RESEARCH BRIEF:

Hydraulic Jacking in Concrete Spillway Chutes

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Hydraulic jacking, a long-recognized failure mode for concrete spillway chutes, quickly became a primary focus for the dam engineering community following the catastrophic spillway chute failure at California's Oroville Dam in 2017. The event led to a large-scale evacuation of 180,000 people and required repairs and improvements totaling $1.1 billion. Although infrequent on large-scale projects, there have been several hydraulic jacking failures in recent history. Bureau of Reclamation (hereinafter, simply "Reclamation") experience includes three notable failures: the fifth drop structure on the St. Mary Canal in Montana (2020), Big Sandy Dam spillway in Wyoming (1983), and Dickinson Dam spillway in North Dakota (1954). The latter two were analyzed by Hepler and Johnson (1988).

INTRODUCTION

Hydraulic jacking occurs when high-velocity flow in a spillway chute or similar structure passes over an open joint or crack at which the flow surfaces on opposite sides of the joint are displaced relative to one another so that the downstream surface is offset into the flow (i.e., an upward step in the floor as the flow moves downstream or a similar misalignment of chute walls). The problem may start with a joint that is shifted from its original alignment by differential movement of the foundation (e.g., expansive or contractive soils, consolidation or frost heave), a crack in a concrete slab, or a damaged concrete surface (a spall) located adjacent to a joint. Flow hitting the offset is brought suddenly to rest (stagnation), creating high pressures at the floor of the channel that can propagate through the opening and force flow into the joint. Suction on the top surface of the downstream slab also occurs due to flow separation just downstream from the offset, but the magnitude of this pressure change is slight compared to the increase below the slab and will be ignored in the remainder of this article. The high pressure can extend under the slab for significant distances, especially if there are voids in the foundation below the slab. If pressures are high enough, total forces capable of lifting (jacking) the slab further up into the flow are possible, which amplifies the problem and can cause explosive failure (Figure 1a). Additionally, flow through the opening and under the slab may cause erosion if not contained by a drainage system. This can create or enlarge voids, progressively extending the area exposed to uplift pressure and creating the potential for slab collapse into the void (Figure 1b). Either failure mode destroys the integrity of the chute lining, which allows rapid erosion of underlying material. Headcut erosion following the initial failure of the chute lining at Oroville caused concern for possible uncontrolled release of the reservoir until the advancing headcut stabilized in resistant rock beneath the spillway.

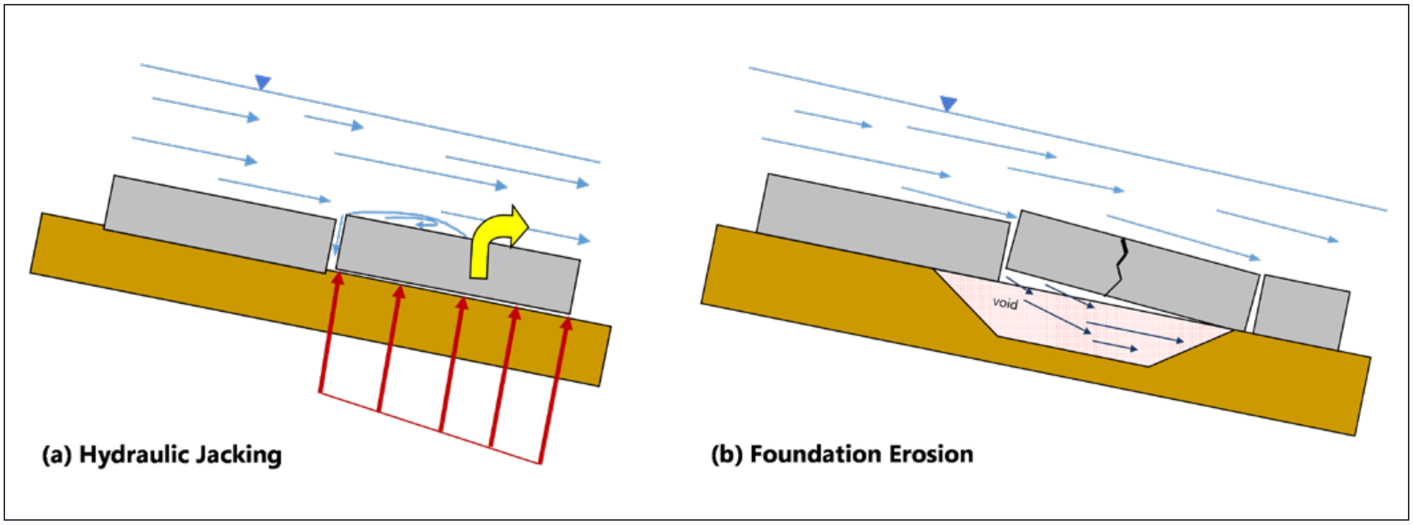

Figure 1 Failure Can Occur Due to (a) Jacking of a Slab Up Into the Flow, or (b) Collapse of a Slab Into an Eroded Void

