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Effect of boundary layer conditions on uplift pressures at open offset spillway joints

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ABSTRACT: Uplift pressures generated at spillway joints or cracks with offsets into the flow have the potential to cause hydraulic jacking failures of spillway chute slabs, demonstrated by failures at Dickinson Dam (1954), Big Sandy Dam (1983), and Oroville Dam (2017). Previous laboratory tests by the Bureau of Reclamation (Johnson 1976; Frizell 2007) demonstrate a relation between uplift pressure, joint or crack geometry, and channel-average velocity head. Unfortunately, these studies were conducted in short flumes or water tunnels with thin boundary layers whose properties were not measured, so the influence of the boundary layer velocity profile has not been demonstrated experimentally. A new research program at Reclamation is planned to investigate boundary layer influences. A review of the previous studies and considerations for the design of the new test facility are presented.

RÉSUMÉ: Les sous-pressions générées au niveau des joints ou fissures d'évacuateurs de crue avec des sauts dans l'écoulement peuvent provoquer la rupture des dalles de coursiers d'évacuateurs par soulèvement hydraulique, comme cela fut le cas lors des incidents des barrages de Dickinson (1954), Big Sandy (1983) et Oroville (2017). Les essais de laboratoire déjà réalisés par le Bureau of Reclamation (Johnson 1976; Frizell 2007) démontrent une relation entre les sous-pressions, la géométrie du joint ou de la fissure et la vitesse d'écoulement moyenne. Malheureusement, ces études ont été conduites dans de courts canaux ou dans des tunnels avec des couches limites minces dont les propriétés n'ont pas été mesurées. L'influence du profil de vitesse de la couche limite n'a donc pas été démontrée expérimentalement. Un nouveau programme de recherche du Bureau of Reclamation est prévu pour étudier les influences de la couche limite. Une revue des études réalisées précédemment et des considérations sur la conception de la nouvelle installation d'essai sont présentées.

1 INTRODUCTION

1.1 *Hydraulic jacking*

Hydraulic jacking is a potentially serious problem for spillway chutes and other hydraulic structures experiencing high-velocity flow. As structures age, surface deterioration, spalling, cracking, frost heave, and differential settlement all have the potential to produce misalignment of flow surfaces. The most serious problems are those that create offsets into the flow combined with unsealed openings to the foundation. Flow stagnating against offsets leads to the development of stagnation pressure, a conversion of the kinetic energy of the flow into high pressures that can penetrate through cracks or unsealed joints and reach the foundation. If under-slab drain systems are not adequate or are not present, high pressures generated at joints or cracks can affect sizable areas beneath a structure, resulting in large uplift forces. Hydraulic jacking occurs when the forces acting to lift a spillway slab exceed the forces resisting upward movement. Resisting forces include the weight of the slab itself, the capacity of foundation anchors, and the pressure applied to the top of the slab by water flowing in the chute.

Net uplift force results from the combination of increased pressure below the slab and reduced pressure above the slab (i.e., lift). The potential for low pressures above a slab is limited by the vapor pressure of water, so high pressures due to flow stagnation are usually the primary contributor to uplift. High pressure water entering a foundation can also cause internal erosion of erodible soils when this flow is not captured or retained within a drainage system. When internal erosion leads to the development of large voids beneath a slab, this may enable high pressures generated at a crack or joint to more readily act over a large area beneath the slab.

The geometry and construction details of joints vary, which affects their vulnerability to uplift and seepage flow. Modern design standards for spillway joints (e.g., Bureau of Reclamation 2014) include details to prevent the development of offsets and gaps (e.g., keys and structural reinforcement) and limit flow through joints (waterstops), but many older spillways lack some or all of these features or have other deficiencies (e.g., poorly prepared foundations, inadequate or deteriorated drainage systems, etc.) that make them vulnerable to uplift failures.

