Spillway Chute Joints – the Devil's in the Details

JOHN HARRISON

THOMAS HEPLER

The Oroville Dam spillway chute failure provides difficult but clear lessons: past performance is no guarantee of future results, and routine inspections and rigorous dam safety programs may not be adequate to prevent a significant incident or even failure. There is a need to dig into the details of our dams and appurtenant structures, particularly older dams that may have been constructed prior to incorporation of practices that we consider standard today. Spillway chute and joint design is one instance where we need to dig deep into the design details, and if needed, perform explorations to verify assumptions.

Figure 1: Oroville Dam Primary Spillway after Initial Failure (Ref. California Department of Water Resources)

The Oroville Dam Spillway Incident Independent Forensic Team (IFT) Report notes that there was no single root cause of the Oroville Dam spillway incident. Rather, the incident was caused by a "complex interaction of relatively common physical, human, organizational, and industry factors, starting with the design of the project and continuing until the incident."

The physical factors included inherent vulnerabilities in the spillway designs and as-constructed conditions, subsequent slab deterioration, and poor spillway foundation conditions in some locations. The IFT Report concluded that the slab likely failed by hydraulic jacking:

"Water injection through both cracks and joints in the chute slab resulted in uplift forces beneath the slab that exceeded the uplift capacity and structural strength of the slab along a steeply sloping section of the chute. The uplifted slab section then exposed the underlying poor quality foundation rock at that location to unexpected severe erosion, resulting in removal of additional slab sections and additional erosion."

According to the IFT Report, the original design documentation indicated that the drains were only intended to collect groundwater seepage from the foundation. Shortly after construction, however, the chute slabs cracked over the foundation drains (which protruded into the slab instead of being recessed into rock), and high drain flows were observed. Thus, not only did the drains collect foundation seepage, but significant leakage through the joints and cracks in the concrete slabs, as well as surface water infiltration into the wall backfill. Although the drain flows were considered "unusual," the IFT Report notes that they were quickly deemed to be "normal."

It is understandable that a cursory consideration of the design elements might lead one to conclude that neither slab jacking nor foundation erosion would be likely, after all, the slabs were reportedly anchored into "good quality" rock, and the spillway had performed well for discharges in excess of the flow at which slab failure ultimately occurred. The IFT Report lists the following contributing physical factors in the hydraulic jacking of the spillway:

- Lack of drain system redundancy
- Cracks at underdrains (reduced concrete section)
- Lack of waterstops
- Lack of concrete cutoffs
- Slabs lightly reinforced
- Inadequate anchor strength

These detail items are discussed below as they relate to current state of the practice in spillway chute joint design.

SPILLWAY CHUTE FAILURE MODES

The two most common spillway chute failure modes are hydraulic jacking and foundation erosion. Both typically result from spillway flow entering open joints in the spillway floor. Accordingly, these failure modes are more often associated with older dams that were constructed prior to the current standard practice of incorporating waterstops in spillway joints.

These failure modes are often included in potential failure mode (PFM) analyses and risk assessments. An event tree for the Hydraulic Jacking PFM is illustrated below. Note that for the Oroville Dam spillway incident, "failure" (i.e., uncontrolled release of reservoir storage) did not occur, hence the 'incident" terminology is typically used.

- ► Spillway releases occur
  - ► Open joints, offsets, and/or cracks exist in chute slabs
    - ► Uplift mitigation measures ineffective or non-existent
      - ► Significant uplift pressure occurs
        - ► Chute slab jacking occurs
          - ► Unsuccessful intervention
            - ► Headcutting leads to uncontrolled release

Spillway PFM 1 – Hydraulic Jacking

Hydraulic jacking occurs when all or a portion of velocity head from spillway flow is converted to uplift pressure. The manual *Best Practices in Dam and Levee Safety Risk Analysis* (*Best Practices*), jointly developed by the Bureau of Reclamation (Reclamation) and U.S. Army Corps of Engineers (USACE), contains several chapters related to hydraulic potential failure modes of spillways. Chapter VI-1, entitled "Stagnation Pressure Failure of Spillway Chutes" details defensive design measures to significantly reduce the potential for hydraulic jacking. *Best Practices* uses the work by Frizell (Reclamation,

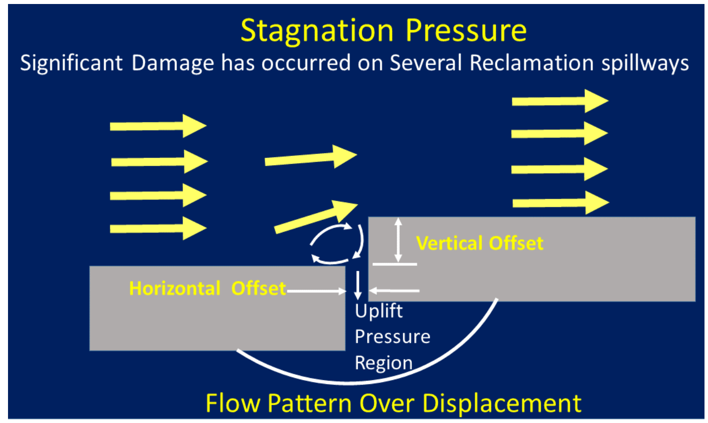

Figure 2: Stagnation Pressure Development (Ref. USBR/USACE *Best Practices* Chap. VI-1)

2007), a follow-up to the early work by Hepler and Johnson (1988). Figure 2 from *Best Practices* effectively illustrates the formation of stagnation pressure beneath a spillway chute, where kinetic energy of high velocity spillway flow is converted to uplift pressure beneath the slab.