Defensive measures to reduce the potential for hydraulic jacking include the following:

- Proactive design of joints with offsets away from the flow so that small movements do not immediately create offsets into the flow
- Keyed joints and heavy reinforcement to prevent differential movement that would create offsets into the flow
- Waterstops to prevent flow from penetrating through the joints (impermeable barriers embedded into joints during construction)
- Anchors to secure slabs to the foundation
- Drainage systems to alleviate pressure buildup and safely convey flow out of the foundation

Design of the latter two measures requires accurate estimates of uplift pressure and flow rates through affected joints.

The Oroville failure was carefully investigated by an Independent Forensic Team (IFT, 2018); the design lacked waterstops and keyed joints, had insufficient anchorage due to age-related corrosion and weak foundation materials (anchored into soil rather than rock), and probably lacked adequate drainage. Many older spillways have similar characteristics. The IFT evaluations of anchorage and drainage systems carried significant uncertainty due to limited experimental studies of hydraulic jacking in either laboratory or field conditions. Notably, the IFT report suggested relating uplift pressures to the flow velocity in the boundary layer of the chute rather than the mean velocity averaged over the full flow depth, but this concept had never been tested experimentally.

New Research

Just prior to the Oroville spillway failure, Reclamation initiated a new research project on hydraulic jacking. This study was intended to build upon the only two previously known studies, which were also performed by Reclamation (Frizell, 2007; Johnson, 1976). Reclamation has a strong interest in the problem because many of its projects are equipped with older spillways and chutes constructed on soil or rock foundations. These structures are more prone to hydraulic jacking than spillway chutes integrated into mass concrete arch or gravity dams, since the spillway lining is a relatively thin veneer over a variable-quality foundation. Consequently, hydraulic jacking failure modes are commonly considered in Reclamation's risk assessments.

The study by Johnson (1976) was focused on small canal wasteway structures and used an open channel laboratory flume limited to velocities of 15 ft/s with measurements of uplift pressure only. Frizell (2007) used a water tunnel to generate velocities approaching the joint up to 48 ft/s and considered square, chamfered, and radius joint edges. Measurements of flow rate through joints were also reported by Frizell (2007), but the flows were collected with unknown backpressure conditions below the joints and thus have little predictive value. Both studies showed that uplift pressure was directly dependent on chute velocity head, and that uplift increased with the height of the offset and decreased with increasing width of the gap. Unfortunately, both studies presented results primarily in dimensional form (curves that indicated uplift pressure as a function of absolute joint dimensions and velocities), which does not facilitate application to other scales or flow conditions.

The first phase of the new research (Wahl et al., 2019) combined and reanalyzed data from the Johnson (1976) and Frizell (2007) laboratory studies, developing relations between uplift pressure and the dimensionless aspect ratio of an open joint, $\beta = s/h$, where h is the height of the offset into the flow and s is the gap width illustrated in Figure 2. The relative uplift pressure head was expressed as $\Delta H/h_v$, where ΔH is the uplift pressure, defined as the increased pressure head in and under the joint compared to the hydrostatic pressure associated with the flow depth, and h_v is the velocity head calculated from the mean velocity in the chute. The value of $\Delta H/h_v$ was shown to vary from about 0.1 to 0.7, increasing with decreasing β and possibly approaching a maximum value of 1.0 for $\beta = 0$, although test data for very large and small β ratios were limited. Scatter of the available data was significant. The reanalysis also attempted to develop relations between uplift pressure and boundary layer velocities, although neither previous study directly measured the boundary layer velocity conditions approaching the tested joints. As a result, boundary layer velocities could only be estimated for the previous studies, and the resulting relations between uplift pressure and boundary layer velocity had even more uncertainty than the relation based on mean channel velocity.

