LABORATORY STUDIES OF HIGH VELOCITY FLOWS OVER OPEN OFFSET JOINTS

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ABSTRACT

Laboratory tests were completed in Reclamation's Water Resources Research Laboratory to extend the available data on uplift pressures generated by high velocity flows over offset joints. In addition, magnitudes of flows into the joints or cracks were measured for various configurations. Three joint geometries were tested: sharp edges (90-degree), 1/8-inch chamfered edges (45-degree), and edges with a 1/8-inch-radius in combinations of joint/crack gaps ranging from 1/8-inch to 1/2-inch and offsets into the flow ranging from 1/8-inch to 3/4-inch. Only sharp-edged joints will be reported in this paper. Velocities ranging from about 10 ft/s up to 55 ft/s were tested. Mean uplift pressures downstream from the offset were measured for all cases. The cavity beneath the test section could be closed, generating the maximum uplift, or opened to allow flow to enter the cavity through the joint/crack. This test facility feature allowed for measurement of a slightly reduced uplift pressure and flow rates through the open joint/crack area. Uplift pressure and flow rate data from this study will be used to reduce the uncertainty in analyses used during risk assessments to provide improved estimates of the level of effort required to bring a spillway or outlet works into a safe operating condition for a variety of geometries.

INTRODUCTION

Flow driven uplift forces in hydraulic structures historically have been a common topic of interest for safe and reliable design of spillway and outlet works chutes. The majority of prior research on uplift pressures in hydraulic structures has focused on lined and unlined plunge pools subject to free-falling water jets from spillways or outlets. The transmission of pressures beneath engineered plunge pool slabs or into a fissured rock matrix depends largely on joint location, geometry, and design (water stops) along with the jet properties. The generation of significant uplift pressures in both lined and unlined basins with open joints has been documented in studies by Bollaert (2002) detailing the generation of large dynamic pressures, especially when air entrainment is present. In a related study, Melo, et al. (2006) discussed the influence of joint location and geometry in concrete-lined plunge pools subjected to jet impact. Numerous other researchers have also contributed to the overall understanding of the physical processes affecting uplift and rock scour. While some of the processes are similar in uplift and chute-supported flows, i.e. conversion of velocity into pressure through stagnation principles, the prior research can not be applied.

This paper will describe recent investigations that address unknowns related to uplift pressures and resulting flows into cracks and joints caused by high velocity chute-

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supported flows. Such flow conditions have been less studied; however it is a common problem that can occur in spillways and outlet works of various sizes, types, and head ranges. The uplift force in a chute-supported flow can consist of a component due to reduced pressures on the flow surface of a slab caused by flow separation resulting in a localized pressure reduction, and the transfer of dynamic pressures to the lower side of the slab through an open crack or joint. In addition there is also the possibility of uplift forces due to excess leakage or piping from the reservoir in the foundation material of the chute. Uplift on chute slabs due to the transmission of pressure through open cracks and/or joints have long been an area of concern at Reclamation and there have been numerous occasions where damage has occurred due to this phenomenon. Hepler and Johnson (1988) described typical analysis of spillway failures due to uplift and discussed a couple case studies within Reclamation. Johnson (1976) performed a model study depicting a 2-dimensional open channel flow on a steep canal wasteway with a range of offsets and gap dimensions. Johnson did not model flow through the joint but did measure uplift pressures resulting from a variety of offset dimensions (both vertical and horizontal) for flows up to about 15 ft/s. Trojanowski (2004) identified erosion of foundation materials resulting from flows into cracks or joints as a significant problem for spillways on soil foundations. Prior to this study, there were no simple methods for predicting these flows. The results of this study extend uplift pressure data to include velocities in the range of 10 - 55 ft/s and provide additional information concerning joint/crack flow rate.

The generation of hydraulically produced uplift pressures relies on a break in the continuity of the lining and some feature that transfers the effective pressure of the flowing water below the lining. These breaks in continuity can be at contraction joints or cracks that may have developed within the slab. The transmission of pressures and flows through a properly designed and constructed joint would also have to rely on lack of integrity or failure of the waterstop, if so designed. While uplift pressures can also be produced due to transmission of reservoir pressures to the area beneath the lining due to seepage or other problems with the reservoir and/or dam, those issues were not addressed in this work. The pressure distribution on the upper surface of the lining due to the flowing water is typically only the static pressure due to depth of flow. The transmission of pressure to the area beneath the lining is dependent on the gap width, offset height, orientation to the flow direction and a variety of other less important geometry and flow related features. When an offset surface intercepts flow, velocity is converted to pressure through a process known as stagnation. Treating water as an incompressible fluid, the stagnation pressure is the conversion of velocity to pressure (i.e., it is the dynamic pressure in the flow field) and the stagnation point is the location where the velocity goes to zero. The dynamic pressure is defined as:

$$\frac{1}{2}\rho V^2 = p_o - p \qquad (1)$$

where r is the density, V is the velocity, p is the static pressure, and p_o is the stagnation pressure. In the treatment of the stagnation pressure for this study, the mean free stream velocity was used to compute the maximum stagnation pressure that is physically possible. The actual pressure that a particular sized offset experiences may be quite reduced due to boundary layer development at the particular location on the lining.

In typical reinforced concrete-lined chutes, the stability of the slabs depends on the overall concrete design; including joint and waterstop details, reinforcement, anchorage, and a functioning, filtered underdrain system. Usually drainage under the slab is provided to prevent the build up of uplift pressure and subsequent instability due to seepage and natural foundation groundwater conditions. Typically damage resulting from hydrodynamic uplift on slabs begins at the joints, where offsets or spalling has occurred, Figure 1. Spillway flows over these offsets can introduce water into the foundation, which can lead to structural damage due to uplift or erosion of the foundation material. If this problem persists there can be complete failure and removal of chute slabs, Figure 2. Reclamation has used predictive data to evaluate potential uplift problems; however sufficient methods, specific to estimating the amount flow into cracks or joints that could be possible, have not been developed primarily due to limited availability of data. This later problem is generally more of a concern for structures where the chute and the underdrain systems may be in poor condition due to aging or improper design, and is especially critical for chutes that are founded on soil since joint/crack flow can lead to erosion and undermining (Figure 3) of the chute foundation and structural collapse of a chute slab (Figure 4).