Chapter VI-1 of *Best Practices* contains study results related to uplift pressure for various joint gaps (horizontal offsets) and configurations, vertical offset heights, and drain conditions (i.e., sealed or vented). Figure 3 presents the results for a sharp-edge joint, 1/8 inch gap and sealed cavity (no drainage) for a range of vertical offset heights. The study notes that the sealed cavity results are likely conservative. For the vented (i.e., drained) results, the study notes that the total gap flows were controlled by the drain system which remained constant for all modeled configurations; therefore, the study notes, if enough drainage was provided to accommodate all flow that tended to enter the crack, the uplift pressures could be lower than presented in the graphs. The maximum uplift pressure is the stagnation pressure based on the full velocity head. The study provides a good basis for estimating uplift in the assessment of spillway chutes having joints without waterstops, and the user should have an understanding of the drainage conditions of the spillway under evaluation. Reclamation is planning further hydraulic model studies of both sealed and vented drainage conditions.

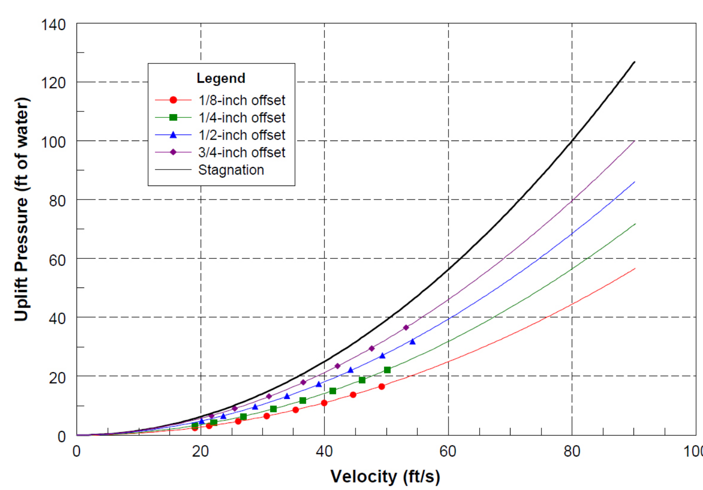

Figure 3: Uplift Pressure as Function of Velocity and Offset Height for Conditions Indicated (Ref. USBR/USACE *Best Practices* Chap. VI-1)

ISSN 1944-9836 - Association of State Dam Safety Officials

Another common spillway chute failure mode is foundation erosion. It is more commonly associated with soil subgrades, but, as seen in the case of Oroville Dam, can attack poorer quality (potentially undocumented) zones of otherwise competent rock. Foundation erosion often takes years to exhibit symptoms on the spillway surface. If unfiltered exit(s) exist, water entering joints and cracks will, over time, carry soil particles to the exit points, slowly enlarging voids until collapse occurs. The following event tree assumes that structural collapse occurs during spillway releases due to the additional weight of the water.

Spillway PFM 2 – Erosion and Collapse

- ► Spillway releases occur
  - ► Open joints, offsets, and/or cracks exist in chute slabs
    - ► Defensive design measures ineffective or non-existent
      - ► Significant foundation erosion occurs
        - ► Chute slab collapse occurs
          - ► Unsuccessful intervention
            - ► Headcutting leads to uncontrolled release

A third, but much less common PFM for spillways is related to cavitation. As high velocity flow passes over a surface, a potential exists for the surface to be damaged by cavitation. Cavitation will occur whenever irregularities in the flow surface cause the local pressure in flowing water to drop below the vapor pressure. Factors that determine whether or not the surface will be damaged include the magnitude of the flow velocity, the air content of the water, the intensity of the cavitation, the resistance of the surface to damage, and the length of time the surface is exposed (Falvey, 1990). Cavitation damage will first appear immediately downstream of a surface irregularity, and will grow in the downstream direction. The potential for cavitation damage is typically mitigated by minimizing abrupt and gradual irregularities in the flow surface, and by air entrainment.

JOINT SELECTION

Selecting and locating joints for spillway chutes are important design considerations. Joints in spillway slabs separate and limit the size of placements, and can serve to relieve tensile stresses and reduce shrinkage cracks. Typical joint spacing is 15 to 40 feet and panels should be nearly square, with a maximum length to width ratio of about 1.5:1. However, unique spillway geometries may require non-square panels or larger ratios. Slab dimensions should also be governed by concrete placing capacity, forming requirements, and foundation conditions. The various types of hydraulic structure joints are presented below:

- Contraction Joints
  – Unbonded; smooth dowels across joint
- Control Joints
  – Unbonded; reinforcement crosses joint
- Construction Joints
  – Bonded; reinforcement crosses joint
- Expansion Joints
  – Unbonded; compressible material within joint

Of these, the first two (contraction and control joints) are more commonly used in spillway chutes. Expansion joints are not typically used in spillway chutes due to the eventual loss of filler material, and the related flow disruption and cavitation potential related to the resulting surface irregularity.