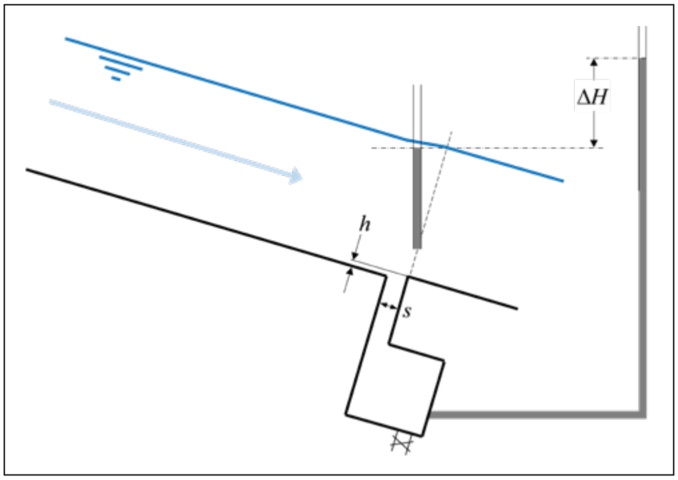

Figure 2 Schematic Illustration of Simulated Spillway Joint and the Uplift Pressure Head, ΔH

New Laboratory Experiments

In early 2021, Reclamation constructed a new laboratory facility to study the relation between boundary layer velocities and uplift pressure and to evaluate flow rates through spillway joints and cracks (Figure 3). The 2-ft-wide smooth acrylic flume on a 15° slope is equipped with an adjustable spillway joint located near the downstream end. The approach distance to the joint is about 40 ft, enabling a fully developed flow profile. Flow enters through a jet box (Figure 4) that can be used to give the incoming flow a head start at a high Froude number if desired. Tests have been performed at discharges up to 19 ft^3/s (unit discharge 9.5 ft^3/s/ft) and mean flow velocities at the tested joint up to about 32 ft/s. Joints have been tested with offsets ranging from 1/32 in. (0.75 mm) up to 1/2 in. (12.6 mm) and gap widths ranging from about 0.018 in. (0.45 mm) up to 3 in. (76 mm). Tests have spanned β ratios of 0.044 to 32—almost 3 orders of magnitude. Tests have included square-edged joints, chamfers, radius edges, and skewed and tilted joint orientations. Except for the tilted joint tests (illustrated later), most tests have considered situations where the downstream side of the joint is offset perpendicularly into the flow, as shown in Figure 2. One test was conducted with a very wide gap and a small offset away from the flow and only slight uplift pressure was measured in the joint. Most tests have used the smooth acrylic approach flow surface of the constructed flume, but a few tests have been performed with a range of artificially roughened floor overlays that change the boundary layer velocity characteristics.

Figure 3 Hydraulic Jacking Research Flume Showing the Jet Box (top), Spillway Joint (right foreground), and Receiving Channel and V-Notch Weir (foreground)

Figure 4 A Jet Box Regulates the Depth and Velocity of Incoming Flow

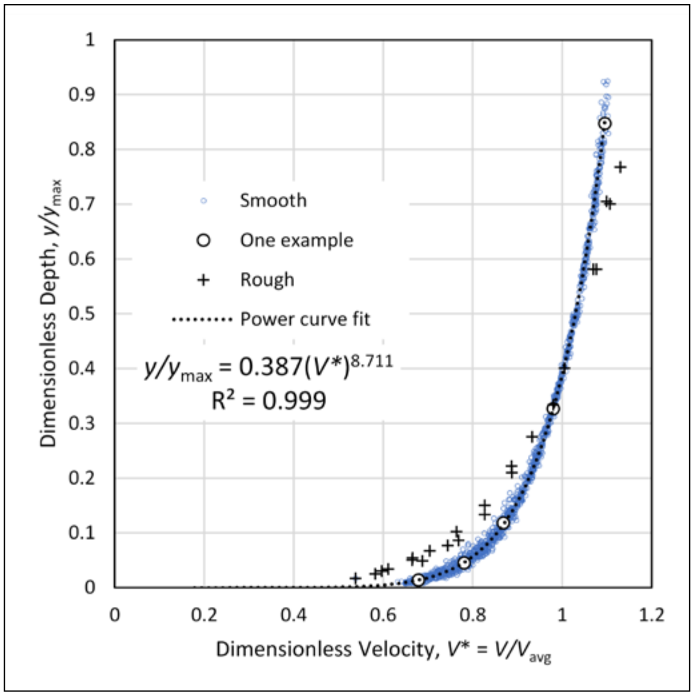

Figure 5 Dimensionless Flow Velocity vs. Dimensionless Depth. The dense cloud of points comprises data from about 230 smooth-floor tests, with one example profile and its power curve trend line highlighted. Rough data are from a small set of tests with 80-grit sandpaper applied to the approach channel floor. As the relative roughness increases, the exponent of the depicted power curve equation decreases.

For each test condition, the velocity profile above the spillway chute surface (Figure 5) is measured from the floor to near the water surface using a Pitot tube positioned just upstream from the joint. These measurements define the boundary layer velocity profile and average velocity, and they are also used to compute the flow depth, since direct measurement of the turbulent water surface is not possible. The mean uplift pressure within the modeled joint is measured through piezometer taps connected to a manometer board. Initially, the maximum uplift pressure is measured with the chamber below the joint sealed so that there is no net flow through the joint.