Figure 1. Initial damage due to uplift generally occurs at the contraction joints.

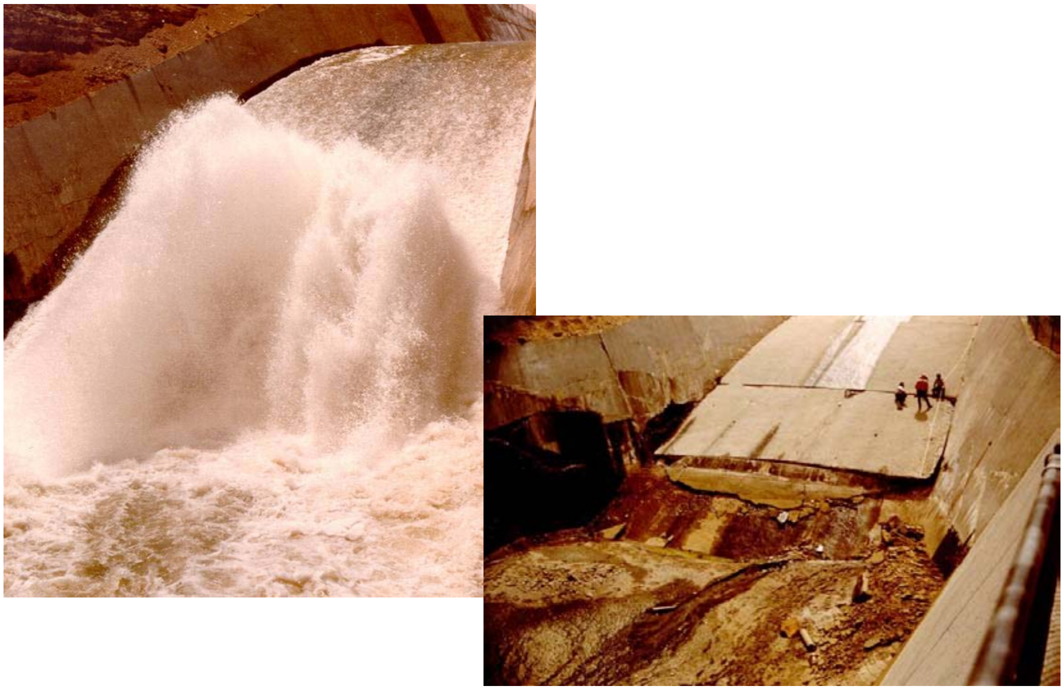

Figure 2. If flow is allowed to continue, slabs may lift resulting in wild spray and rooster tails, and when the water recedes - slabs are damaged or missing.

Figure 3. Undermining of the chute slab has occurred due to flow entering at joints and cracks and transporting foundation material through unfiltered drains.

Figure 4. Structural collapse of the slab system occurs when enough undermining has occurred to cause loss of support. Damage is typical of slabs placed on soil foundations.

With the advent of the risk assessment process as an approach to assist dam safety decision makers in determining if repairs or replacement of hydraulic structures are needed, Reclamation engineers have identified a critical need for additional data that would allow reduced uncertainty in the prediction of possible uplift or structural collapse failure modes. A sampling of data that was collected is presented in this paper, extending the available data on uplift and providing new estimates of crack and joint flows that have previously been unavailable. Development of a simple spreadsheet tool using new and existing data can assist in making these predictions in a timely manner, with more certainty, and ultimately lead to wiser use of limited financial resources that project owners are faced with.

LABORATORY MODEL

Representing high velocity flows, typical of a spillway chute, over offset joints or cracks in a laboratory setting can pose difficulties. In addition to providing relatively deep, high-velocity open channel flow which requires large flow rates, the dimensions of joint/crack gaps and offsets can be relatively small in comparison with overall spatial scales for the prototype structure. While open channel flows are typically dominated by gravitational and inertial forces, physical processes involving flow through small cracks or joints along a channel boundary are dominated by viscous and inertial forces. These issues point toward using a full scale representation of the joint/crack details to ensure the measured joint/crack flows and pressures are free from scale effects related to viscous forces (i.e., requires Reynolds number similitude).

The test setup for this study comprised a sectional representation with prototype joint/crack gaps, offsets, and velocities (10 – 55 ft/s) using a water tunnel connected to the laboratory's high-head pump facility. This facility has the ability to generate a moderate flow rate (6 ft^3/s) at heads approaching 600 feet and with proper design of the water tunnel test section is capable of producing velocities up to about 55 ft/s. Figure 5 shows a plan view schematic diagram of the overall layout. The test section (Figure 6) features a 4-inch-wide by 4-inch-high square cross-sectional geometry. While not a true representation of open channel flow, the forces dominating the processes in this problem, as previously mentioned, are not gravity driven; hence flow depths are not a critical component and the closed conduit flow approximation can be applied.

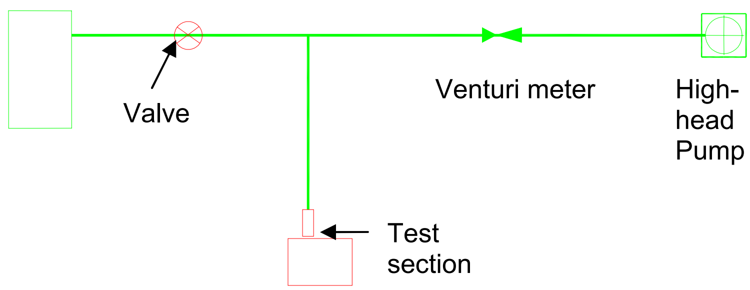

Figure 5. Plan view schematic of model layout showing pump, piping, valve, and test section.