DEFENSIVE DESIGN MEASURES

Proper detailing of spillway chute joints with defensive design measures can mitigate the development of adverse hydraulic conditions such as stagnation pressure and/or cavitation potential. The current best practices for spillway joint design are presented in Reclamation's *Appurtenant Structures for Dams (Spillways and Outlet Works) Design Standard 14,* Chapter 3 (DS14, 2014). The main features of spillway joint design are as follows (in general order of importance) and illustrated in Figure 4:

- Waterstops
- Transverse cutoff
- Reinforcement (or dowels) across joints
- Rock anchors (firm formation)
- Filtered underdrains
- Insulation (cold climates)

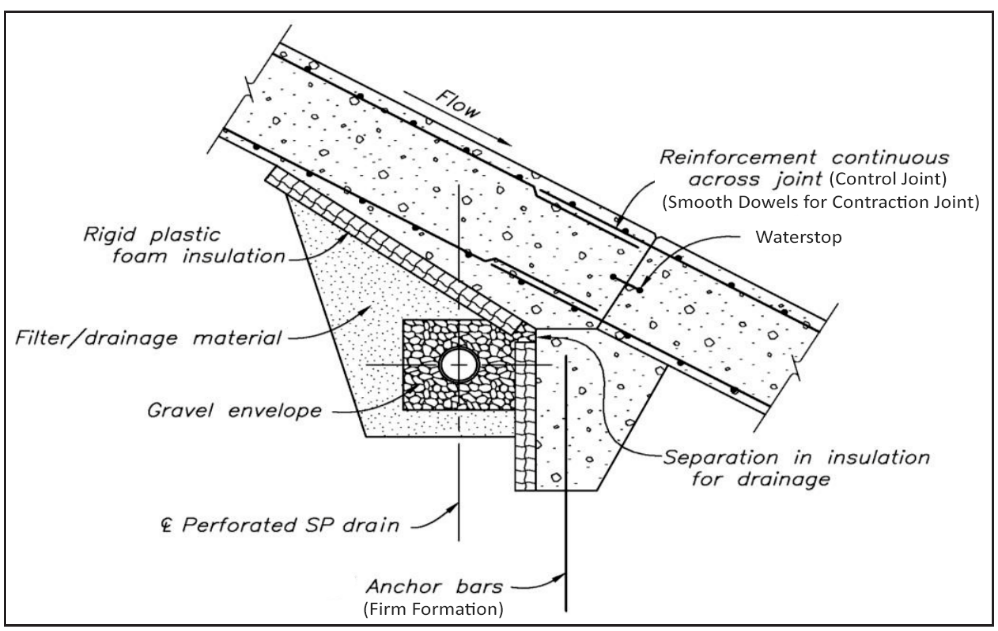

Figure 4: Defensive Design Measures (Adapted from *Best Practices* Chapter VI-1)

Although *Best Practices* lists the features of spillway chute design in the above order, it is arguable that filtered underdrains could rank with higher priority on earthen foundations.

State of the practice for spillway joints has evolved significantly over the years, with the importance of waterstops rising to the forefront as the first line of defense against uplift. The evolution of the use of waterstop in dam and spillway design is an interesting sidelight. One of the earliest known uses of "patented state-of-the art" copper waterstops in dam construction was in the contraction joints of Hoover Dam (c. 1930), used "to allay development of pore pressures in the body of the dam" (Rogers, p 171). The first uses of waterstops in spillway chutes is less clear, but their application steadily gained popularity throughout the middle of the 20th century. Edition 1 of *Design of Small Dams* (DSD, 1960) shows waterstops in some of the joint details, and describes several applications where their use would be beneficial, but still indicates that their use is discretionary "where water tightness is desired" or "where leakage is to be minimized." Such language persisted through the next two editions of DSD (1973, 1987), but by the third edition (1987) the joint details exhibited a steady progression of thought, with waterstops indicated more prominently in details and with fewer subjective modifiers. Fast forward to 2014, DS 14 (Reclamation) notes that "with very few exceptions, waterstops should be included with any flow surface."

The DSD third edition (1987) is the first edition to present details of joint geometry that include all of the best practices of spillway joints now considered standard: transverse cutoff with slab rest, dowels, waterstops, underdrains, and anchor bars. Interestingly, the first two editions of the DSD show a 1/2" vertical offset of the downstream slab in the standard joint detail. They note that the offset is included "to forestall a high buildup of dynamic head...which could introduce water at high pressure under the slab, which would result in uplift or dislodgement." Although no longer a standard detail, it indicated a recognition that it was prudent to avoid impingement of high velocity flow on a joint offset into the flow. The third edition of DSD no longer includes this detail, instead showing a flush joint surface, apparently recognizing that any irregularity in a joint profile could potentially lead to flow disturbance and cavitation on steeply sloping chutes. On milder slopes where cavitation is less of a concern, the older detail will likely not cause damage; however, there may still be flow disturbances related to the offset, and constructability may be an issue.

SLAB THICKNESS

There is no universal guide to slab thickness for spillway chutes. In general, the greater the unit discharge (cfs/ft of width), the thicker the slab. All three editions of DSD note that slab thickness is selected empirically in conjunction with drainage system, cutoff, and foundation anchor design to "stabilize the floor." However, a minimum slab thickness of 12 inches is commonly used.