Next, valves on the bottom of the chamber are incrementally opened to permit flow through the joint. The reduced uplift pressure is recorded, and the associated flow rate through the joint is measured by a V-notch weir (Figure 6).

Figure 6 Valves Regulate the Backpressure and Flow Out of the Chamber Below the Joint, and the Joint Flow Is Measured Through a V-Notch Weir

Figure 7 Flow Attached to the Flume Floor as It Passes Over a Small Offset (top), and a Free Jet Detached From the Floor by a Large Offset (bottom)

A striking feature of the flow over an offset into the flow is that it will fully detach from the flume floor if the offset is large relative to the flow depth (Figure 7). If the jet breaks up in the air before landing again in the chute, it will remain detached. For deep flows, full jet breakup does not occur, and the jet remains attached to the floor since air cannot get under the jet. This is the usual condition for most prototype flows of interest, but both conditions can be produced in the lab over a large range of flows. Specifically, an attached jet condition can be established by starting at a large discharge that produces naturally attached flow, then reducing the discharge. Alternately, at low flow rates, the detached jet can be physically forced down to the floor with a deflector plate; once attached, the flow will remain attached down to a very small unit discharge. Attached jet conditions are the primary focus of the study, but measurements are made for both conditions whenever possible; jet detachment leads to greater uplift (up to about 8% of the approaching velocity head) and the data are being used to develop relations for estimating the uplift during attached conditions and the increase that occurs with detachment.

The newly collected uplift pressure data have been used initially to test the relation developed by Wahl et al. (2019) between β and $\Delta H/h_v$. A similar trend between the variables has been observed, but still with significant scatter. The new tests cover a broad range of joint geometries and flow conditions, with differences between measured uplift pressures and the predictions of the Wahl et al. (2019) equations ranging up to about ±30%. Those equations do not provide a means for incorporating the effects of varying chute surface roughness and also leave uncertainty about the maximum uplift pressure ratio; data trends from the Frizell and Johnson studies suggest a maximum of about $\Delta H/h_v = 60\%$, but there are few data approaching a gap width of zero.

A new analysis approach that uses the boundary layer velocity has reduced the uncertainty of uplift pressure predictions dramatically and provided new insight about the upper limits of potential uplift pressure and the role of surface roughness. The measured velocity profiles have been used to compute the boundary layer velocity head, h_v*, for only the layer of flow between the bed and the tip of each tested offset. Expressing the uplift pressure head relative to this boundary layer velocity head provides new insight. Figure 8 shows that for a given β value, $\Delta H/h_v*$ increases with the ratio y/h, where y is the flow depth and h is the offset height. For large values of y/h, the uplift pressure fraction approaches a limit of $\Delta H/h_v* = 1.0$, and for given values of y/h, the uplift pressure ratio increases with decreasing β. Thus, the largest uplift pressures occur when the offset is tall, the gap width is small, and the flow depth is large relative to the offset height. Note that there will be an increased uplift for depths below the previously mentioned threshold for jet detachment, but for depths much greater than that threshold, the uplift caused by an attached jet will exceed that of a detached jet. The form of the observed trends is similar for all values of β, and preliminary relations have been developed that allow estimation of uplift pressure with an error band of about ±10%, a threefold improvement over the Wahl et al. (2019) equations. The relations are also effective for both rough- and smooth-floor conditions. The boundary layer velocity head must be known to apply the relations. In the experimental data set, h_v^* is determined from the Pitot tube measurements, while in practical applications, it will be possible to determine h_v^* as a function of the mean channel velocity head and the friction factor of the channel, which determines the shape of the fully developed velocity profile. Typical friction factors in prototype concrete chutes are in the range of $f = 0.015$ to 0.025, with exponents in the velocity profile relation of $N = 7.2$ to 9.2, where $V \propto y^{1/N}$.

