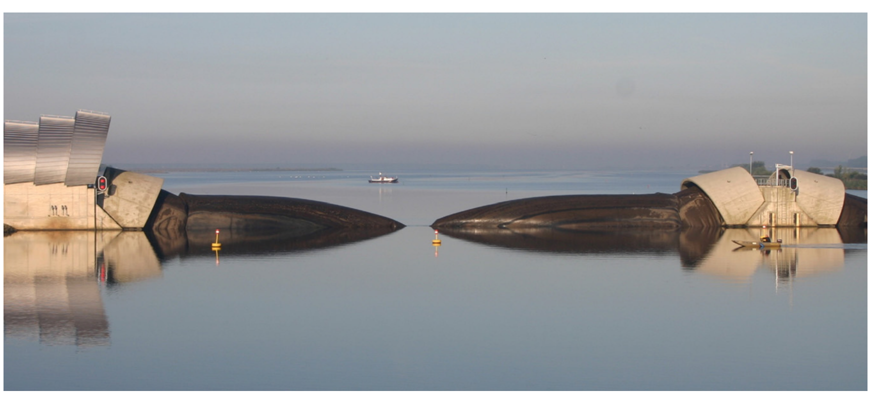

Figure 16. Balgstuw bij Ramspol Inflatable Dam, Netherlands
(BAM Infraconsult BV)

The largest Obermeyer gate installation found was 8m (26.2-feet) high by 60m (197-feet) wide at the Nanming River in Guiyang, China (Figure 17). Current Obermeyer gate production is suited for heights up to 10m (32.8-ft). Taller gates are technically feasible but with increased cost (Robert Eckman, personal communication, January 11, 2016). To date, no installations of inflatables for the sole purpose of dewatering another gate were found. However, inflatable systems are more cost competitive on a per square meter basis with other MCS types if maintenance can be limited to low flow seasons such that the required MCS height is much less than the spillway gate.

Figure 17. Nanming River Obermeyer Gate, China (Obermeyer Hydro)

4. RECENT TRENDS

Maintenance has become part of the design criteria of new dams and a growing concern for existing aging gates. Many relatively new large dams, such as Folsom spillway in the United States and Three Gorges Dam in China, utilize taller and narrower high-head gates such as radial gates and vertical lift gates in lieu of shorter, wider gates such as drum gates and roller gates, which were popular for large dams in the early 1900s. New spillways are constructed with vertical slots within the dam so that a bulkhead or emergency gate may be lowered upstream of each individual gate. However, for existing dams, retrofitting such slots is rarely practical. For dams without heavy installation equipment but with fairly stable water levels, float-in systems are often used.

In addition to scheduled maintenance, there is an increasing desire to develop MCS deployable in emergency situations and in a wider range of environmental conditions, including variable pool levels.

The Design-Build process has been used for many maintenance closure structure projects. This project delivery method is a collaborative process in which the engineer and contractor work together throughout the design and construction process, allowing a shortened overall project schedule and striving to reduce risk and overall project costs to the owner. This method has become more widely accepted by various public and private entities worldwide and is expected to become more prevalent for MCS projects.

5. CONCLUSIONS

A wide variety of maintenance closure structures have been utilized around the world to facilitate maintenance, remediation, and inspection of large spillway gates. Provision for dewatering of gate bays has become a key design consideration for new spillways and an ongoing challenge as existing spillways age and deteriorate. While some MCS types are clearly better suited to a particular site than others, selection of an optimal system requires careful consideration of a variety of factors, such as safety, installation time, durability, and capital and operations costs. The selection process should include close collaboration between owners, engineers, and contractors. The majority of MCS found in our research were traditional steel, concrete, and wood systems; however, technological advancement of other materials, such as fabrics, plastics, and programmable controls offer potential improvements. These technologies may provide such benefits as enhanced corrosion resistance, easier handling, and reduced operator error.

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