Flow entering the test section was measured with a venturi meter and mercury manometer to reproduce testing set-points and determine mean test section velocities (V = Q/A, where V is the mean velocity through the test section, Q is the volumetric flow rate, and A is the test section cross-sectional area). Mean differential pressures across the slab downstream from the joint/crack offset were measured with a Sensotec Model A-5 differential pressure transducer (15 PSID). A Model GM signal conditioner supplied excitation to the sensor and featured a 0-5 Volt output proportional to full scale. The amplifier/display used a shunt calibration feature that was periodically checked and adjusted throughout testing. Figure 7 shows the location of the pressure measurement and details the flow splits. The voltage output was read using an IOTech Wavebook 516 and a laptop PC. Data were anti-alias filtered and collected at 200 Hz for 50 s and then time-averaged. This was done both with the lower cavity sealed, and with it open to allow flow through the joint/crack. Volumetric flow rates through the joint/crack were initially measured using the mean of 5 tests form a volume/time method. This check was performed at a couple of joint/crack gaps. The flow rate was then correlated with the difference in the differential pressure between the sealed- and open-cavity conditions for given test configurations, using physically-based theory. The resulting correlation allowed use of only the measurement of the differential pressures in order to deduce the joint/crack discharge. Each joint/crack configuration was tested for a range of test section velocities from about 15 ft/s to 55 ft/s.

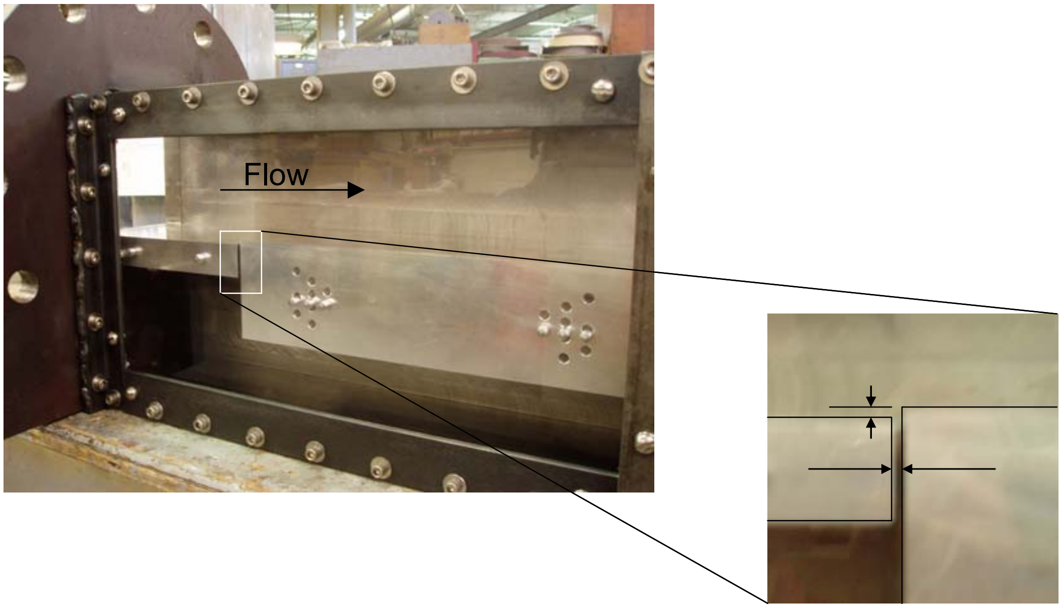

Figure 6. Laboratory model test section. Note detail of offset and joint/crack gap.

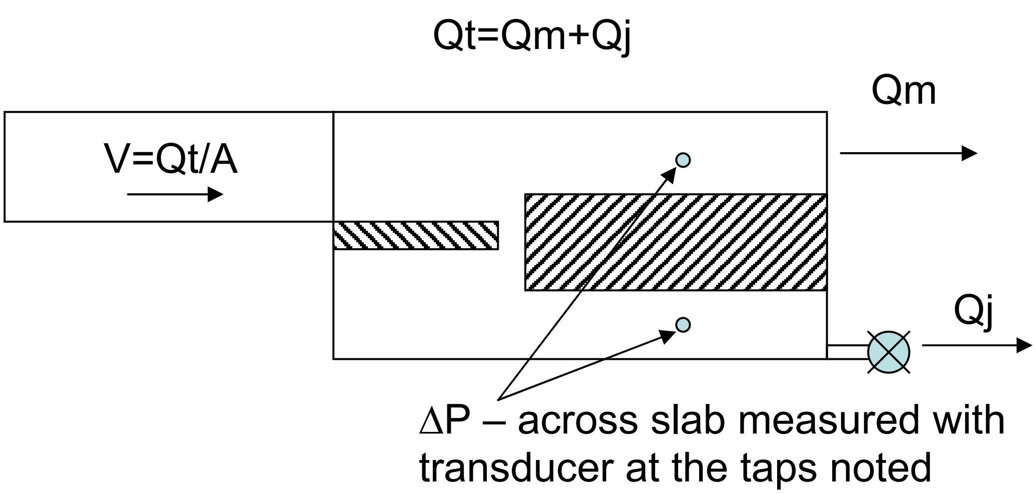

Figure 7. Side-view schematic of test section showing location of uplift pressure taps.

RESULTS

Results will be presented for the sharp-edged configuration only. A complete presentation of the data can be found in Frizell (2007).

Pressure and flow rate data were collected according to the process described in the previous section. The data are presented in graphical form as uplift pressure and unit discharge versus velocity with equations for best-fit curves appearing in tabular form.