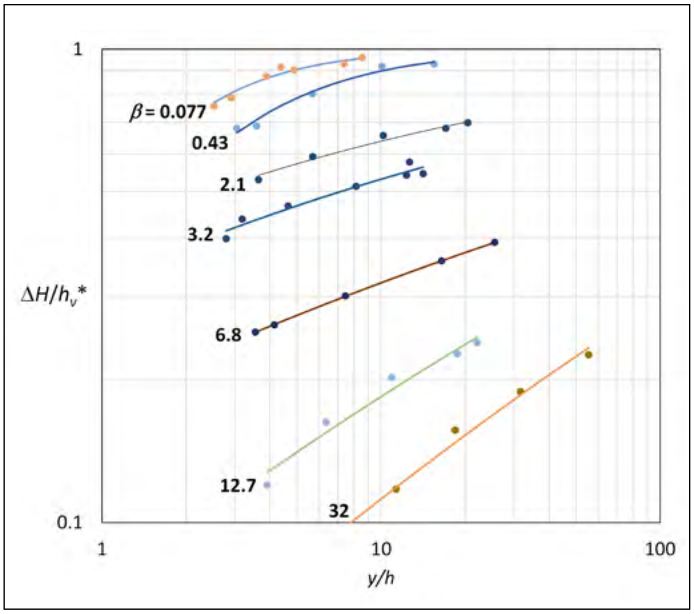

Figure 8 A Subset of the Experimental Data Showing Uplift Pressure Head as a Fraction of Boundary Layer Velocity Head vs. Ratio of Flow Depth to Offset Height (Attached Flows Only); Uplift Increases With Decreasing β and Increasing *y/h*

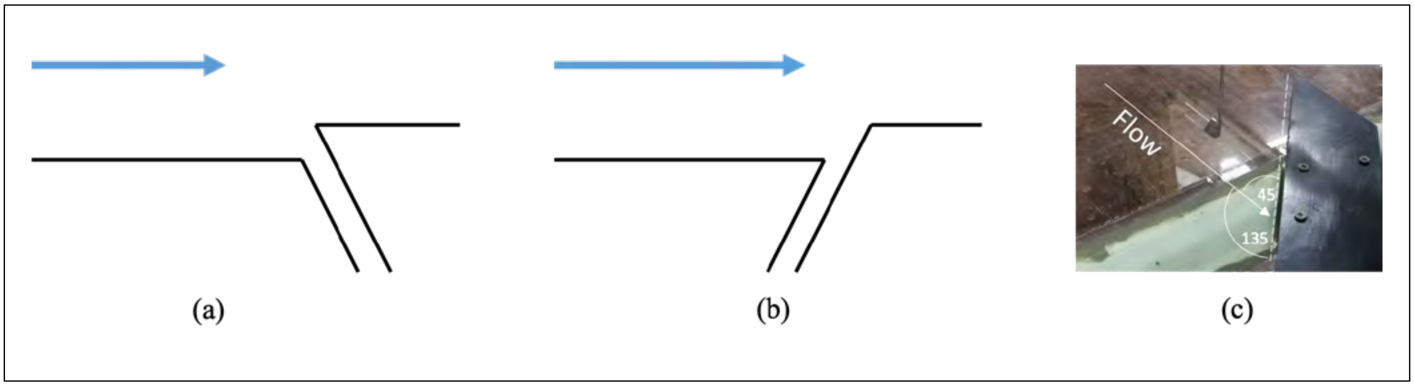

Figure 9 Illustrations of (a) a Joint Tilted Into the Flow, (b) a Joint Tilted Away From the Flow, and (c) a Photo of a Joint With a Skewed Alignment in Which the Joint Opening and the Offset Downstream From It Are Twisted 45° From a Perpendicular Orientation; the Two Legs of the Pitot Tube Point Straight Upstream

Although the new relations predict an uplift pressure fraction that approaches 100% of the velocity head of the boundary layer that impacts the offset (h_v^*), the offset height is always a small fraction of the flow depth in practical situations that produce large uplift, and h_v^* is a significantly reduced fraction of h_v. Thus, the practical upper limit of developed uplift pressure as a fraction of the mean channel velocity head (h_v) is still about 60%. This has been confirmed by tests that have covered a range of β ratios spanning almost 3 orders of magnitude, extending to offsets that are up to 30 times taller than the gap width.

Limited testing has been performed for other joint geometries, including chamfers, radius edges, skewness in the plane of the chute floor, and tilt into or away from the flow direction (Figure 9). Chamfers and rounding reduce uplift pressures by making the offset effectively shorter, reducing the obstruction of the flow. Skewing of the joint angle (twisting the axis of the joint in the plane of the chute surface) reduces uplift significantly, as does a tilt away from the flow (rotation in the vertical plane that parallels the flow direction); joints tilted into the flow seem to increase uplift pressure by only a small amount. Additional testing of these variations is planned. Plans are also being made to test a realistically cracked concrete specimen to evaluate the application of the developed relations to midslab cracks.