2 CASE STUDIES

The most recent and notable case of hydraulic jacking occurred in the service spillway at Oroville Dam (California, USA) in 2017. A sudden failure of a small section of concrete slab at a flow rate well within the historical operating range of the spillway led to progressive, catastrophic damage to most of the downstream chute and adjacent areas when the damaged spillway was forced to continue operating for several weeks during a large regional flood event. Attempts to limit flows through the spillway also led to activation of the emergency spillway for the first time in its history, and rapid headcut erosion in the unlined channel of that spillway led to an evacuation order affecting about 188,000 downstream residents. An independent forensic team concluded that the service spillway failure occurred due to uplift (IFT 2018). The point of initiation and type of defect that allowed high pressure water to penetrate through the slab could not be determined exactly, but possible causes included extensive cracking of the slab, inadequate slab thickness and reinforcement, no waterstops in joints, an inadequate underdrain system, and inadequate or deteriorated anchorage.

Hepler & Johnson (1988) and Trojanowski (2004) documented hydraulic jacking failures in Bureau of Reclamation spillways at Dickinson Dam (North Dakota, USA) in 1954 and at Big Sandy Dam (Wyoming, USA) in 1983 (Figure 1). At Dickinson Dam there was a lack of defensive design features such as foundation grouting, anchor bars, or waterstops, and the

Figure 1. Hydraulic jacking failure at the Bureau of Reclamation's Big Sandy Dam (Wyoming, USA) in 1983.

underdrain system was compromised by subfreezing temperatures. There were several possible mechanisms that could have led to joints with offsets and openings that permitted pressurized flow to enter the foundation. In addition, unfiltered gravel zones around the underdrain system were implicated as a factor in internal erosion that led to the development of voids beneath the slabs. At Big Sandy Dam, freezing temperatures over many years caused deterioration of the spillway concrete, damage to the underdrain system, and slab movement that produced open and offset joints. Uplift pressures at the time of failure were large enough to pull the foundation rock anchors out of the soft sandstone foundation (1.2-m long, 25-mm diameter bars on 1.5-m centers, with a design capacity of 44 kN each). It was speculated that the anchors may have been only 50 percent effective due to deterioration of the grout-foundation contact and could have been failed by an uplift pressure head greater than 49 percent of the mean velocity head (Trojanowski 2004).

3 LITERATURE REVIEW

Despite the historical cases of hydraulic jacking, efforts to quantify the uplift pressures generated by high-velocity flows over cracks or open spillway joints have been very limited. Most studies of uplift have focused on stilling basins and plunge pools, where fluctuating pressures generated by hydraulic jumps and impinging jets are the driving mechanism (e.g. Fiorotto & Rinaldo 1992; Bellin & Fiorotto 1995; Liu & Li 2007; Mahzari & Schleiss 2010). High pressures generated in the joints and cracks of rock masses have also been studied extensively as a driving mechanism for scour in rocky plunge pools and unlined rock channels (Bollaert & Schleiss 2003; Pells 2016). Key features of the flows driving these processes are jets impinging at large angles to the flow surface, aeration and disintegration of jets both above and below the water level of the pool, and large pressure fluctuations applied to slab surfaces and joints. These characteristics are much different from those of gradually varied, unidirectional flows over spillway chute surfaces.

The only known studies of uplift pressure due to unidirectional high-velocity flow over offset spillway joints are those of Johnson (1976) and Frizell (2007), both performed at the Hydraulics Laboratory of the Bureau of Reclamation (USA). Those two studies are reviewed in detail here and the data are further analyzed with a view toward general application.

3.1 *Open channel tests*

Johnson (1976) studied uplift pressures beneath simulated linings of steep canal chute laterals using a 152-mm wide by 2.44-m long open channel flume that contained an adjustable joint with a vertical offset into the flow located 0.91 m from the downstream end (Figure 2). The width of the joint opening (gap) was set to values of 3.2, 6.4, 12.7, and 38.1 mm and the vertical offset was set to heights of 3.2, 6.4, 19.1, and 38.1 mm. The flume appears in photos to be set on a flat slope, but this cannot be absolutely verified. Flow was provided through an adjustable vertical slide gate so that the velocity at the offset could be varied from 2.29 to 4.57 m/s, measured by a Pitot tube. The open joint allowed high pressures generated at the offset to enter a chamber beneath the flume that was tightly sealed. Pressures in the chamber were measured with a dynamic pressure transducer whose output was recorded on a strip-chart. The joints studied were all oriented normal to the bed of the flume and extended perpendicular to the flow direction across the full width of the flume. The report also discussed the possibility of testing joints oriented at other angles to the flow, but this work was apparently never completed.