Data for the 1/8-inch joint/crack gap with sealed lower cavity are presented in Figure 8. Uplift pressure versus flow velocity for the case of flow through the joint/crack is shown in Figure 9. Lines through the data are best fit power curves and the corresponding equations appear in Table 1. The bold upper line represents the stagnation pressure calculated from dynamic pressure $P_d = \rho V^2/2$ where ρ is the density of water and V is the mean flow velocity. The stagnation pressure represents the conversion of velocity entirely to pressure. This occurs when the flow impacts a boundary such that the velocity goes to zero. The resulting pressure, P_d is the maximum pressure that is physically possible for that particular flow condition. Unit joint/crack discharge for the drain configuration modeled is shown on Figure 10.

Data for the case of a 1/4-inch joint/crack gap with sealed lower cavity are presented in Figure 11. Uplift pressure versus flow velocity for the case of flow through the joint/crack is shown in Figure12. Unit joint/crack discharge for the drain configuration modeled is shown on Figure 13.

Data for the case of a 1/2-inch joint/crack gap with sealed lower cavity are presented in Figure14. Uplift pressure versus flow velocity for the case of flow through the joint/crack is shown in Figure 15. Unit joint/crack discharge for the drain configuration modeled is shown on Figure 16.

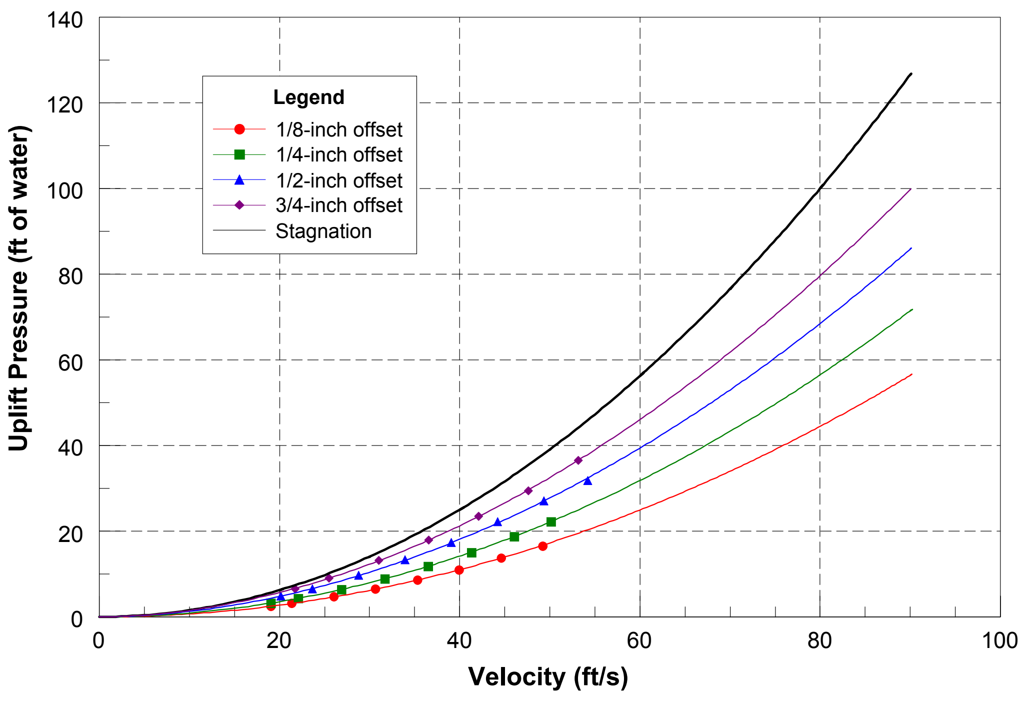

Figure 8. Mean uplift pressure, sharp-edged geometry, sealed cavity, 1/8-inch gap.

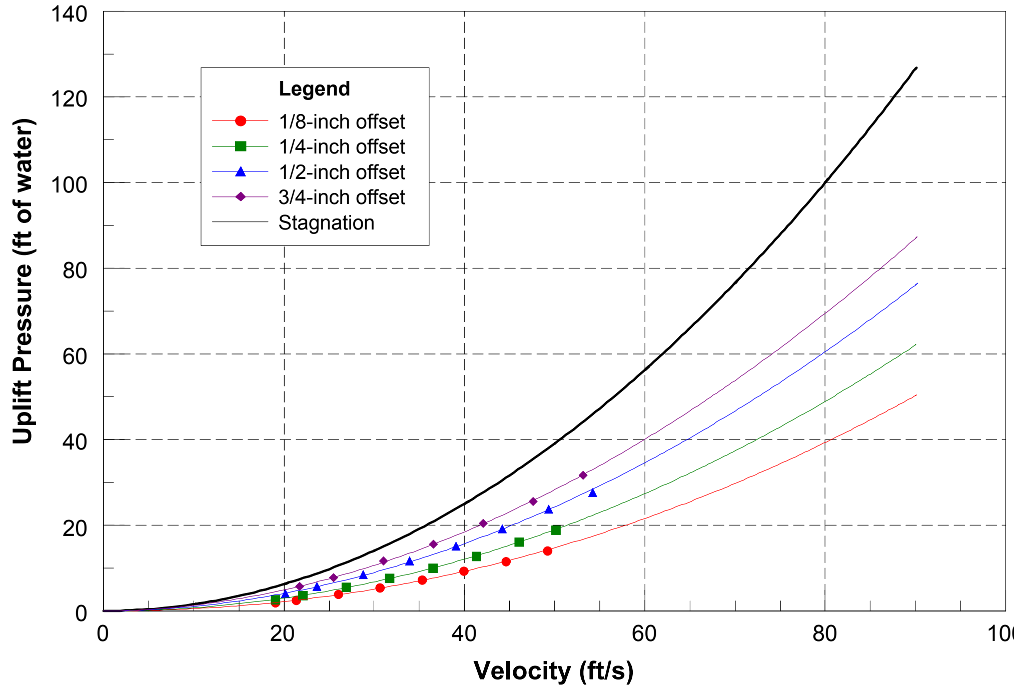

Figure 9. Mean uplift pressure, sharp-edged geometry, vented cavity, 1/8-inch gap.