Flow Rates Through Joints

Tremendous flow rates—much larger than expected—have been observed in the joint flow rate tests, primarily due to the large driving head created by flow stagnation. An open joint behaves as an orifice, with discharge increasing as a function of gap width and driving head. The pressure head acting to force flow through the joint is determined in the experiments as the difference between the sealed uplift pressure measured with no flow through the joint and the reduced uplift pressure measured below the joint when the bottom valves are incrementally opened to release flow. This assumes that the sealed uplift pressure corresponding to no flow still exists at the top of the joint when there is flow through the joint. For each test, a discharge coefficient, C_d, is determined for the joint acting as an orifice. Values of C_d generally increase from 0 toward 1.0 with increasing values of the ratio V_{gap} / V_{chute}, the velocities through the gap and down the spillway chute (Figure 10). The discharge coefficient primarily represents the efficiency of flow entry into the joint (i.e., an entrance loss); for practical joint sizes there has been little dependence of C_d on the gap width of the joint or the thickness of the simulated chute slab (i.e., the length and associated friction losses for the flow path from the chute surface to the bottom of the joint). The relations will provide a means for computing flow through a joint, even though the velocity through the gap is not known until the discharge is determined; the preliminary relations that have been developed converge quickly when solved iteratively starting from an assumed value of the discharge coefficient.

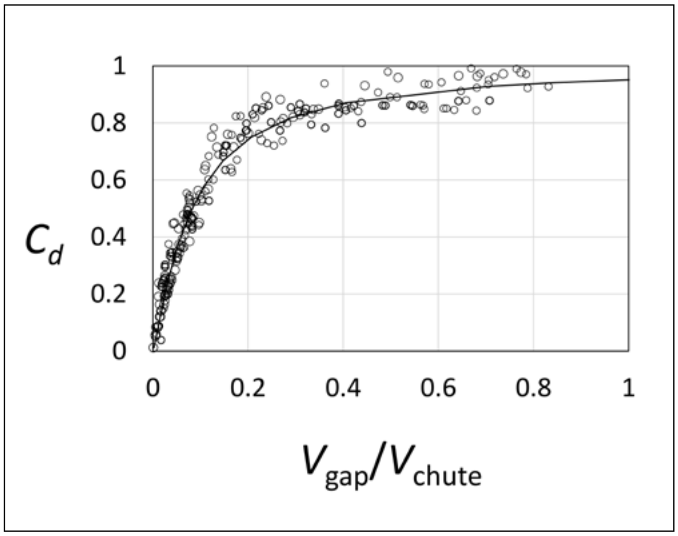

Figure 10 Joint Discharge Coefficients vs. Velocity Ratio at the Joint Entrance

Research Status

The general findings outlined in this article are presently being verified and refined for practical use, with some lab testing and peer review checking of the relationships still underway. Since the test flume has a fixed slope, computational fluid dynamics (CFD) modeling is being used to study other slopes. This is readily accomplished in CFD by changing the orientation of gravity relative to the defined geometry. Results thus far confirm that the uplift pressure relationships are not affected by the chute slope. This finding is also consistent with a recent study by Sánchez (2022) that used CFD to recreate some of the testing by Frizell (2007) and simulated flow over offset joints on different slopes. Pressures that develop beneath a chute lining downstream from a joint will increase above the uplift generated at the joint due to hydrostatics associated with the difference in elevation, but this can be readily accounted for analytically.

The initial objectives of the study included evaluation of the effects of aerated flow. The slope of the laboratory flume, the available flow development length, and discharge limitations have prevented the development of highly aerated flow in the test facility. Aeration that has been produced is limited and thus far has had no measurable effect on uplift pressure or flow rate through chute joints. No quantitative measurements of air concentration have been made, but even when aeration is visibly significant near the water surface, minimal air bubbles are observed near the bed. This is a typical situation for moderate to low-slope spillways (up to about 1.5H:1V, or 34°) that tend to be constructed as concrete chutes on soil or rock foundations, so the testing is believed to be applicable for most important spillway cases. Note that very steep spillways that could generate highly aerated flow are typically less likely to suffer uplift failures because such chutes are often integrated into the face of a mass concrete structure (a gravity or arch dam) without distinct surface and subsurface structural layers.

Application Example

The Oroville spillway forensic report (IFT, 2018) estimated theoretical stagnation pressures for the flow conditions at the inception of the Oroville failure when flow was being increased from 30,000 to 54,000 ft^3/s. A range of potential offset heights was considered using theoretical estimates of the boundary layer velocity profile. The IFT report did not consider the influence of the gap width; it only estimated the stagnation pressure at the face of the offset, not the fraction that would actually www.brayman.com