Average pressures and the pressure value that exceeded 95% of the instantaneous dynamic pressures were both determined from the strip-chart records. The latter was arbitrarily selected to represent maximum uplift pressures that might affect a chute slab, and the 95% maximum pressures were typically about 15 to 40 percent greater than the average pressures. Net uplift pressure heads were reported as the difference between the pressure head measured in the

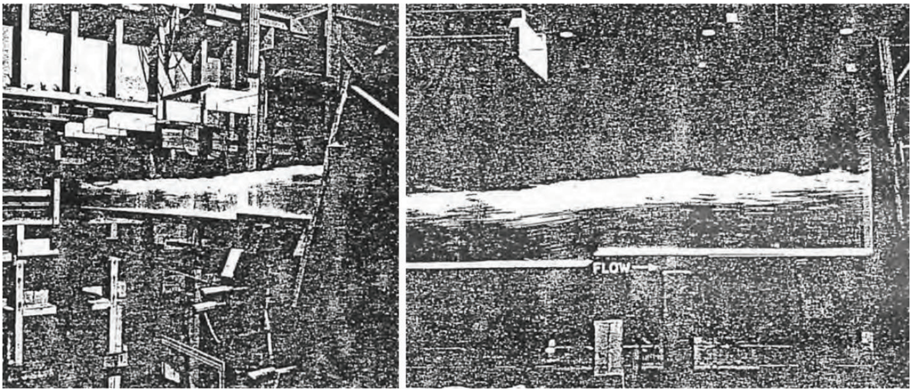

Figure 2. Photographs of open channel test facility at the Bureau of Reclamation (Johnson 1976). Flow is left to right in both photos.

chamber and the average depth of flow measured over the joint, but separate pressure and depth measurements were not reported. Uplift pressure heads were presented as dimensionless percentages of the velocity head computed from the average flow velocity in the channel. Figure 3 shows examples of the data presented by Johnson (1976). The report discussed possible boundary layer effects on the test results, but boundary layer characteristics were not measured during the experiments, nor were any attempts made to analytically estimate the boundary layer conditions of the tests. Specific flow depths, discharges, and channel slope data for each test were not reported. However, the short distance from the entrance of the flume to the joint location suggests that the boundary layer in these tests was relatively thin. Notable trends observed in the data were:

- Uplift pressures decreased with larger gap widths.
- Uplift pressures increased for larger vertical offsets, most rapidly when vertical offsets were small. At large vertical offset heights, the uplift pressure tended to approach a constant percentage of the velocity head.
- For higher velocities, the uplift pressures tended to be a slightly smaller percentage of the channel-average velocity head.

3.2 *Water tunnel tests*

Frizell (2007) studied uplift pressures generated at spillway joints by delivering high-velocity flow to a pressurized square water tunnel containing an idealized spillway joint that could be

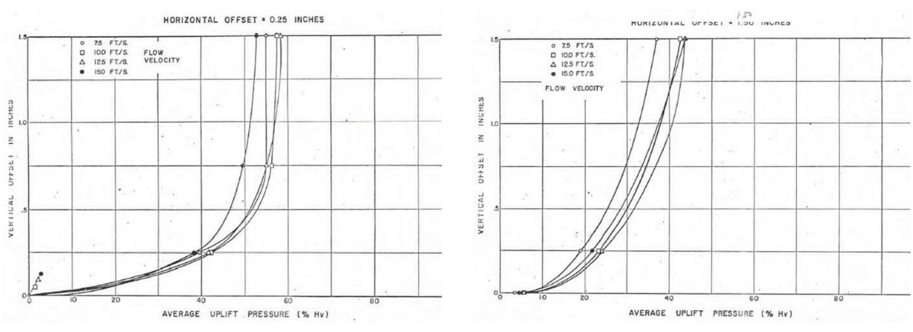

Figure 3. Examples of open channel uplift pressures measured by Johnson (1976).