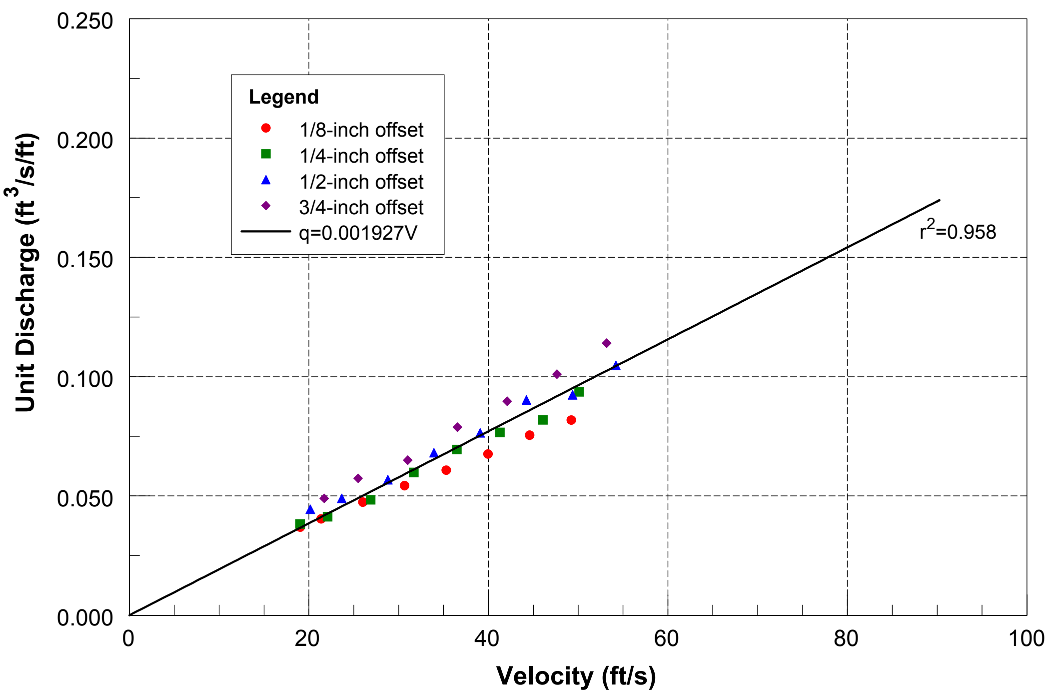

Figure 10. Unit discharge for joint/crack, sharp-edged geometry, 1/8-inch gap.

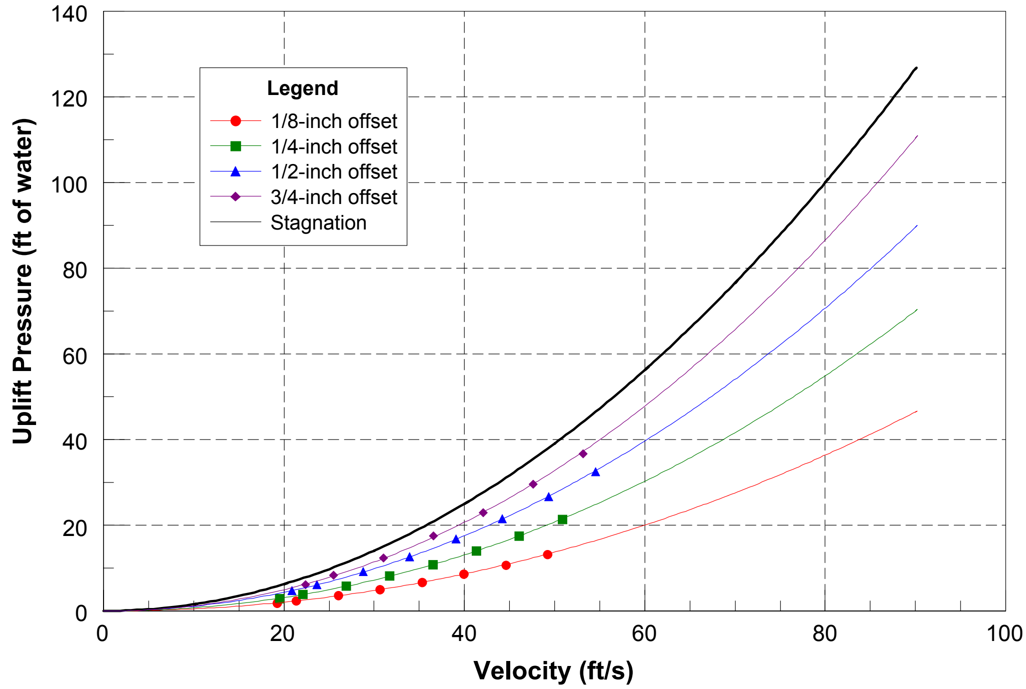

Figure 11. Mean uplift pressure, sharp-edged geometry, sealed cavity, ¼-inch gap.