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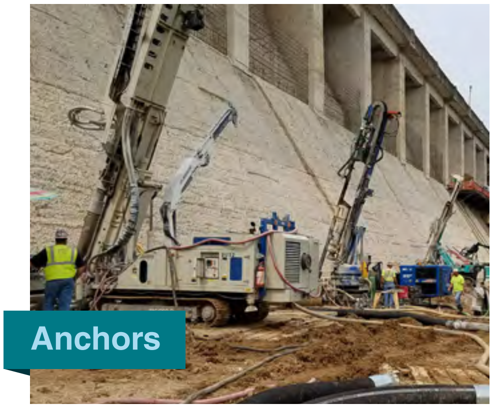
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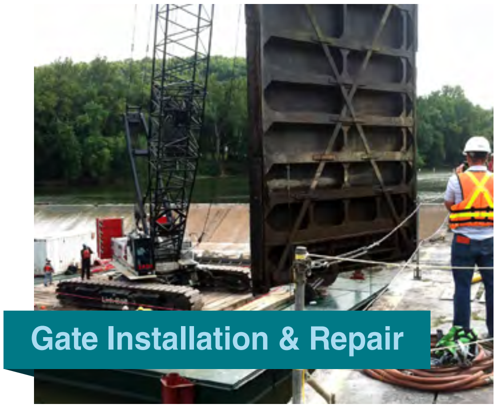
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propagate into a joint. Using preliminary relations developed from Reclamation's recent laboratory testing, Table 1 shows estimates of uplift pressure *in the joint* for a range of gap widths and the same offset heights considered by the IFT. The process for making these estimates involves the following steps:

- Calculate a basic water surface profile, using a tool such as SpillwayPro (Wahl & Falvey 2022) to obtain the depth, velocity, and friction factor at the station of interest.
- Use the friction factor to estimate N, the exponent of the fully developed velocity profile.
- Calculate the boundary layer velocity head h_v^* for the portion of the flow between the bed and the tip of the offset, as a function of the mean velocity.
- Calculate the uplift pressure as a function of h_v^*, $\beta = s/h$, and the relative flow depth, y/h.

The resulting uplift pressures are about 25–50% of the IFT's stagnation pressure estimates. However, these pressures are still large enough to have caused slab movement if anchorage was poor or if pressures were applied across large void areas beneath a slab.The Oroville report (IFT, 2018) also estimated flow rates that might occur due to seepage through cracks or open joints between slabs. These estimates considered only the width of potential gaps and the pressure head due to flow depth, not the increased driving head that would be generated by stagnation of the flow against offsets that project into the flow. The estimates also did not consider the change in discharge coefficient versus V_{gap} / V_{chute} that has been observed in Reclamation's recent testing. Table 2 compares the IFT estimates to values computed with preliminary relations developed from the lab work. The calculations assume fully vented conditions below the slab (i.e., a drainage system that can freely carry away all flow). The estimated flow rates range from about 30 to 100 times the forensic seepage flow estimates. This is quite significant considering that the forensic team concluded that the drainage system was probably undersized to handle even their estimated seepage flows if a high percentage of the length of existing joints and cracks was open to flow.

TABLE 1 **ESTIMATES OF UPLIFT PRESSURE HEAD (FT) IN SPILLWAY JOINTS OF DIFFERENT GAP WIDTHS, COMPARED TO IFT (2018) ESTIMATES OF STAGNATION PRESSURE AT THE FACE OF A RANGE OF OFFSETS.**

	OFFSET HEIGHT (INCHES)			
	⅛	**¼**	**½**	**1**
GAP (INCHES)	**Uplift Pressure Head (ft)**			
⅛	11.1	15.5	21.4	29.5
¼	10.6	15.2	21.2	29.4
½	9.2	14.1	20.7	28.7
1	7.3	11.8	18.7	27.9
Forensic estimate of stagnation pressure, ft	**28.4**	**38.8**	**49.2**	**59.6**
Assumed flow conditions: Q = 54,000 ft³/s, y = 3.09 ft, V = 98.6 ft/s				

TABLE 2 ESTIMATES OF UNIT DISCHARGE THROUGH OPEN JOINTS OFFSET INTO THE FLOW, ASSUMING FULLY VENTED CONDITIONS BELOW THE JOINT, AND COMPARISON TO ESTIMATES OF SEEPAGE FLOW FROM THE OROVILLE FORENSIC STUDY (IFT, 2018).

	OFFSET HEIGHT (INCHES)				
	⅛	¼	½	1	
GAP (INCHES)	Unit Discharge (ft^3/s/ft)				Forensic Estimate of Seepage Flow (ft^3/s/ft)
⅛	2.9	3.5	4.2	5.0	**0.04**
¼	5.7	7.0	8.3	9.9	**0.11**
½	11	13	16	20	**0.30**
1	19	24	31	39	**0.70**

CONCLUSIONS

Prior research studies of hydraulic jacking are limited, but Reclamation is now developing a more reliable method for estimating the uplift pressure and flow through joints and cracks associated with offsets into the flow. Accurate estimates of forces and flow rates are crucial for assessing risks presented by existing structures and planning and prioritizing maintenance and rehabilitation work.