adjusted to create offset heights of 3.2, 6.4, 12.7, and 19.1 mm and gap widths of 3.2, 6.4, and 12.7 mm (Figure 4). The test section was located 2.44 m downstream from a tee on the pump discharge line. A 0.91-m long round to square transition tripled the velocity of the flow before it entered a 102-mm by 102-mm square duct that carried the flow another 1.72 m to the simulated joint. The tests could be conducted with flow velocities of about 5.2 to 14.6 m/s approaching the joint. The exit height of the test section was reduced from the nominal 102-mm height of the approach section due to the raised offset. In addition to tests of rectangular sharp-edged joint geometries, tests were also performed on joint openings with 3.2-mm by 3.2-mm 45° chamfered edges and rounded edges with a 3.2-mm radius. Tests were conducted in a sealed configuration, where no flow was allowed to exit the chamber beneath the spillway joint, and a vented condition in which flow could exit through a valve. The size of the exit valve was not reported, but its flow capacity was not sufficient to keep the chamber fully vented, so back pressure existed below the spillway joint in the vented tests, but was not directly measured. Uplift pressures were measured with a differential pressure transducer connected to taps above and below the movable downstream block (Figure 5).

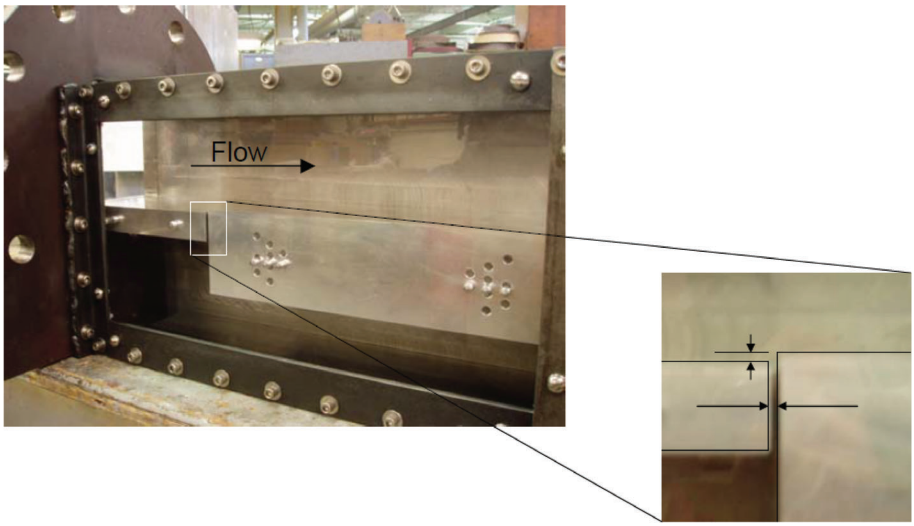

Figure 4. Water tunnel test apparatus (Frizell 2007).

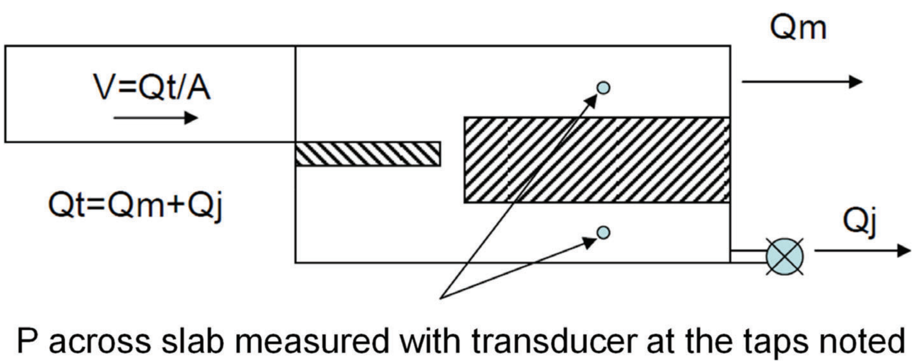

Figure 5. Schematic of test section with adjustable spillway joint in water tunnel, with location of pressure taps (Frizell 2007). The flows labeled Qm and Qj exit to the atmosphere.

