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The hydraulics and resulting bed scour within the vicinity of submerged single span arch bridges.

Donal Ryan¹, Gerard A Hamill², John McRobert³, William Smyth⁴

¹School of the Built Environment, University of Ulster, Shore Road Newtownabbey. BT37 0QB

²School of Planning, Architecture & Civil Engineering, Queen's University Belfast, David Keir Building, Stranmillis Road, Belfast.

³DRD Roads Service, Highway Structures Unit, County Hall, Galgorm Road, Ballymena. Co. Antrim.
email: d.ryan@ulster.ac.uk, g.a.hamill@ulster.ac.uk, john.mcrobert@drdni.gov.uk, william.smyth@swc.ac.uk

ABSTRACT: As a consequence of climate change there is now a more frequent occurrence of extreme rainfall events where, with higher rates of urbanisation, the built environment has become increasingly affected by flooding. This is of particular importance in relation to the stability of bridge structures that span rivers and canals etc. In November 2009, the UK and Ireland were subjected to extraordinarily severe weather conditions for several days. The rainfall was logged as the highest level of rainfall ever recorded within the UK, and as a direct consequence, unprecedented flooding occurred in Cumbria. This flooding led to the collapse of three road bridges which were generally 19th century masonry arch bridges, with relatively shallow foundations. In the UK, knowledge of the combined effect of bridge scouring and inundation has been not been particularly widely studied. Research carried out by Hamill et al [1] considered the hydraulic analysis of single arch bridges under flood conditions, but no consideration was given towards the likely damage to these structures due to scouring. Prior to this, Bierry and Delleur [2] produced a classic paper in predicting the discharge downstream of an inundated arch, focussing on predicting afflux as opposed to bridge scour. Further work on backwater effects was carried out by Martin-Vide & Prio [3] in semi-circular arch bridges. Both pressurized and free-surface flows at the bridge were investigated. Flows on a mobile bed in clear-water conditions were compared to those with a rigid bed, but no predictive equation for scour under pressurised conditions was considered. This paper will present initial findings from an experimental investigation into the effects of surcharged flow and subsequent scour within the vicinity of single span arch bridges. Velocities profiles will be shown within the vicinity of the arch, in addition to the depth of clear water scour, for a series of flows and model spans. The data will be presented, where results will be correlated to the most recent predictive equations that are proposed.

KEY WORDS: Scour, pressurised flow, sediment, bridge.

1 INTRODUCTION

In November 2009, the UK and Ireland were subjected to extraordinarily severe weather conditions for several days. The rainfall recorded at Seawaith Farm, Borrowdale was in excess of 316mm over a 24-hour period, and was the highest level of rainfall ever recorded within the UK. As a consequence, unprecedented flooding occurred in Cumbria. Due to a combination of rainfall, and the terrain, the flooding led to the collapse of three road bridges and the same number of footbridges around Cockermouth and Workington and resulted in considerable negative economic, social and environmental impacts. The bridges were generally of masonry arch construction, built in the 19th Century and with relatively shallow foundations. The causes of these collapses are likely to be related to a combination of factors, including (1) Foundation Scouring (2) Upwards pressure on the arch soffit, causing separation of the arch stones (3) Lateral water pressure and (4) Debris impact.

In answer to questions from the House of Commons Transport Committee it was stated that "scour is considered to be the most common cause of bridge failure" and that the combination of scour and lateral forces has been considered to have led to the collapse of the bridges in Cumbria.

In addition to the above, Highways Agency published a revision to BA 74/06 "Assessment of Scour at Highway Bridges" in 2012. The new revision (i.e. BD 97/12) advises on how to determine the level of risk associated with scour

effects. Highways Agency also refers to BA59/94 "The Design of Highway Bridges for Hydraulic Action" provides design guidance based on references from publications prior to 1994. The significance of these reference dates is that the reference material cited does not take into account the current situation in relation to climate change.