If founded on rock with anchors, the minimum slab thickness will need to consider adequate embedment depth for dowels and bending stresses in the slab. On earthen subgrades, the effectiveness of drainage becomes more critical, since it is often not economical to increase slab thickness alone for stability. However, it is good practice to design the thickness of the slab (and other elements) to withstand part or all of the anticipated uplift pressure (i.e., assuming drains are not functioning or are only partially effective). If the chute slab will serve as a footing for the training wall, structural considerations may govern the minimum slab thickness. The concrete should normally have a minimum design compressive strength of 4500 psi at 28 days (DS14 and ACI 350).

WATERSTOPS

The importance of waterstops is commensurate with the risk of harm to life and property should they fail. Of the various waterstops available, internal PVC waterstops are the most common type incorporated into concrete hydraulic structures. The size (width) is commonly 6, 9 or 12 inches, and generally based on hydrostatic head and slab thickness (Figure 5). The following guidelines from DS 14 generally apply when selecting waterstops:

- Width (W) < slab thickness
- Width (W) >= 6 x MSA of concrete mix (where MSA = maximum size aggregate)
- Depth below surface > ½ W

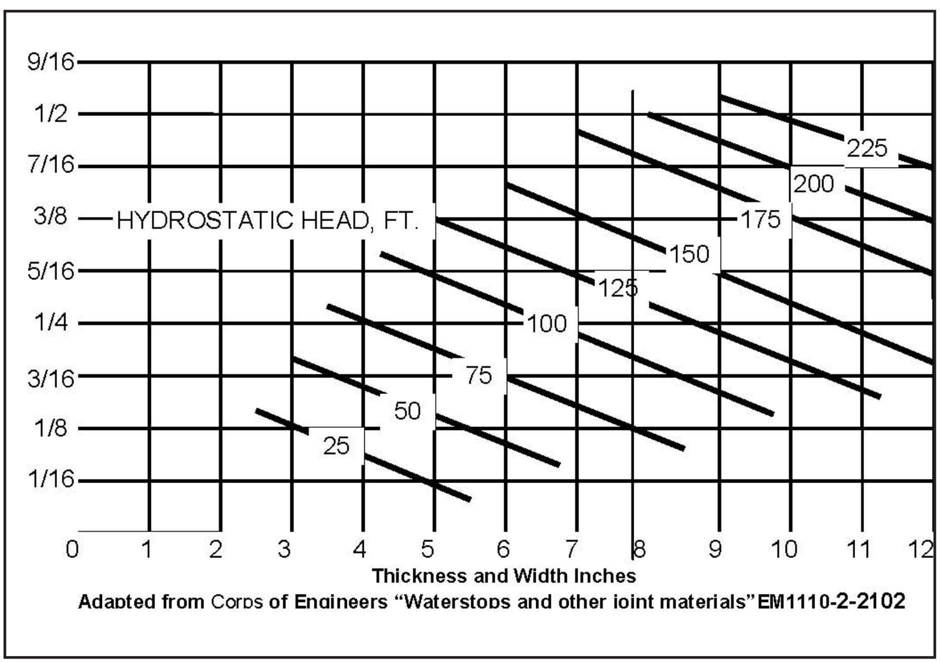

Figure 5: Waterstop Selection Guide (Ref. Sika Greenstreak, from EM 1110-2-2102)

ISSN 1944-9836 - Association of State Dam Safety Officials

Waterstop profile depends on application. Centerbulb waterstops are provided for moving joints (e.g., contraction joints in chute design, expansion joints in parapet design), while flat ribbed or end bulb waterstop are for non-moving joints (Figure 6).

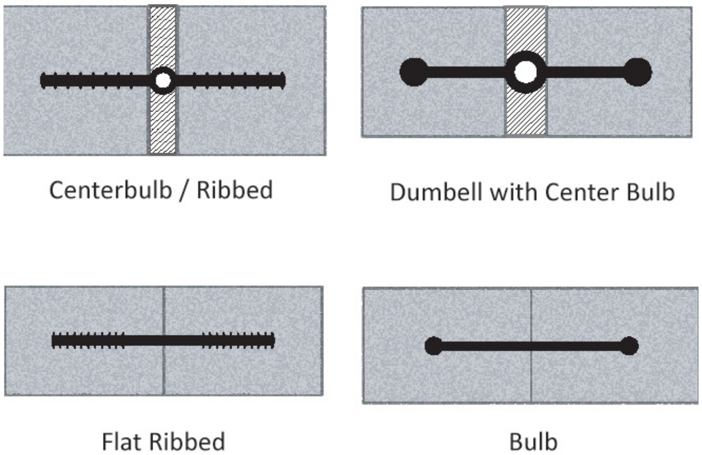

Figure 6: Common Waterstop Profiles (Ref. Sika Greenstreak)

However, to avoid difficulties at the intersection of two different waterstop profiles, it is common to globally use ribbed centerbulb waterstops where only some moving joints are present (for example, a transverse contraction joint in a spillway wall meeting a horizontal construction joint at the wall base). In general, it is good practice to require prefabricated waterstop junctions (Figure 7) in hydraulic structures, allowing only straight splices in the field.

