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Boundary Layer Effects on Hydraulic Jacking in Spillway Chutes

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14. ABSTRACT
Hydraulic jacking is a serious threat to concrete spillway chutes, illustrated by the catastrophic chute failure that occurred in 2017 at Oroville Dam, a California Department of Water Resources facility. To support Reclamation's efforts to mitigate against hydraulic jacking failures, experimental data from the existing literature were reanalyzed and new experiments were conducted. Analysis of previous work produced new relations between uplift pressure and the dimensionless aspect ratio of offset height and gap width at an open spillway joint. New laboratory testing led to further improvement, with new equations for estimating uplift pressure, flow rate through joints and cracks, and the effects of various methods of remediating existing offsets. The new laboratory tests included measurement of boundary layer velocity profiles approaching a modeled spillway joint. Uplift pressures were normalized to the velocity head near the boundary rather than the mean channel velocity head used by previous investigators. This normalized uplift varies with the joint aspect ratio and the flow depth to offset height ratio. This reduces the uncertainty of predicted uplift pressures by a factor of about 3 compared to previous methods that ignored the boundary layer. The new tests of flow through joints showed that extremely large flow rates are possible. Testing of joints and cracks with irregular geometries led to useful relations for estimating uplift at joints that are chamfered, rounded, skewed, beveled, or otherwise relieved to reduce uplift. Finally, the new relationships developed in this research were incorporated into spillway analysis software tools used at Reclamation.

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Hydraulic jacking, uplift, boundary layer

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Mission Statements

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

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Cover Image – The center and bottom-right photos show the Oroville Dam spillway failure in 2017 (California Department of Water Resources). All other photos depict laboratory testing conducted in Reclamation's Hydraulics Laboratory (Tony Wahl / Bureau of Reclamation).

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Contents

Executive Summary

Hydraulic jacking failures have always been a concern for spillways and other high-speed waterways. Concrete chutes develop cracks and must necessarily be constructed with various joints, all of which are prone to displacement over time that can create offsets into the flow. Some specific causes for offsets are expansive or contractive soils, consolidation or frost heave, and damage to concrete surfaces (e.g., spalls) adjacent to a joint. Hydraulic jacking can occur when the flow strikes such an offset and is brought suddenly to rest, similar to a pedestrian tripping on a sidewalk crack. The localized stoppage of flow at the offset creates dangerously high pressures that can be injected into the foundation if cracks or joints are open to allow water penetration. Open joints may exist in older spillways that were not constructed with waterstops, or in newer spillways due to misinstallation or failure of waterstops. When high pressure water penetrates through cracks or open joints and pressurizes large areas of the foundation, the result can be an explosive jacking failure since any lifting of the slab amplifies the flow stagnation effect. Flow into the foundation can also lead to erosion beneath the slab that destabilizes the structure and allows high pressures to be applied to larger expanses of the slab.

Modern spillways incorporate multiple layers of protection against hydraulic jacking. Keyed and heavily reinforced joints are meant to prevent the development of offsets, while waterstops within joints are meant to prevent water intrusion (both pressure and flow). Older structures that might lack some of these modern features still have multiple layers of protection, including the weight (thickness) of the slab itself, anchors to hold the slab down, and subsurface drains meant reduce the buildup of pressure. When offsets are known to exist in a spillway, corrective measures may include grinding and beveling to reduce or eliminate them. Unfortunately, the design of anchors, drains, and related features requires knowledge of the pressure forces created by flow stagnation, the quantity of water that can be injected into an opening, and the modification of uplift and flow that comes from remedial measures. The catastrophic failure of the spillway at Oroville Dam (California) in 2017 showed that the capacity of anchors and drains can be exceeded.

This report summarizes the end products of a series of research efforts funded by the Science & Technology Program and Dam Safety Technology Development Program. The work began in late 2016 with a small literature review and scoping study aimed at building upon two earlier Reclamation research efforts related to hydraulic jacking. During this initial phase of the project, the failure at Oroville Dam occurred and the subsequent forensic investigation demonstrated that the fundamental fluid mechanics phenomena that drive the hydraulic jacking process were still poorly understood.