In the UK, the above standards clarify that the recommended design guidance documentation for highway bridges does not provide advice on predicting/designing to reduce scour under pressurized flow conditions. The rationale behind this paper is to address the current knowledge gap when looking at pressurized flood flows/inundation on existing structures, with particular emphasis on structures with limited spans. The impact of this research will become significant to stakeholders and designers, where the findings will inform maintenance guidance and provide design advice to engineers.

2 BACKGROUND RESEARCH

2.1 Bridge Hydraulics

Several Authors have investigated the hydraulics of flow in the vicinity of an arch bridge. The majority of that work was carried out for normal flow conditions, where arch inundation was not considered. Previous authors were also interested in the prediction of afflux and discharge through the bridge

structure. However, when the soffit of a bridge is submerged there were two specific conditions that can exist : (1) Sluice Flow and (2) Orifice flow where Equations 1 and 2 are proposed below:

$$Q = C_d a_w \left[2g \left(Y_u - \frac{Z}{2} + \frac{\alpha_u V_u^2}{2g} \right) \right]^{1/2} \quad (1)$$

$$Q = C_d a_w (2g \Delta H)^{1/2} \quad (2)$$

where C_d (= 0.35 to 0.6) is the discharge coefficient, a_w is the total area of the opening flowing full (m^2), Y_u is the upstream depth (m) and Z is distance between the soffit and the bed level (m). Equation 3 defines ΔH as:

$$\Delta H = \left[\left(Y_u - \frac{Z}{2} + \frac{\alpha_u V_u^2}{2g} \right) - \left(Y_d - \frac{Z}{2} + \frac{\alpha_d V_d^2}{2g} \right) \right] \quad (3)$$

The subscripts u and d denote upstream and downstream respectively. The above equations have never been tested for Arch Bridges, and the only equation for predicting Discharge was proposed by Biery & Delleur [2] as:

$$Q = C_d \sqrt{2g} \frac{17}{24} y_1^{3/2} b \left[\begin{array}{l} 1 - 0.1294 \left(\frac{y_1}{r} \right)^2 \\ - 0.0177 \left(\frac{y_1}{r} \right)^4 \end{array} \right] \quad (4)$$

where y_1 is the depth of flow at the section of maximum backwater (m), b is the span width at the spring line of the arch (m) and r is the radius of curvature of the arch (m). The limitation of Equation 4 is that the C_d value must be determined from Tables within the publication itself, and the same equation determines discharge for both sluice and orifice conditions, where no clear evidence from tests is demonstrated within the publication.

The above equations have been widely used to predict bridge afflux and have also been utilised to determine the flow through the bridge constriction and hence the average flow velocity through the same. As the velocity increase within a bridge constriction, formulae were developed to determine scour depth as a function of the relationship between upstream average velocity (v_u) and the average velocity through the constriction (v_b). A value for v_b is determined from Equation 4 for an arch bridge.

2.2. Bridge Scour

Shan et al [4] suggested the following equations to predict pressurized clear water scour under vertical contraction only:

$$y_2 = \left[\frac{k_u Q^2}{D_m^{2/3} W^2} \right]^{3/7} \quad (5)$$

And

$$\frac{t}{h_b} = 0.5 \left(\frac{h_b h_t}{h_u^2} \right)^{0.2} \left(1 - \frac{h_w}{h_t} \right)^{-0.1} \quad (6)$$

Where h_b is the vertical size of the bridge opening prior to scour (m), T is the height of the obstruction including girders/deck/parapet (m), h_u is the upstream normal depth (m), D_m is the median grain diameter (m), W is the upstream channel width (m), k_u is a dimensionless parameter (0.025), Q is the upstream flow (m^3/s) and y_2 is the scour depth (m). The value for h_b is subtracted from $(y_2 + t)$ to get the total depth of scour (y_s). Q is calculated using Equations 1, 2 and 4. V_{uc} and V_b are the velocities upstream and through the bridge respectively.