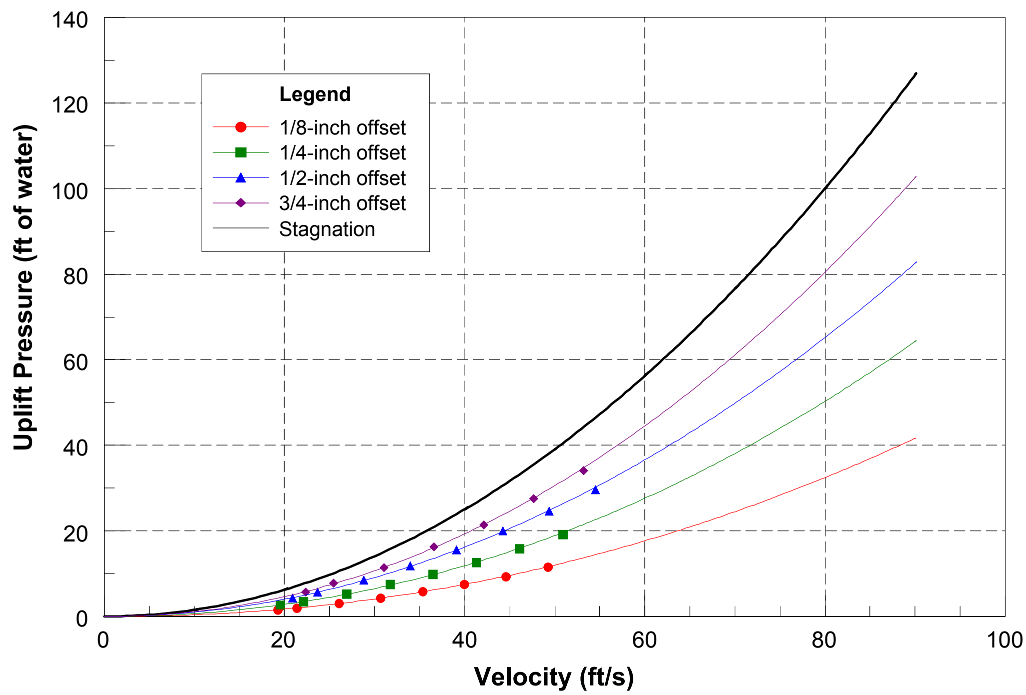

Figure 12. Mean uplift pressure, sharp-edged geometry, vented cavity, 1/4-inch gap.

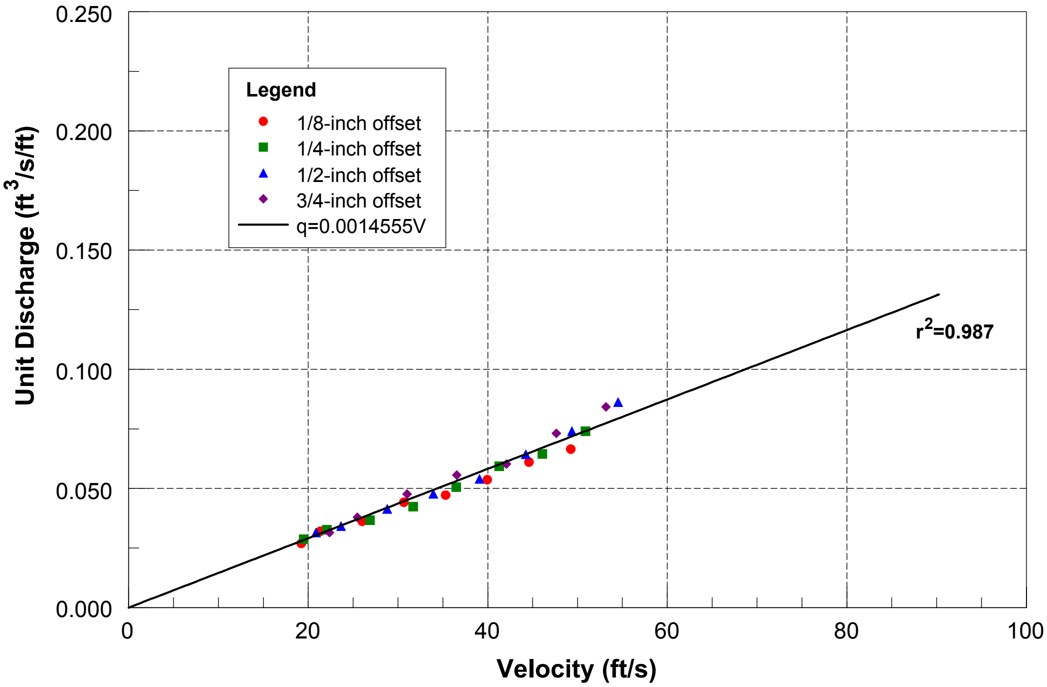

Figure 13. Unit discharge for sharp-edged joint/crack, 1/4-inch gap.

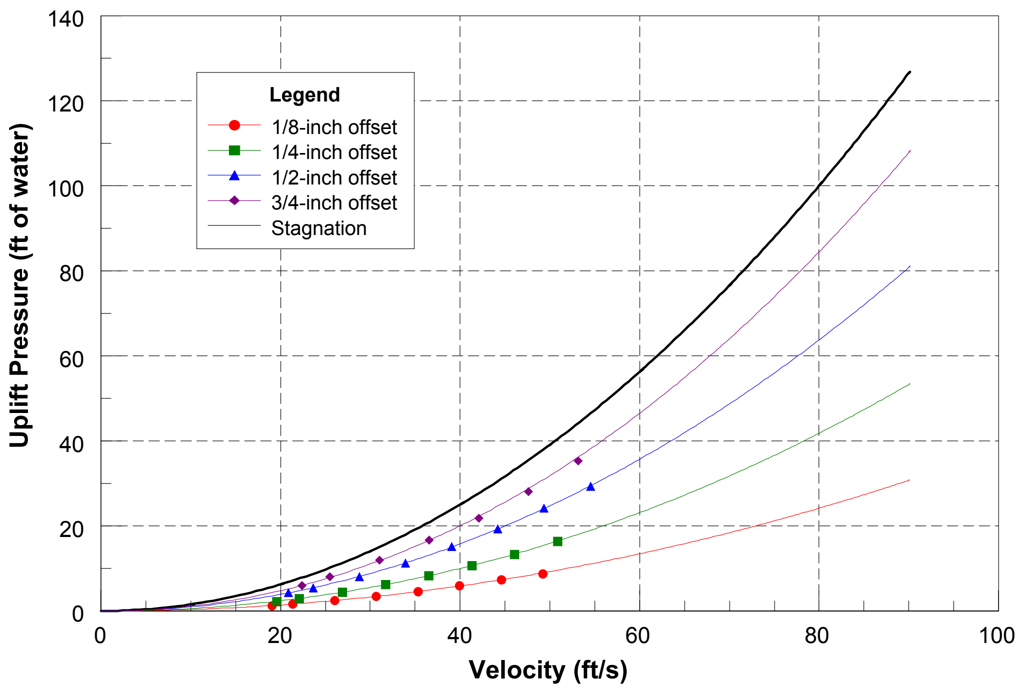

Figure 14. Mean uplift pressure, sharp-edged geometry, sealed cavity, ½-inch gap.