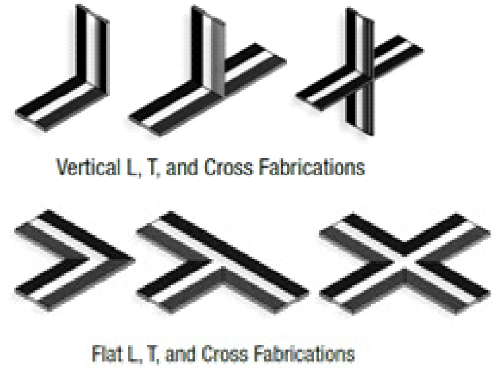

Figure 7: Common Prefabricated Junctions (Ref. Sika Greenstreak)

A base seal waterstop is a less common profile, but has found application in thin (e.g., 6”) overlays of existing spillways where internal type waterstops could lead to spalling at the joint (Figure 8).

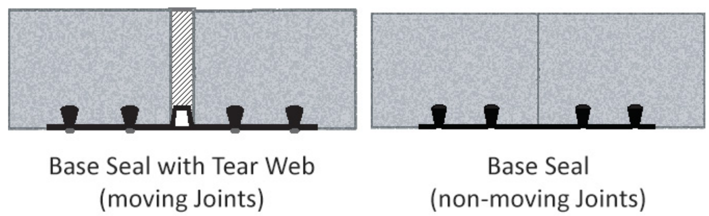

Figure 8: Base Seal Waterstop (Ref. Sika Greenstreak)

Waterstops should be firmly secured in place to prevent displacement by concrete. Figure 9 shows a photo of good waterstop installation. To decrease the risk of incorrect or incomplete installations, the contract documents should include details of waterstop installation in plan, profile and section. For more complicated installations, an isometric representation of the installation is extremely helpful, whether provided on the contract drawings or required as a submittal.

Figure 9:. Properly Securing Waterstop (Ref. Sika Greenstreak)

Another helpful quality control measure is to require the contractor to construct a small concrete mockup of a waterstopped joint. The mockup should contain all of the required waterstop splices (e.g., vertical contraction joint meeting a horizontal construction joint), and once satisfactorily completed, becomes the standard against which all subsequent waterstop installation on the project is measured.

When joining new concrete to old in a hydraulic structure, attaining a water-tight connection may require more attention to detail. PVC retrofit waterstop systems are available from manufacturers, and are applicable to both moving and non-moving joints. The PVC waterstop is affixed to the existing concrete with epoxy and stainless steel batten bars and bolts, followed by embedding the remaining leg of the waterstop in new concrete (Figure 10, left image).

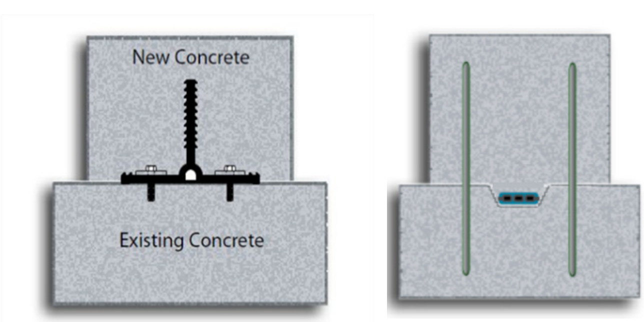

Figure 10: Retrofit Waterstop (left); Hydrophilic Rubber Waterstop (right). (Ref. Sika Greenstreak)

Another means of providing a watertight seal between old and new conrete in non-moving joints is the use of swell-type hydrophilic chloroprene rubber waterstop (Figure 10, right image). Since this type of seal is attained by compression of the swelled waterstop against the joint walls, it is only effective if the two concrete faces are tightly joined together, such as by reinforcing crossing the joint, or by other means of confining movement. A potential problem with a swell-type waterstop is the risk of swelling prior to encapsulation in the conrete or prior to attaining adequate concrete strength. To reduce the potential for this, hydrophilic chloroprene rubber waterstops typically include an expansion delay coating which will delay expansion for several days after wetting. Care should be taken to install the waterstop shortly before encapsulation in the joint. Bentonite-type swelling waterstops are typically discouraged from use in hydraulic structures due to their more rapid and higher expansion rates.

Additonal helpful information regarding design and construction details, installation guidance, and QA/QC procedures can be found in Kudritz, et. al. 2017. Also, instructive YouTube videos can be found on line to educate field staff on correct welding procedures and acceptance criteria.

CUTOFFS

Cutoffs (with slab rest) serve several essential functions. The slab rest (i.e., horizontal surface supporting the upstream slab) prevents vertical offsets at transverse joints. The cutoff intercepts underseepage, directing water to the drainage system, while also potentially intercepting permeable strata, increasing seepage path, and providing restraint from downslope creep (DSD 1987). Typical cutoff geometry is shown in Figures 4, 11, and 13.

LONGITUDINAL REINFORCEMENT/DOWELS

DS 14 contains numerous details of contraction and control joints, both of which are commonly used in spillway chute construction. Contraction joints are unbonded joints commonly constructed with smooth greased dowels to allow for slab (or wall) shrinkage due either to drying shrinkage or temperature contractions (Figure 11). A bond break is created by application of asphaltic paint, curing compound, or similar product to the joint surface prior to the second concrete placement. Care should be taken to orient the dowels parallel to the surface of the slab to maintain proper alignment.

For contraction joints, many doweling options are available to designers. Many allow plastic sleeves to be affixed to the forms and encapsulated in the first placement (Figure 12). After stripping of forms, the steel dowels or plates are inserted into the sleeve prior to the second concrete placement. Care is required when placing concrete around the plastic sleeves, which can easily become dislodged if concrete is placed directly on the sleeve. Some square dowel sleeves contain foam inserts or ridges in the sleeve that allow horizontal movement in two directions as the concrete contracts, but no vertical movement. This helps to reduce the risks and implications of misaligned dowels.