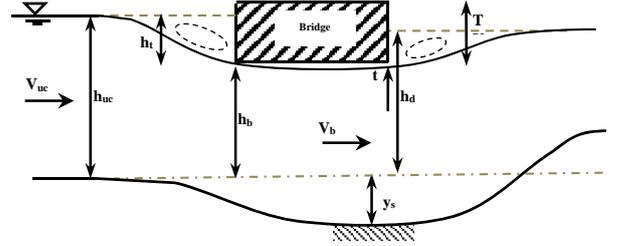


Figure 1: Parameter Definitions for Maximum Scour

The limitations to the above relationship are that the constriction is only vertical. With an Arch Bridge, the constriction is both vertical and horizontal and the validity of the above equations has yet to be tested.

3 EXPERIMENTAL SET-UP & DATA ACQUISITION

3.1 Velocity Testing

Previous Authors, including Arneson & Abt [5], Arneson & Abt [6], Gou [7] and Shan et al [4], carried out extensive physical modelling on sediment scouring. However, there was no evidence of attempting to understand the flow velocities within the vicinity of the bridges. Each author cited the work of early authors such as Laursen [8] and Arneson et al [5] in relation to examining critical velocity of sediment (V_c), but made little attempt to carry out any work in establishing a relationship between scour depth and velocity within the vicinity of the bridge, under pressurized low. There seems to be an emphasis on upstream average critical velocity (V_{uc}) and the average velocity through the bridge (V_b). These are averaged, based of continuity equation, and using Equations 1-4, depending on the physical conditions.

The present investigation considers the nature of these velocities through an arch bridge, in order to gain a better understanding of the nature of flow through a pressurized arch. Velocity measurements are taken by using a SonTEK 2D Acoustic Doppler Anemometer, with a sampling frequency of 50Hz. Measurements were taken for an initially flatten bed, stabilized by using an Epoxy Resin treatment. Following this, the scour holes were allowed to fully develop to the equilibrium stage of erosion (approx. 80mins), and measurements taken for the purposes of making comparisons with the flat bed condition.

A Grid System is used both upstream and downstream of the arch models, where the grid density for velocity measurement. The grid density is increased within the

vicinity of the higher velocities to that of a 20 x 20mm Grid. Outside the confines of the arch, the grid was increased to a density on 50 x 50mm.

Velocity measurements were taken on the XY plane at three positions (1) 500mm upstream of the flow entering the arch, (2) at 20mm upstream of the flow entering the bridge arch and (3) 20mm downstream of the flow exiting the bridge arch. The data was then analysed to determine how the velocity profiles varied with distance through the arch.

3.2 Bridge Model & Scour Tests

All of the uPVC model bridge experiments have been carried out within a 10-metre long Perspex channel of dimensions 760 mm × 250 mm. Water is supplied via a reservoir and 2 No. impeller pumps and is capable of supplying 100 l/s to the upstream supply reservoir. A recessed channel is constructed within the channel for the purposes of these experiments to a total depth of 230 mm. A bridge model structure was inserted half way down the channel and is illustrated in Figure 2.

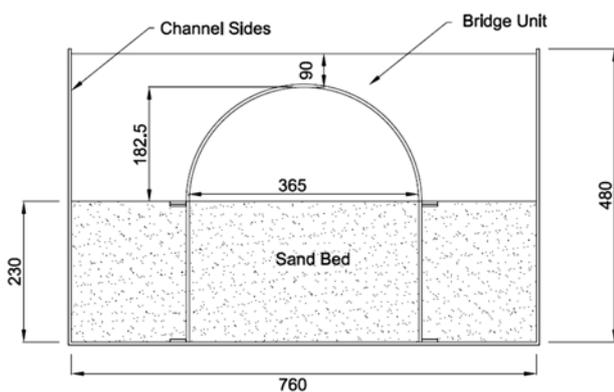


Figure 2: Scale Model of Bridge Cross-Section for Typical Arch.