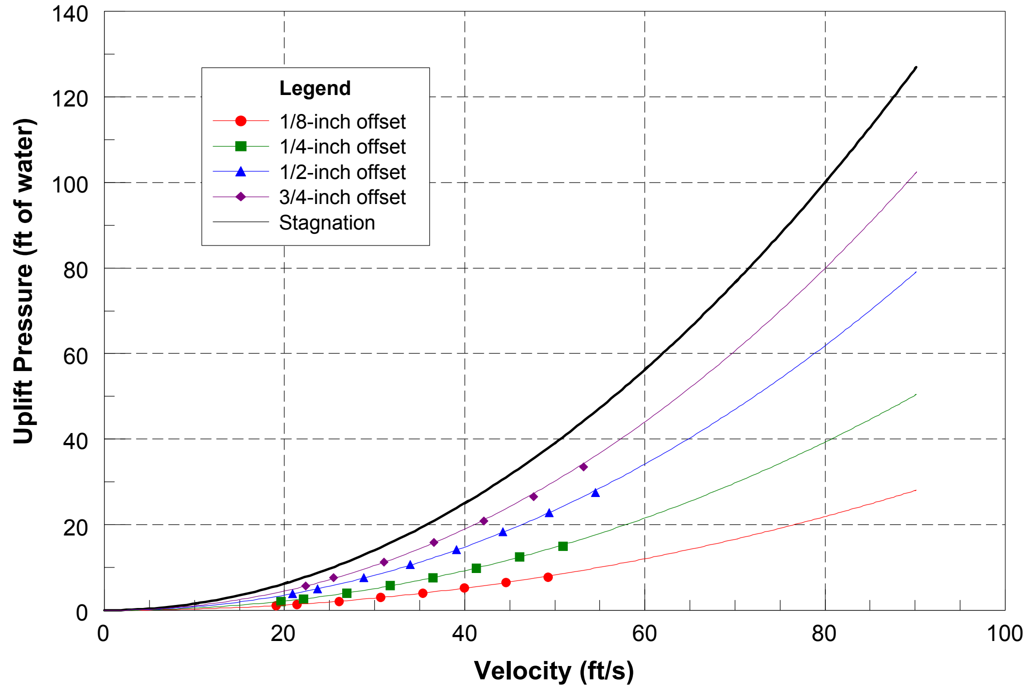

Figure 15. Mean uplift pressure, sharp-edged geometry, vented cavity, 1/2-inch gap.

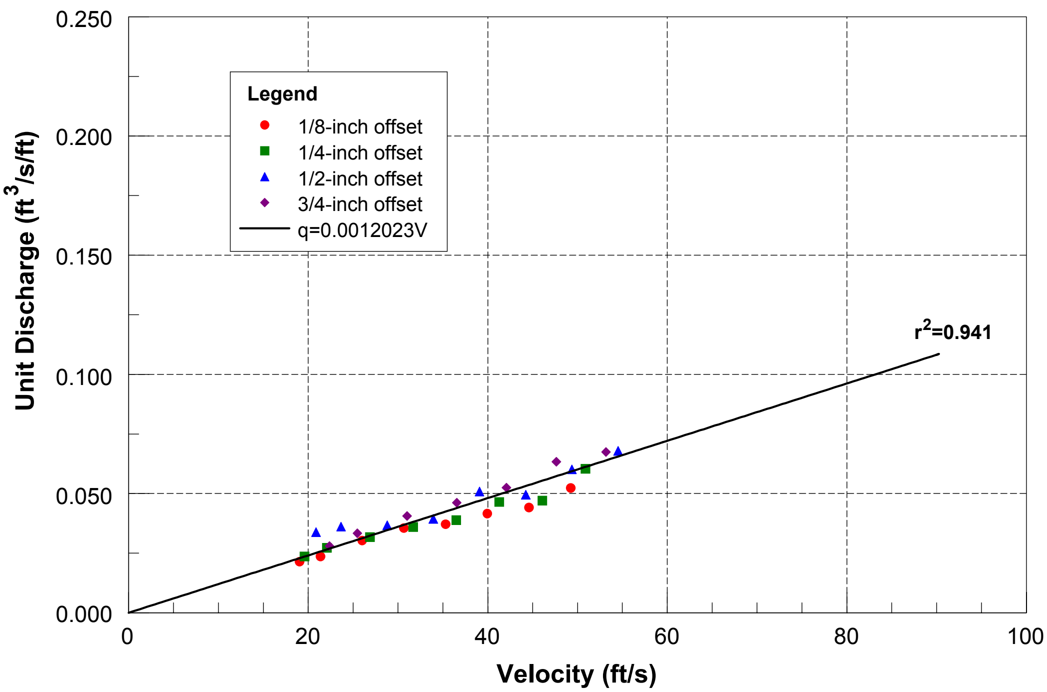

Figure 16. Unit discharge for sharp-edged joint/crack, 1/2-inch gap.

Table 1. Coefficients of power curve fits for sharp-edged geometry. Equation is in the form $P= a U^{b}$, where U is the velocity and P is the uplift pressure (sealed or vented).