Particle Image Velocimetry (PIV) was also used in the Frizell (2007) study to map velocity fields above and within the joint for a small subset of the tests (the chamfer-edged joints with 3-mm and 13-mm gap widths and 13-mm offset heights). Finally, accompanying computational fluid dynamics (CFD) models were configured and run using the FLOW-3D software package developed by Flow Science, Inc. CFD models were created to simulate both the test facility and a prototype spillway joint. The PIV measurements and CFD models were used primarily to visualize the flow field in the vicinity of the joints. There is potential for CFD studies to be used to study uplift pressures, but quantitative uplift pressure results were not obtained from this study.

The collected uplift pressure data were originally presented by Frizell (2007) in plots showing the raw differential pressures versus the average velocity over the offset, downstream from the raised offset. An example is shown in Figure 6 with power curve lines fitted to each data set. Curve fit equation parameters were provided for each unique combination of joint type, gap width and offset height, and this allowed uplift pressures at other velocities to be calculated. No general relationship was developed that could be applied to any range of joint dimensions. The data were not presented in a dimensionless manner that would allow direct comparison to the Johnson (1976) results. Like Johnson (1976), Frizell (2007) also observed that boundary layer effects could have a substantial impact in a prototype, but made no analysis of the boundary layer conditions that existed in the tests, presuming that the boundary layer was thin and that uplift pressures would be closely related to the mean velocities. The tests of chamfer-edged and rounded joint openings showed similar trends as the tests of sharp-edged openings, with a tendency for the chamfered and rounded openings to behave like sharp-edged openings of a slightly larger dimension.

3.2.1 *Flow through Joints*

The Frizell (2007) study attempted to determine flow rates through the joints in a vented condition, but the valve shown in Figure 5 that controlled the outflow (Qj) from the chamber beneath the joint was too small to fully vent the bottom of the joint. The only pressure measurements made were the differential pressures across the joint, so the backpressure beneath

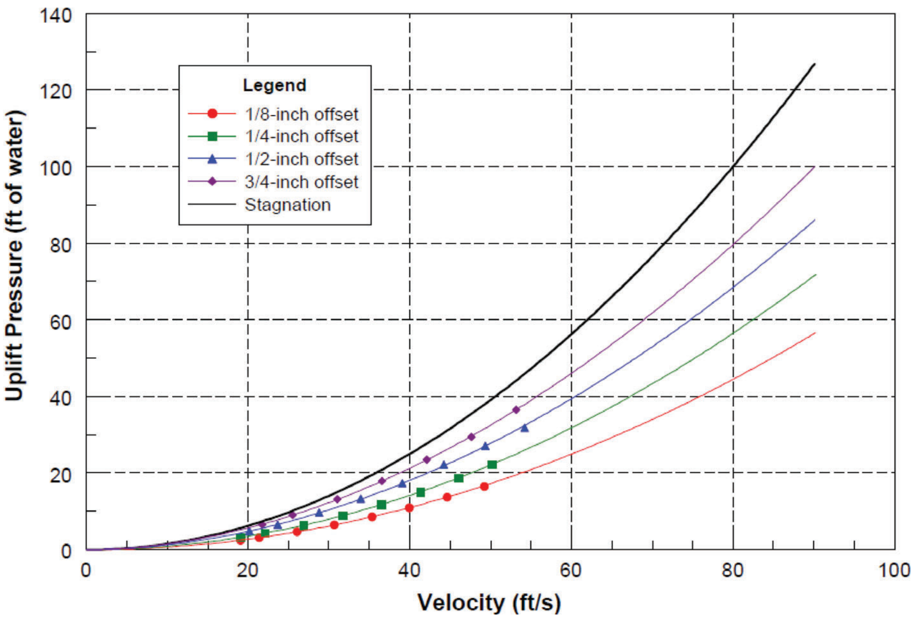

Figure 6. Example of average uplift pressure data provided by (Frizell 2007). The case shown is for a sharp-edged joint with a 3.2-mm gap width and a sealed cavity below the joint.