The two previous Reclamation studies were a relatively low-velocity flume experiment by Perry Johnson in 1976 and a higher-velocity water tunnel experiment by Warren Frizell completed in 2007. These studies—both performed at Reclamation's Hydraulics Laboratory in Denver, Colorado—provided a basic understanding of the phenomena but left many details undefined.

The most important of these were the effect on uplift pressures of the boundary layer velocity profile in the spillway chute and the measurement of flow rates through open and offset joints.

The first major task of the new research effort was to learn as much as possible from the previous studies. Combining their data showed initial disagreement between the Johnson and Frizell data sets; the Frizell uplift pressures were generally larger in the range where the test conditions overlapped. The water tunnel test environment used by Frizell proved to be the cause, and when venturi effects and friction and transition losses were accounted for, the uplift pressure data came into better alignment. Further insight was gained when uplift pressure normalized by the depth-averaged velocity head was related to a dimensionless aspect ratio of the joint, $\beta = s/h$, where s and h were gap width and offset height, respectively. But still, uncertainty remained high, with about ±30% scatter of the data around a mean prediction line. Even though no boundary layer velocities had been measured in the early studies, attempts were made to normalize the uplift pressures with respect to estimated boundary layer velocities. Unfortunately, the resulting relationships were not a significant improvement. This work was documented in a peer-reviewed article in the ASCE *Journal of Hydraulic Engineering* (Wahl, Frizell, and Falvey 2019).

In early 2021 testing began in a new laboratory facility constructed specifically to create a range of measurable boundary layer conditions. The experimental work continued into late 2023 and the results were dramatic, with a threefold reduction of the uncertainty of predicted uplift pressure and the development of the first methods for estimating discharge through open offset cracks and joints. This work was documented in a series of three additional articles in the *Journal of Hydraulic Engineering* (Wahl and Heiner 2024a, 2024b, 2024c). The topics of these articles are briefly: 1) uplift pressure generated by stagnation at an offset; 2) flow rate into joints; and 3) uplift pressure and flow rate at joints with irregular (non-square) geometries. These articles present the equations for predicting uplift pressure and flow rate at a single location in a spillway for specified flow conditions and joint or crack geometry. A fourth paper presented at the 2024 International Symposium on Hydraulic Structures demonstrates the application of the new methods to the complete length of a spillway over a full range of discharges.

Following completion of most of the testing we discovered an older data set published by structural engineering researchers outside Reclamation who studied flow through very narrow cracks in concrete structures (Kanitkar et al. 2011). A reanalysis of their data provides supplemental information for determining friction factors and improving estimates of flow through very narrow cracks. This work was published as a technical note in the *Journal of Hydraulic Engineering* (Wahl and Mortensen 2024).

In addition to physical model testing, some limited computational fluid dynamics (CFD) modeling was performed to confirm the early assumption made during the experimental design phase that conversion of kinetic energy into stagnation pressure was independent of the chute slope and thus could be studied in a fixed-slope facility. Results of these CFD studies were never published by Reclamation, but the findings were independently confirmed by other studies, most notably the M. Sc. thesis by Sánchez (2022) which came to light after Reclamation's initial CFD modeling efforts.

In September 2024 a one-day workshop on the topic of hydraulic jacking was held at Reclamation as part of the Association of State Dam Safety Officials (ASDSO) Annual Conference. The workshop presented the results of the study to approximately 70 ASDSO attendees and 25 Reclamation staff from the Technical Service Center. The workshop also included extensive discussions relating to risk assessment, rehabilitation and repair methods, and resilient design approaches.

The majority of Reclamation's experiments from 2021-2023 involved clear-water (non-aerated) flow conditions, so the new equations are presently restricted to non-aerated flow. The 15-degree sloped flume used for the experiments was able to produce only slightly aerated flow conditions, and in limited testing no significant effect of aerated flow could be detected. New research that will use a steeper flume to study hydraulic jacking in aerated flow conditions is being initiated in late 2024 at the Laboratory of Hydraulics, Hydrology, and Glaciology of ETH-Zurich in Switzerland.