Gap (inches)	*Offset (inches)*	*Sealed*		*Vented*	
		a	*b*	*a*	*b*
0.125	0.125	0.00659	2.01212	0.00422	2.08575
	0.25	0.00897	1.99619	0.00707	2.01796
	0.50	0.01519	1.92002	0.01207	1.94415
	0.75	0.01881	1.90587	0.01599	1.91156
0.25	0.125	0.00410	2.07475	0.00308	2.11373
	0.25	0.00632	2.06971	0.00546	2.08292
	.050	0.01055	2.01044	0.00994	2.00543
	0.75	0.01023	2.06377	0.00973	2.05841
0.50	0.125	0.00316	2.04049	0.00243	2.07779
	0.25	0.00500	2.06108	0.00420	2.08693
	0.50	0.00931	2.01530	0.00732	2.06328
	0.75	0.00948	2.07542	0.00909	2.07265

General Trends: In general, for all cases tested, the uplift pressure increases with increased flow velocity and increased vertical offset height. However, increased joint/crack gaps show slight reductions in uplift pressures. Venting the cavity below also produces a reduction in uplift pressure for all test configurations. With regards to joint/crack unit discharge, the results consistently show that increased joint/crack gaps produce reduced unit discharges. In all cases tested, the flow through the gap was controlled by limitations in drain capacity. This is most likely to be the case in prototype installations as well. The application of basic head loss theory then makes it relatively easy to predict gap flows for a variety of drain-loss configurations. Venting of the sub cavity to atmospheric pressure, while unlikely to occur, does produce the highest flows into the gap.

DISCUSSION

The tests performed during this research study provide increased insight into the behavior of uplift pressures and joint/crack flows for a variety of joint parameters. Increased knowledge of how joints and or cracks transmit both pressures and flows beneath a slab is of particular value to those tasked with evaluating maintenance or repair/replacement scenarios that may result from a recommendation of a Comprehensive Facility Review (CFR), Issue Evaluation (IE), or a Corrective Action Study (CAS). Better estimates of possible problems resulting from uplift pressures or flows will reduce the uncertainties that engineers are faced with when performing risk-based analyses. The work presented here is not without limitations and definitely does not address every possible scenario.

Prior to this work, many of the recent decisions regarding potential uplift problems have been largely based on work performed by Johnson (1976) as part of Reclamation's Open and Closed Conduit Systems Committees' (OCCS) research program. This research was further applied and documented in a paper by Hepler and Johnson (1988) where its application to spillway failures was presented. Others within Reclamation have used this data, rearranged graphing parameters and analytically extended the range to produce a set of graphs for varying horizontal offsets (Trojanowski, 2004), Figure 17 shows this result for 1/8 inch gaps.

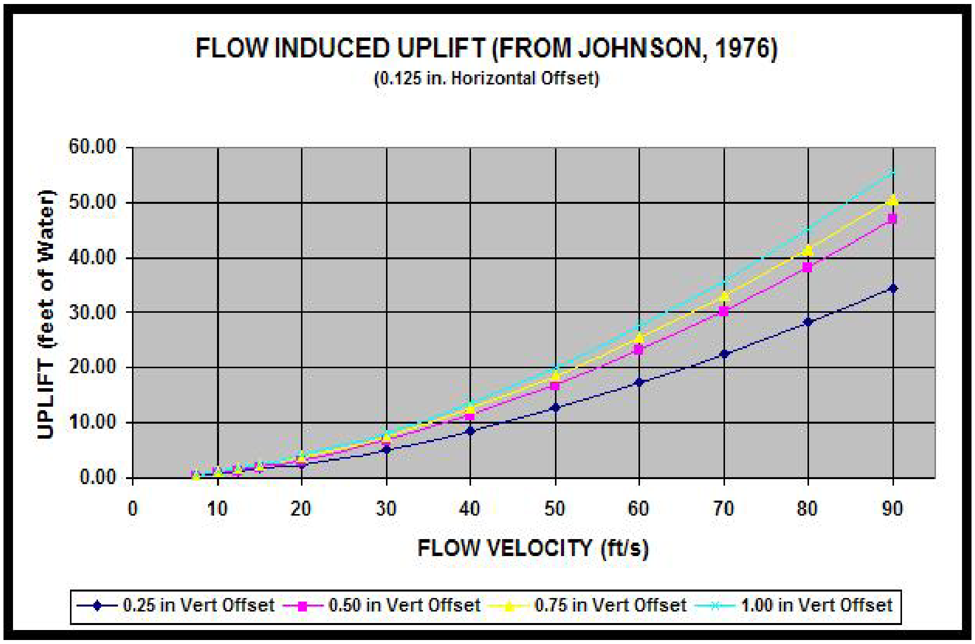

Figure 17. Graph derived from Johnson's work in 1976 on uplift of steep chute lateral linings.

The major question regarding the use of this data has always been in the scale-up process. Data were limited to a model velocity of 15 ft/s and then Froude number-based scaling laws were used to extend the data to the higher velocities reminiscent of typical spillway flows.

Similar trends for the uplift pressure data were found between the sharp-edged joint and Johnson’s (1976) data. Although the actual magnitudes differed, the trend for a decrease in uplift pressure with an increase in the horizontal gap dimension for a given offset height was consistently observed during this testing. It may be postulated that this is due to formation of a driven recirculation zone at the point of the gap entrance that effectively blocks transmission of the full stagnation pressure from reaching the area under the lining. This was further demonstrated by use of particle-image-velocimetry (PIV) on the laboratory model during this present research program.

Finally, it is important to note that the effect of turbulent fluctuations were not investigated, but potentially have a significant influence on uplift pressures. Depending on frequency and cavity configuration, fluctuation pressures resulting from turbulent flow may produce cavity resonance (an effect that is more likely when gaseous entrainment occurs). Such physical processes have been observed for high-velocity flows in the vicinity of rock fissures (Bollaert, 2002). However, this condition was not included in this study.

Adaptation of the results from this study into a spreadsheet application allow for quick evaluations of a given crack or joint condition. Perhaps of more concern however, is the condition of features that cannot easily be inspected. The underlying joint details, condition of the waterstops (if equipped), and condition of the drainage system are features that are equally important in the overall evaluation of the spillway or outlet works system and have a direct bearing on the ultimate performance of the hydraulic structure.

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