ISSN 1944-9836 - Association of State Dam Safety Officials

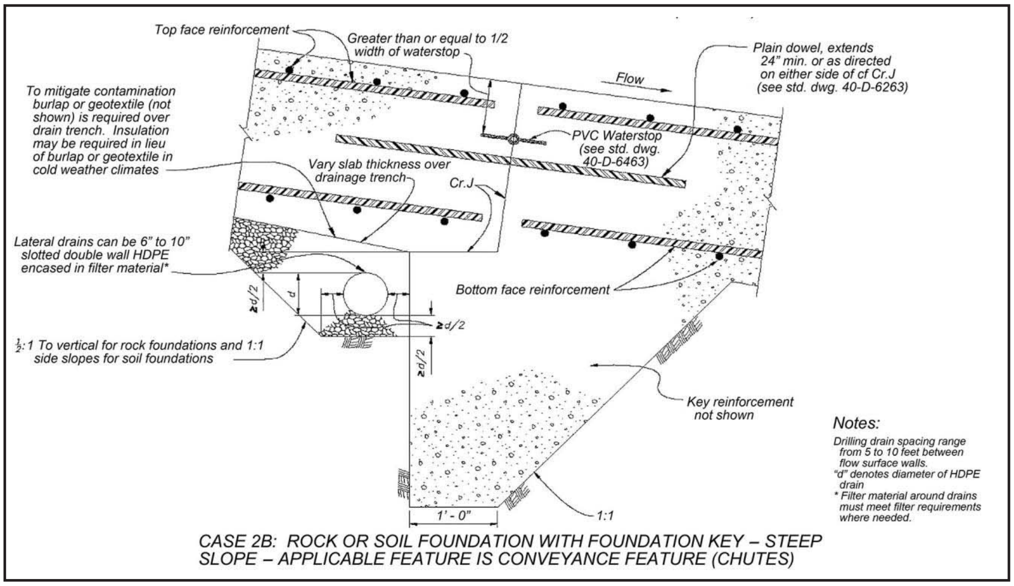

Figure 11: Contraction Joint Detail (Ref. USBR DS 14, Chapter 3)

Control joints are fully reinforced unbonded joints that are capable of transmitting a moment across the joint (Figure 13). DS 14 shows a clear preference for control joints in spillway construction because they provide greater constraint and ability to bridge localized subgrade defects, but also acknowledges that chutes with control joints may be more susceptible to shrinkage cracking. Shrinkage cracking may be mitigated by the use of special admixtures in the concrete.

FILTERED UNDERDRAINS

Drainage beneath chute slabs collects and conveys seepage from multiple sources: leakage through chute joints and cracks, groundwater, and infiltration from behind chute walls. If a chute is constructed over or adjacent to an embankment (i.e., generally limited to low embankments), it will collect embankment seepage from beneath and adjacent to the chute. Underdrains control excessive water pressure, mitigating potential uplift failure of the slab. Even a minor amount of groundwater can result in structural damage if it is not drained freely but rather is allowed to build up (DS14).

Figure 12: Alternative Doweling Methods

To adequately mitigate uplift pressures, the drainage system must be appropriately sized. It is common for designed drain capacity to be at least an order of magnitude greater than the estimated seepage quantity. The NRCS *Chute Spillway Drainage Guide* (1995) suggests that the drainage system convey 30 times the computed seepage quantity, underscoring the difficulty in accurately estimating seepage flows. When estimating seepage quantity, an allowance for some joint leakage is advisable even when waterstops are used.

Underdrains must be adequately filtered to prevent movement of foundation materials into the drainage system and initiation of foundation erosion. NRCS *Gradation Design of Sand and Gravel Filters* (2017) provides design guidelines for proper gradation of filter materials; Reclamation, USACE and FEMA provide similar guidelines. Figures 11 and 13 are applicable to both soil and rock subgrades, but only illustrate a one-stage filter which would be more appropriate for rock subgrades. For soil subgrades, it is common to incorporate a fine filter (typically ASTM C33 sand) beneath the entire chute slab (beginning at an appropriate distance downstream of the control section), coupled with a gravel drain and perforated pipe upstream of each transverse cutoff.