The end result of these studies is a vastly improved understanding of hydraulic jacking. Designers and risk analysts will be well-equipped in the future to estimate uplift pressure heads, flow through joints and cracks, and the effects of different joint and crack remediation strategies. The primary application of this work is for spillways, but there are also potential applications to coating failures in pipelines and other high-velocity flow environments, to sediment bypass tunnels that are often lined with granite panels for wear resistance that are susceptible to uplift failure, and to unlined rock channel spillways where hydraulic jacking leads to the plucking and removal of individual rock blocks. A final end product of this study is a new engineering monograph titled *The Fluid Mechanics of Hydraulic Jacking*, which combines all of the results contained in the previously mentioned journal articles under a single Bureau of Reclamation cover.

Figure 1. — Hydraulic jacking failures from left to right at Oroville Dam, California (2017), St. Mary Canal Drop #5, Montana (2020), and Big Sandy Dam, Wyoming (1983).

1.0 Annotated End Products Summary

The products of this study are fully documented in a series of peer-reviewed journal articles, most of which are available open-access to the general public. An annotated summary of each article is provided here:

1. **Wahl, Frizell, and Falvey (2019) – Uplift pressures below spillway chute slabs at unvented open offset joints. ASCE *Journal of Hydraulic Engineering*. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001637.** This article combines the data of Johnson (1976) and Frizell (2007) to develop new relations between uplift pressure head, channel velocity head, and the joint aspect ratio. Attempts were also made to develop relations to boundary layer velocity, but the resulting equations were more uncertain than relations to mean velocity. A pre-press version of this article was included in the appendix of the next item (Wahl 2021), which is available from the Reclamation web site.
2. **Wahl (2021) - Uplift Pressure and Flow through Open Offset Joints in Spillway Chutes. Final Report ST-2021-19170-01.** This closeout report for the FY2019-FY2021 funding cycle presented initial laboratory test results.
3. **Wahl and Heiner (2023) – Research brief: Hydraulic jacking in concrete spillway chutes. ASDSO *Journal of Dam Safety*.** This overview article provides a summary of the new experimental program and gives general findings without providing specific equations for computing uplift pressure or joint flow rates.
4. **Wahl and Heiner (2024a) – Laboratory measurements of hydraulic jacking uplift pressure at offset joints and cracks. ASCE *Journal of Hydraulic Engineering*. OPEN ACCESS. https://doi.org/10.1061/JHEND8.HYENG-13871.** This article develops the equations that relate uplift pressure head in a joint to the flow conditions in the chute and the geometry of the joint, considering boundary layer effects.
5. **Wahl and Heiner (2024b) – Discharge through open offset joints and cracks in spillway chutes. ASCE *Journal of Hydraulic Engineering*. OPEN ACCESS. https://doi.org/10.1061/JHEND8.HYENG-13898.** This article develops the equations for calculating discharge through an open offset joint, neglecting friction losses through the joint.
6. **Wahl and Heiner (2024c) – Effects of joint and crack geometry on hydraulic jacking in lined and unlined spillways. ASCE *Journal of Hydraulic Engineering*. OPEN ACCESS. https://doi.org/10.1061/JHEND8.HYENG-13994**. This article addresses uplift pressure head and flow rate through irregular (non-square) joints, including joints with existing offsets that have been beveled or otherwise modified to reduce uplift pressure. Uplift and flow at irregular mid-slab cracks is also tested.

7. **Wahl and Heiner (2024d) – Predicting uplift pressures and joint flows along a spillway chute. 10th IAHR International Symposium on Hydraulic Structures, Zurich, Switzerland. OPEN ACCESS. https://doi.org/10.3929/ethz-b-000675921.** This article applies the equations for hydraulic jacking uplift pressure and crack flow to the full length and design discharge range of the Oroville Dam spillway to demonstrate the variation of hydraulic jacking risks for a wide range of practical flow conditions.
8. **Wahl and Mortensen (2024) – Friction factors for flow through cracks in concrete hydraulic structures. ASCE *Journal of Hydraulic Engineering*. OPEN ACCESS. https://doi.org/10.1061/JHEND8.HYENG-14048.** This article uses other investigators' data to develop estimates of friction factors for flow through narrow cracks in concrete structures.
9. **Wahl and Heiner (2024e) – Engineering Monograph 46: *The Fluid Mechanics of Hydraulic Jacking*. https://www.usbr.gov/tsc/techreferences/hydraulics_lab/** This monograph presents the full body of hydraulic jacking knowledge gained through this study.

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