the joint was unknown. In addition, the indirect technique for determining flow rates indicated that flows increased as the gap width decreased, which is not a sensible result. This may have been due to changing backpressure beneath the joint. The conclusion from a detailed review of these data is that the flow rate measurements were unreliable. Any new research should attempt to obtain reliable flow measurements, as they would be of great interest for the evaluation of the drainage beneath a spillway slab.

4 ANALYSIS

To estimate uplift pressure heads acting on the Oroville Dam spillway, IFT (2018) proposed that the uplift be set equal to the velocity head of the flow streamline located in the boundary layer at the mid-height of an offset. The width of the gap was not considered to be a factor affecting the uplift pressure.

The two experimental data sets from Johnson (1976) and Frizell (2007) offer an opportunity to test this concept, but since velocity profiles were not measured in either study, the mid-height velocity must be estimated by analytical means. Wahl et al. (2019) made estimates of the boundary layer velocity profiles in each experiment, relying on the fact that in the initial stages of boundary layer growth over a smooth surface, the boundary layer properties are a function of the mean flow velocity and the length of the boundary layer from its point of initiation. Once the boundary layer conditions were estimated, the uplift pressure heads could be expressed as percentages of the velocity head in the boundary layer at the mid-height of the tested offsets, or as percentages of the channel-average velocity head. Figure 7 shows the

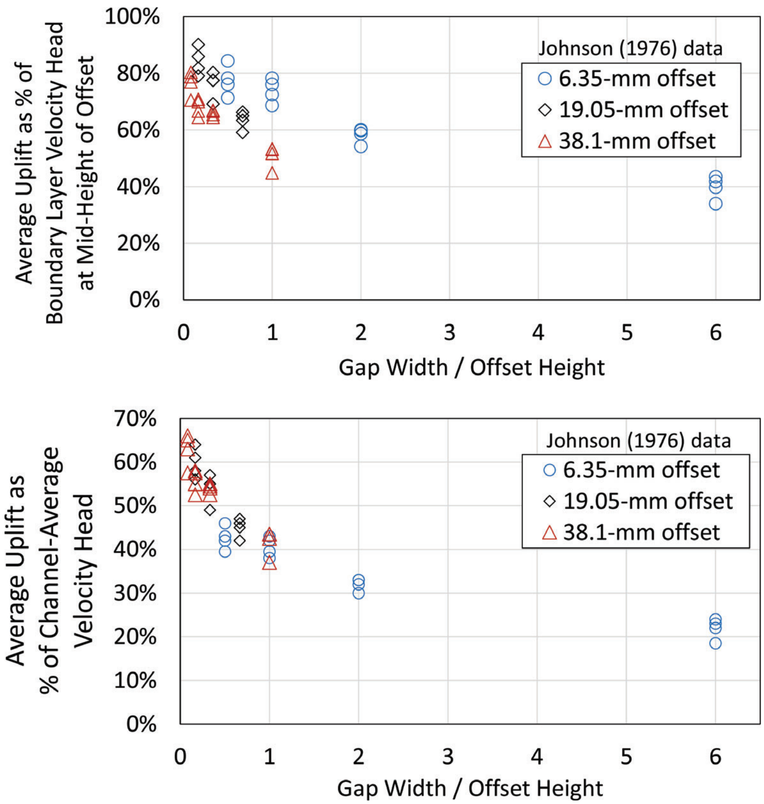

Figure 7. Uplift pressures measured in open channel tests by Johnson (1976), related to boundary layer velocity and channel-average velocity, as a function of the gap width to offset height ratio.

uplift pressure heads measured by Johnson (1976) related to both velocity heads, plotted versus the gap width to offset height ratio. The figure shows that both forms of dimensionless uplift pressure head are inversely related to the gap width to offset height ratio. When the uplift pressure is nondimensionalized with the boundary layer velocity, there is also some dependence on the offset height. However, when the uplift pressure is nondimensionalized using the average channel velocity, the curve relating uplift pressure to the gap/offset ratio is independent of the offset height.