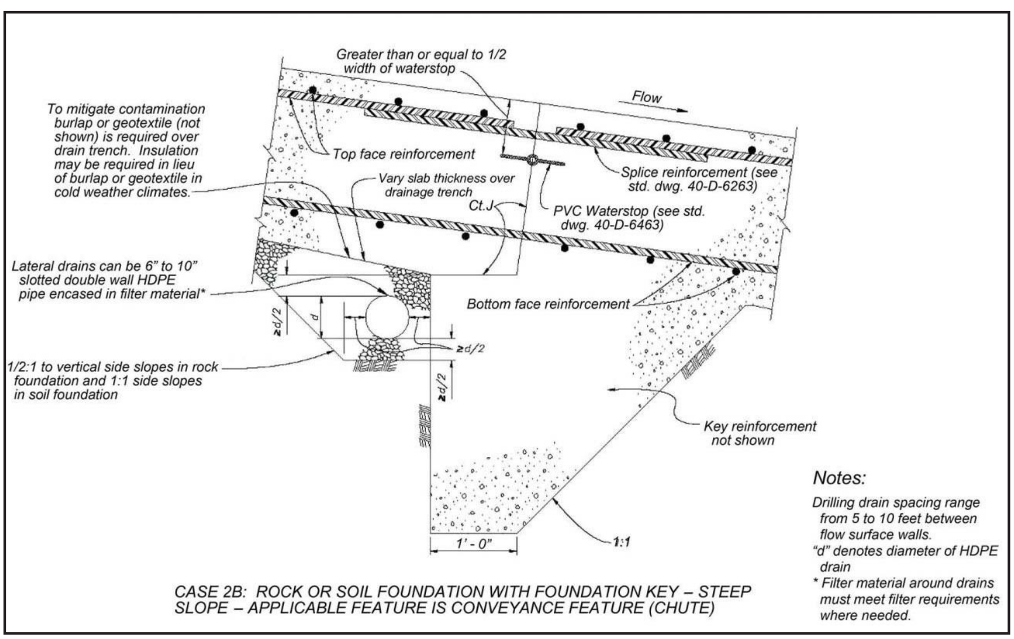

Figure 13: Control Joint Detail (Ref. USBR *Design Standard 14*, Chapter 3)

DS 14 also presents several variations of the above details, including longitudinal joints and mildly sloping slabs. It also provides details for drilled drains where relief of confined pressure in stratified rock is required to stabilize the chute.

Lastly, redundancy is required in chute drainage. As was learned in the Oroville Dam incident, lack of redundancy was a contributing factor in jacking of the slab, where the herringbone pattern allowed drainage only to one side, and many laterals were connected to a single manifold and outlet. At a minimum, two outlets should be provided for each branch of the drainage system in the event one of the outlets becomes clogged. Where significant pressure variability is likely (such as drain outlets through chute blocks in a stilling basin), it is common to vent the collector system to the atmosphere to buffer the pressure fluctuations. Lastly, current designs also commonly include cleanouts for inspection and maintenance of the drainage systems.

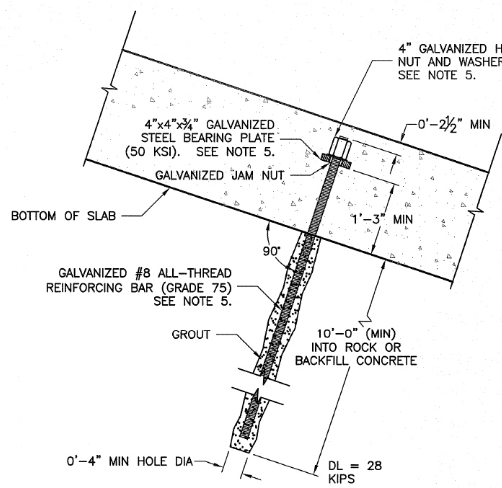

Figure 14: Thread Rod Passive Anchor (Ref. Schnabel Engineering)

ANCHOR BARS

Passive anchor bars are commonly used to help prevent uplift failure of spillway chutes founded on rock. Anchor bars are placed and grouted into drilled holes in the foundation rock, with typical spacings of 5 to 10 feet on center (Figure 14). When designing/analyzing anchors (as with slab thickness), it is common to assume a reduced effectiveness of the drainage system (if present).

It is typical to apply a factor of safety of 2 for grout to ground bond strength for the drilled hole. A load test to ultimate bond capacity (200% design load) on sacrificial anchor(s) can be performed to confirm assumed bond; thereafter, pull tests to 150% of design load on at least 10% of anchors is recommended for quality control testing. Where variable rock subgrades are exposed during construction, additional testing should be performed (and potentially additional/longer anchors installed) as recommended by a geotechnical engineer.

It is common to specify thread bar for some or all of the anchors to facilitate pull testing. Corrosion resistance is often provided by specifying epoxy, galvanized, or MMFX ® reinforcing or thread rod. If using galvanized anchors, they should be separated from plain reinforcing bars by a minimum of 2" to reduce potential for galvanic corrosion.

INSULATION

There have been several reported cases of spillway failures resulting from freezing of the underdrainage system, leading to heaving of slabs, loss of drain capacity and uplift failure of the chute slabs. In very cold climates, a good defensive design measure is providing insulation over the drain pipe beneath the chute as shown in Figure 4. The insulation prevents collected water from freezing, and also prevents frost heave locally (*Best Practices* and DS 14). Insulation typically consists of rigid polystyrene insulating materials.

JOINT SEALANT

A common question is whether to use joint sealant in spillway joints. On steep chutes and high velocity flow, sealant is generally avoided. Similar to expansion joint material, sealant often lasts only a few years, becomes difficult to maintain, and the formed recess creates flow disruption and can induce cavitation. Reclamation has used joint sealant in deep recesses in certain applications to help mitigate surface spalling and delamination at concrete joints from solar radiation (see DS14). When used, a two-component sealant is recommended.

On flatter slopes and chutes with lower velocity flow, joint sealant is more often used. The benefit of incorporating joint sealant is potential reduction of freeze-thaw damage at joints, and allowance for contraction without fouling of the joint with sediment. The deep recess detail provided in DS 14 may be beneficial where freeze-thaw damage of joints is a concern. Additional study and field documentation of this issue would be beneficial.