Starting in 2019, Reclamation used existing data from previous studies to develop better nondimensional methods for estimating uplift pressure. The first attempts highlighted the large scatter in the available data and the need for a different approach and new data to include the influence of the boundary layer of the chute flow. Since 2021, new laboratory experiments have been conducted for a wide range of joint geometries. Results are being used to develop greatly improved methods for estimating uplift pressure and flow rate as functions of β, h_v*, and y/h. Uncertainty in uplift pressures has been reduced by a factor of about 3, and reliable estimates can now be made of the flow rate through open joints.

For the case of the Oroville spillway failure, uplift pressures calculated using the new methods are up to 50% of the theoretical stagnation pressure estimates made by the IFT, while flow rates are 30 to 100 times higher than the IFT's simple seepage flow estimates. This shows that the flow capacities of drain systems may need to be very large to achieve an appreciable reduction of uplift pressures. As research continues, more detailed information will be made available in upcoming peer-reviewed journal articles, including step-by-step calculation methods.

FUNDING

This research has been jointly funded by Reclamation's Research Office (Science & Technology Program) and Dam Safety Office (Technology Development Program).

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ASDSO Peer Reviewers

This article was peer reviewed by Greg Paxson, P.E., D.WRE (Schnabel Engineering) and Blake Tullis (Utah State University).

CORRECTION:

Hydraulic Jacking in Concrete Spillway Chutes

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After publication of the article in issue 20.2, it was discovered that gap dimensions used to calculate joint discharges were not converted from inches to feet, which caused the joint flow rates in Table 2 to be too large by a factor of 12. In addition, two other equations used in the calculation of uplift pressures, and joint flow rates have been adjusted since publication as a result of additional data collection and analysis.

1. The relation between the velocity profile exponent N as a function of the chute friction factor was adjusted. An established relation in the literature was initially used, but the new experimental data justifies a revision to improve the accuracy. The change reduces the value of N, which produces a steeper boundary layer velocity profile. This reduces uplift pressures, which are very sensitive to N. This also reduces joint flow rates since they are driven by the uplift pressure.

2. The curve relating the discharge coefficient to the velocity ratio V_{gap} / V_{chute} (Figure 10) was adjusted slightly as additional test data were obtained. This causes an additional small reduction of joint flows compared to the relationships used initially to generate Tables 1 and 2.

The revised Tables 1 and 2 on the opposite page are corrected for all three issues. Uplift pressure heads are reduced 30 to 45% and joint discharges are reduced by factors of about 15 to 20. Despite these changes, uplift is still very large (about 21 ft for the 1-inch offset, enough to displace a 15-ft thick concrete slab) and the joint flow rates are still larger than the forensic study estimates by factors ranging from about 1.7 to 8.6.

TABLE 1 **ESTIMATES OF UPLIFT PRESSURE HEAD (FT) IN SPILLWAY JOINTS OF DIFFERENT GAP WIDTHS, COMPARED TO IFT (2018) ESTIMATES OF STAGNATION PRESSURE AT THE FACE OF A RANGE OF OFFSETS.**

	OFFSET HEIGHT (INCHES)			
	⅛	**¼**	**½**	**1**
GAP (INCHES)	**Uplift Pressure Head (ft)**			
⅛	6.34	9.49	14.1	20.8
¼	5.99	9.29	14.0	20.7
½	5.23	8.60	13.5	20.5
1	4.11	7.23	12.2	19.4
Forensic estimate of stagnation pressure, ft	**28.4**	**38.8**	**49.2**	**59.6**
Assumed flow conditions: Q = 54,000 ft^3/s, y = 3.09 ft, V = 98.6 ft/s				

TABLE 2 **ESTIMATES OF UNIT DISCHARGE THROUGH OPEN JOINTS OFFSET INTO THE FLOW, ASSUMING FULLY VENTED CONDITIONS BELOW THE JOINT, AND COMPARISON TO ESTIMATES OF SEEPAGE FLOW FROM THE OROVILLE FORENSIC STUDY (IFT, 2018).**

	OFFSET HEIGHT (INCHES)				
	⅛	**¼**	**½**	**1**	
GAP (INCHES)	**Unit Discharge (ft^3/s/ft)**				**Forensic Estimate of Seepage Flow (ft^3/s/ft)**
⅛	0.19	0.23	0.28	0.34	**0.04**
¼	0.36	0.45	0.56	0.69	**0.11**
½	0.68	0.86	1.09	1.36	**0.30**
1	1.21	1.58	2.07	2.65	**0.70**