To analyze the water tunnel data of Frizell (2007) and effectively compare the open channel tests and water tunnel tests, the uplift pressures reported in the water tunnel tests must be adjusted to correct for three factors that artificially increase the uplift pressure in the water tunnel configuration. These are the increased velocity head and reduced pressure caused by the constricted outlet of the water tunnel, the head loss caused by the constriction, and the friction loss in the water tunnel between the joint and the location at which the pressure differential was measured. All of these effects artificially increase the measured differential pressure in the water tunnel configuration relative to what would be observed in an open channel. The adjustments are significant, amounting to about 20% to 66% of the measured differential pressure head (Wahl et al. 2019).

With these adjustments made, Figure 8 shows the Frizell (2007) water tunnel data presented in a similar manner as the open channel data in Figure 7. Again, when the pressures are related to boundary layer velocities, some dependence on the offset height is seen, although perhaps less than in the open channel tests. When uplift pressures are related to the channel-average velocity, the data tend to follow a single curve.

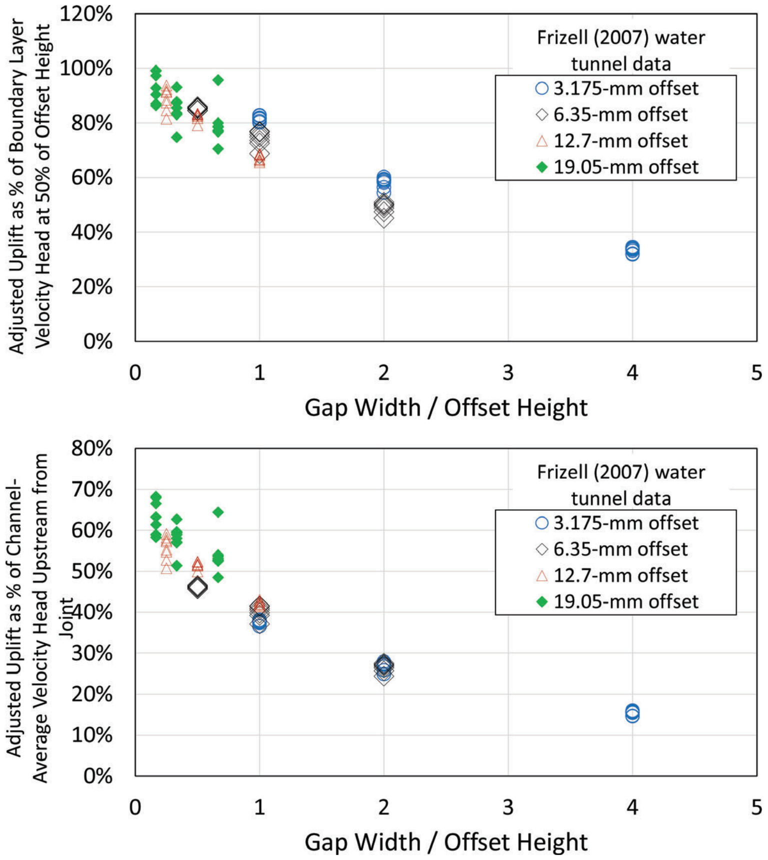

Figure 8. Uplift pressures from water tunnel experiments by Frizell (2007).

5 DISCUSSION

Figures 7 and 8 show that uplift pressure generated at joints offset into the flow is related to both the joint geometry as expressed in the gap width to offset height ratio, and a reference velocity head, either the velocity head at the mid-height of the offset, or the velocity head corresponding to the channel-average flow velocity. When uplift pressures are made dimensionless with respect to the boundary layer velocity at the mid-height of the offset there is a secondary dependence on the offset height. Analyzing uplift pressures with respect to the average channel in the channel produces a tighter relationship. This may be due to the boundary layer in these experiments being thinner than estimated, so that the stagnation pressure applied to a joint is more directly related to the mean velocity than the boundary layer velocity. In the Johnson (1976) experiments which tested offsets as large as 38 mm, it is likely that these large offsets exceeded the thickness of the boundary layer (approximately 25 mm).