Figure 3 show the model in the channel after a typical experimental run of 4 hours, and were the flow was 32 l/s. The sediment used in the test had a d_{50} of 1.1 mm.



Figure 3: Experimental Setup after test run at 32 l/s.

A joint is visible in the structure at the bottom of the arch, this is the initially flatbed level for the experiments. At the end of each experiment the main superstructure is removed and this makes it possible to take a 3-D scour profile using a uses a hand-held, high resolution 3D laser scanner (HRS). The scanning procedure obtains a coarse resolutions 3-D model, which is then further scanned at a finer 0.5mm resolution.

4 RESULTS AND DISCUSSION

4.1 Velocity Measurements

From the XY measurement for velocities on the flat bed, Surfer™ was used for the purposes of visualising the velocity distributions as the flow progressed through the arch. Figure 4 shows a plot of a 23 l/s flow passing through a bridge under flood conditions.

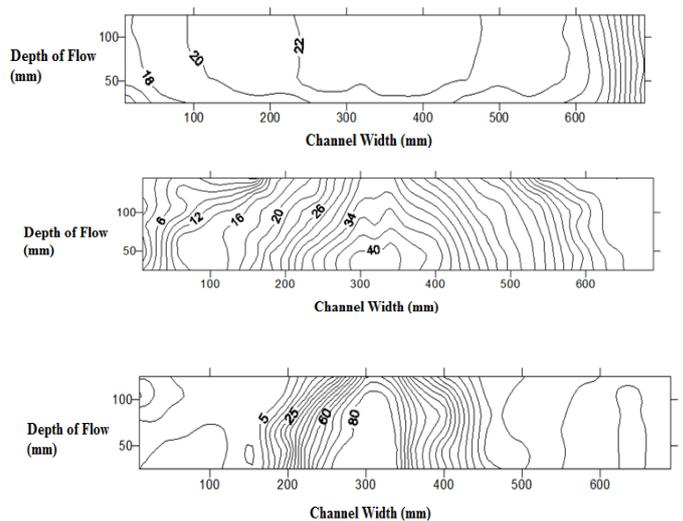


Figure 4: Contour Plot of Flatbed velocities at 500mm upstream, 20mm upstream and 20mm downstream of Arch Bridge unit at 23L/s.

The velocity contour plot clearly shows that the velocity gradient and peak value increase as the flow passes through the arch bridge. The arch is not drawn on these contours, however it can be clearly seen that there is a concentration of high velocities at the position of the arch. Velocities also increase four-fold as it passes through the arch.

Considering these velocities in a 2-Dimensional Plane, these are shown on Figure 5 along the axis of the Arch Centreline.

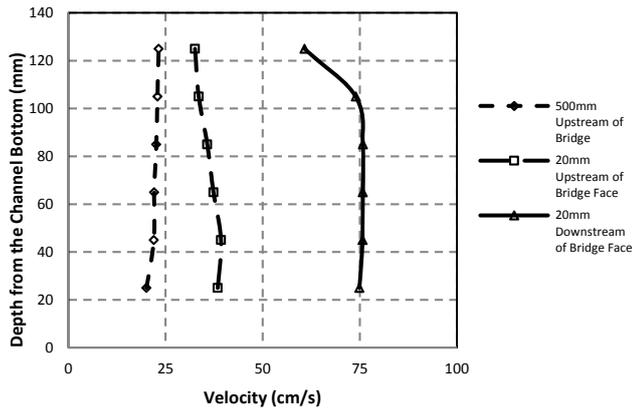


Figure 5: Flatbed velocities at 500mm upstream, 20mm upstream and 20mm downstream of Arch Bridge unit at 23L/s.