CONCLUSIONS

"Failure is simply the opportunity to begin again, this time more intelligently" - Henry Ford

Like it or not, our progress in dam engineering (as for all technology) often builds on the lessons learned from tragedies of the past. Spillway design details are no different. The various design guides referenced herein represent many of the best practices currently used in spillway chute detailing. Hopefully the best practices that we use today will stand the test of time, but we also need to be persistently attentive to improving our designs and reducing risk of failure.

But even when we "get the details right", there is still significant risk of poor construction practices or field conditions that vary from those we assume in design. Poor construction practices include poor concrete consolidation around waterstops, misaligned dowels or rebar, contaminated drainage systems, crushed or plugged drainage pipes, insufficient cutoff depth through permeable strata, and poor QA/QC of concrete and grout, to name a few. At Oroville, lack of adaptation of the design intent to field conditions was a major factor in the chute failure (i.e. decreased concrete cover over drain pipes, relaxation of foundation requirements, and failure to adjust rock anchor lengths). The importance of capable, well-trained and sharp-eyed field staff with ready access to the design team is needed to ensure consistency with the design intent.

ISSN 1944-9836 - Association of State Dam Safety Officials

On existing projects, particularly older dams, we need to dig into the original design details, photos, and if possible, eyewitness accounts to illuminate the design or evaluation team to as-built conditions and identify (and mitigate) credible potential failure modes of the appurtenant structure, with or without dam failure. These periodic comprehensive reviews, as recommended by the Oroville IFT, are a key element in identifying "unrecognized inherent vulnerabilities" and maintaining safe dams.

REFERENCES

Independent Forensic Team Report, Oroville Dam Spillway Incident, 2018.

NRCS, *Gradation Design of Sand and Gravel Filters, Chapter 26*, Part 633 National Engineering Handbook, 2017.

NRCS, South National Technical Center Design Section, *Chute Spillway Drainage Guide*, Fort Worth, Texas, 1995.

Reclamation, USACE, *Best Practices in Dam and Levee Safety Risk Analysis, Chapter* VI-1, "Stagnation Pressure Failure of Spillway Chutes", 2015

Reclamation, *Design Standard 14, Appurtenant Structures for Dams (Spillways and Outlet Works),* Chapter 3: "General Spillway Design Considerations", 2014.

Reclamation, *Design of Small Dams*, Edition 1, 1960.

Reclamation, *Design of Small Dams*, Edition 2, Revised Reprint 1977.

Reclamation, *Design of Small Dams*, Edition 3, 1987.

Reclamation, Report DSO-07-07, *Uplift and Crack Flow Resulting from High Velocity Discharges Over Open Offset Joints*, Denver, Colorado, 2007.

USACE EM 1110-2-2102, *Waterstops and Other Preformed Joint Materials for Civil Works Structures*, USACE, 1995.

Falvey, Henry T., "Cavitation in Chutes and Spillways," Engineering Monograph No. 42, Bureau of Reclamation, Denver CO, April 1990.

Hepler, Thomas E., Johnson, Perry L., "Analysis of Spillway Failures by Uplift Pressure," Proceedings of National Conference on Hydraulic Engineering and International Symposium on Model-Prototype Correlations, ASCE, August 8-12, 1988.

Kudritz, J., Adams, R., Davis, C., "Putting the STOP in Waterstops," ASDSO Dam Safety Conference, San Antonio, Texas, September 2017

Rogers, David J., "Hoover Dam: Construction Milestones in Concrete Delivery and Placement, Steel Fabrication, and Job Site Safety", Hoover Dam 75th Anniversary History Symposium 2010, ASCE.

Schrader, Ernest, "A Proposed Solution for Cracking Caused by Dowels," Concrete Construction, December 1987.

Thomas E. Hepler, P.E.

Schnabel Engineering
Senior Consultant
11 A Oak Branch Dr
Greensboro, NC 27407
(336) 274-9456
thepler@schnabel-eng.com

Thomas E. Hepler, P.E., is a senior consultant for Schnabel Engineering in Greensboro, North Carolina. Mr. Hepler has over 35 years of experience with the Bureau of Reclamation in hydraulic and structural engineering designs for concrete dams and appurtenant structures and joined Schnabel in 2014. He is an experienced dam safety inspector and risk facilitator, and has served on a number of risk analysis and value engineering teams and expert review panels. He is an active member of ASDSO, and is a registered professional engineer in Colorado, Idaho, Montana, and Washington.

John P. Harrison, P.E.

Principal
Schnabel Engineering
3 Dickinson Dr Ste 200
Chadds Ford, PA 19317-8800
(610) 696-6066
jharrison@schnabel-eng.com

John P. Harrison, P.E., D.WRE is a principal for Schnabel Engineering and serves as Technical Leader for dam design in the firm's Chadds Ford (Philadelphia area) office. He has 29 years of experience in dam analysis and design and led the development of structural design tools for evaluating gravity dam stability and reinforced concrete retaining wall design within the company. He also serves as an independent structural design resource and reviewer for Schnabel Engineering, and is an independent consultant for FERC Part 12 Dam Safety Inspections. He was a lead instructor for the 2016 and 2018 ASDSO 3-Day courses "Fundamentals of Reinforced Concrete Design for Hydraulic Structures." He holds professional registrations in PA, NJ, GA, VA and ND.