A relation based on boundary layer velocity would be more useful for prototype applications, since in a long spillway channel the boundary layer may grow to be very thick and velocities near the bed will be greatly reduced from the mean velocity of the channel. In the experimental facilities, the boundary layer velocities at the mid-height of the offsets were about 70–90% of the mean velocities in the channels, but in a prototype it is likely that boundary layer velocities could be well below 50% of the mean velocity.

The experimental work done to date has had a small separation between the mean velocities of the channels and the boundary layer velocities, and thus it is difficult to distinguish which reference velocity is the best choice for predicting prototype performance. The experimental data at this time shows better relations to the mean velocity. To make a more definite determination, testing is needed in a facility that produces a more significant difference between mean velocities and boundary layer velocities, and in which the degree of separation between the two can be adjusted.

To achieve this objective, the Bureau of Reclamation plans to construct a new experimental facility like that used by Johnson (1976), but with a relatively long open channel flume that can produce thick boundary layers at the test location. To allow variation of the flow velocity we intend to supply flow into the flume through a jetbox constructed for recent stepped spillway research (Frizell & Svoboda 2012), based on a design by Schwalt & Hager (1992). The jetbox will enable flow to be introduced to the flume at a wide range of Froude numbers. Some of the variation of velocity will be lost in the long flume, as the flow will tend toward normal depth as it proceeds down the channel. Some slope variation may be incorporated into the design in order to help maintain desired velocities.

To enable a wide range of adjustment of the boundary layer conditions, the floor of the flume will be designed so that the location of boundary layer initiation can be moved upstream or downstream. This will allow tests to be run with the boundary layer velocities close to and significantly different from average velocities. This should enable a clear determination of the reference velocity that is most closely correlated with measured uplift pressures.

The test facility will be configured so that tests can be run with both a sealed and vented cavity beneath the simulated spillway joint. Flow rates through the joint will be measured and related to pressure differentials across the joint to enable future prediction of flow rates through joints with a range of geometric characteristics, subjected to variable hydraulic conditions.

6 CONCLUSIONS

Hydraulic jacking is a significant problem for concrete spillway chutes, especially as structures age. To analyze associated risks and develop designs for anchorage systems designers need to know the pressures that can develop at joints and cracks and how those pressures will propagate beneath a slab. To design underdrain systems that help limit pressure buildup and convey water safely out of the foundation area, knowledge of flow rates through joints and cracks is also needed.

Previous research studies have attempted to address both of these issues. Tests by Johnson (1976) measured uplift pressures in an open channel flow situation at velocities up to 4.6 m/s, while tests by Frizell (2007) measured uplift pressures in a water tunnel configuration at velocities up to 14.6 m/s. In the water tunnel configuration, adjustment of measured uplift pressures is needed to relate the results to a prototype open channel flow situation, and this adds uncertainty to the analysis of the results. Results from both previous studies show that uplift pressures are definitely related to the gap width to offset height ratio of a joint. Attempts to relate the uplift pressures to boundary layer velocities were partially successful, but better correlations were obtained when results were related to average flow velocities. Additional testing should be performed using facilities that allow greater variation between boundary layer and average velocities.

The Frizell (2007) study attempted to measure flow rates through open joints, but the measurements indicated that flow rate increases with decreasing gap width, which is a trend that cannot be sustained down to a gap width of zero. As a result, new studies of flow rates through joints are needed.

The Bureau of Reclamation plans to construct a new open channel flume facility in our laboratory to investigate both uplift pressures and flow rates through spillway joints with a range of geometric configurations. The experiments will measure variables that were not measured in the previous studies, namely boundary layer velocity profiles and back pressure beneath the spillway joint, and the test facility will be designed to permit better experimental regulation of these variables.

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