From Figure 5 it can be demonstrated that, from the upstream to downstream face of the Arch Bridge, there is an acceleration provided by the upstream head where the maximum velocity within the profile increases from 39 to 76 cm/s. This is an increase of almost two-fold. By examination of additional tests, with the same physical conditions, but with flow increases from 26 to 32l/s, similar changes in velocity occur. Therefore, it calls into question whether or not it can be assumed that the velocity through the bridge (V_b) is constant. This is especially the case for vertical constriction only, and should be further investigated. When considering the characteristics of the flow contours within a fully developed scour hole, the contours are shown in Figure 6 below. The flow, in this case is for 23l/s, as previously discussed.

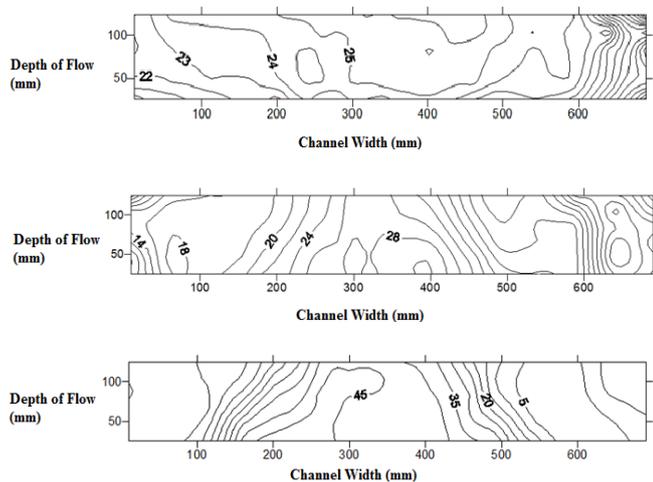


Figure 6: Contour Plot of scour hole velocities at 500mm upstream, 20mm upstream and 20mm downstream of Arch Bridge unit at 23L/s.

In this case, the velocity contours are less pronounced, and the magnitude of these velocities is less pronounced. This is expected as all of the erosion has taken place. However, worth noting is that fact that velocities (some 22mm above the bed) are still in the order of 45cm/s (0.45m/s), which would still exceed the critical velocity of most small to medium sands. It

would be expected that the slope of the scour hole may play a part in the scouring process ending, but the velocities still remaining above their threshold values.

4.2 Development of Scour within the vicinity of the Bridge.

Each scour test was allowed to run for a total of 80 mins at a constant flow, which was deemed as a reasonable estimate of the asymptotic/equilibrium state where no further scouring occurred. The 3D Scanner was utilised to determine the overall scour hole profile and Mountains Software was used to create the surface. Figure 7 shows the 3D Scanner used for the current investigation.



Figure 7: 3D Scanner Equipment for measuring scour depth.



Figure 8: 3D Photo of Scour Hole with reference points (bridge unit removed).

All 3-D profiles were carried out as described above, with the use of a network of reference points (circular plastic stickers) placed over the initially flat bed. A second scan is then carried out at 0.5mm resolution after the placement of new reference points placed, as shown on Figure 8. It can also be seen that the main bridge superstructure has been removed in this case, for the purposes of measurement. Figure 9 shows the scanned image.

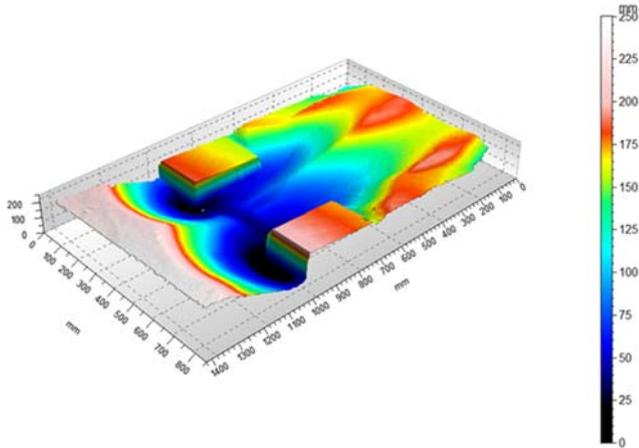


Figure 8: 3D Plot from laser scan produced using "Mountains" Software.

From the above plot, it is possible to determine all depths of scour, position of maximum scour and deposition, volumes of scour and deposition using the software at the end of every test. The line of maximum depth of scour can be determined and to the accuracy of 0.5mm. These plots confirmed that the maximum depth of scour always occurred at the upstream face of the abutment/foundation. This relationship held for all tests completed during this investigation.

4.3 Scour Depth as a function of time

The maximum depth of scour is a function of several experimental parameters that include flow, width of bridge span, sediment characteristics, level of afflux, abutment length, time etc. The key parameter is scour depth, but it is also critical to understand how quickly the maximum depth of scour is reached within a flood situation.

Measurement of the depth of scour, with respect to time, were made for each test and presented with Scour Depth (Y) versus Time (t) as shown in Figure 9.

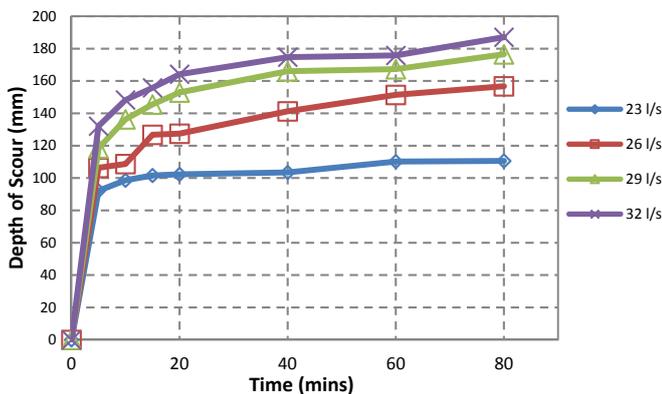


Figure 9: Scour Depth vs Time for Bridge Abutment.

It is clear that the rate of development of scour is high at the early stages of each test, and subsequently decreases after 8 to 10 minutes, where the depth begins to level out as the time approaches 80 minutes.

4.3 Afflux as a Function of Time.

McGahey et al et al [9] carried out a significant amount of work in determining how to predict afflux levels on the upstream side of many bridges throughout the UK and Abroad. The purpose of this work was focussed on predicting the level of afflux and its effect on upstream conditions (i.e. potential for flooding etc.). During the present investigation, the afflux level was measured with time, to determine if there may be a relationship between afflux level and the development of the scour hole. Figure 10 shows the results for 4 No. flows through a model arch bridge, carried out at the same time as the scour test shown in Figure 9.

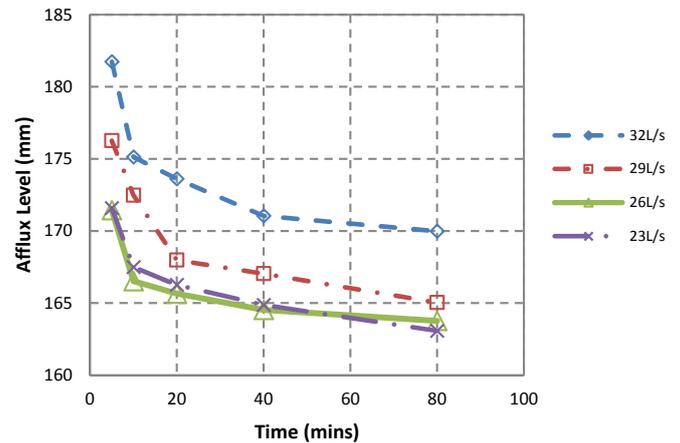


Figure 10: Afflux Level vs time

From Figure 9, it is reasonable to understand that the initial levels of afflux increase with the rising discharge. However, this is not a linear relationship as the afflux values for 23 and 26 l/s are reasonably close. However, considering Figure 9, the same flows demonstrate that scour depth is more sensitive to the small change in flow and, as these flows increase, the scour depth becomes less sensitive. This is the opposite of what is shown in Figure 10, where the difference in afflux is more pronounced between 32 l/s and 29 l/s when compared to the lower discharges. This is not what would normally be expected within pressurised flow conditions and is worth investigating further. It would also suggest that the upstream head may have a more limited effect on scour depth than expected.

4.4 Calculation of Theoretical Scour Depth and comparison with Laboratory Results.

The average velocity was determined by using the velocity area method to calculate the flow for each individual experiment, and then dividing the flow result by the total area of that flow (i.e. width \times depth). It was found that the error between the metered flows and the measured values are less than 1%. These measured discharges were then compared with the predicted values from Equations 5 & 6. Each of these values was, in turn, used to make a prediction of the final depth of scour as a function of the experimental conditions. The results are shown in Table 1.

Measured Flow (L/s)	Flow by Biery & Delleur(L/s)	Measured Scour	Theoretical Scour	

		Depth (mm)	Depth (mm)	% Error Scour
23.02	20.6	111	183.3	40%
26.5	21.3	157	218.8	28%
30.1	22.3	177	254.1	31%
33.2	24.3	187	289.1	35%

Table1: Comparison between Theoretical & Actual Discharges/Scour Depths.

It can be seen from Table 1 that there are two key observations. Firstly, the error between the actual measured velocities varies from 10 – 24% as the velocities increase. This is also shown in Figure 11. Secondly, the theoretical depth of scour is up to 40% in overestimation when compared to the actual scour depths. Therefore, it can be concluded that, for these test, lower theoretical velocities lead to higher depths of scour. This would suggest that the existing equations do not predict pressurised scour for an arch bridge particularly well.

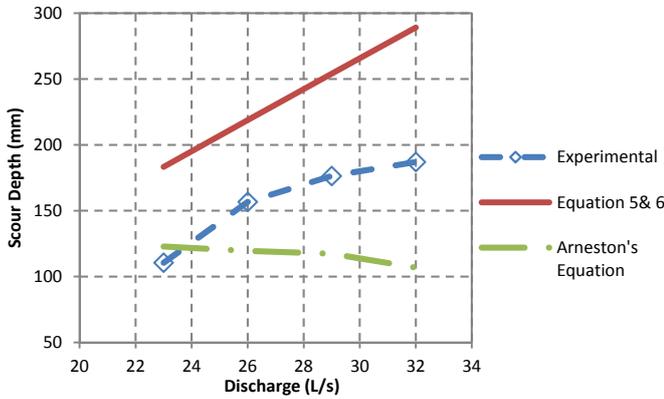


Figure 11: Comparison of Experimental Scour Depths with Existing Equations.

An equation was proposed by Arneson et al [5] to predict pressurised flow as:

$$\frac{y_s}{y_1} = -5.08 + 1.27 \left(\frac{y_1}{H_b} \right) + 4.44 \left(\frac{H_b}{y_1} \right) + 0.19 \left(\frac{V_a}{V_c} \right) \quad (7)$$

Where y_1 is the upstream depth (m), V_a is the average velocity through the bridge opening (m/s) and V_c is the critical velocity for incipient motion (m/s).

When the predictions from Equation 7 are plotted against the current experimental data it is clear that the present data over predicts these predicted values. However, it is a concern that the depth of scour decreases with a rise in discharge/velocity.

5 CONCLUSIONS

For the range of tests carried out for the present investigation, it has been found that there is a clear

relationship between the development of scour depth with time. When considering the afflux levels with time, it is also a decrease in afflux level with time, as scouring progresses. Further testing is currently underway in order to determine if the relationship between scour depth and afflux can be ascertained.

Current methods from Biery & Delleur [2] also under predict discharge through the bridge units. This is possibly due to the fact that the abutment length was not considered to any great detail within that study. This will require further investigation as the current model is utilising an abutment depth (with flow) of 280mm. The work of Biery & Delleur [2] used much shorted lengths, where the arches almost behaved like flat plates. This is possibly the reason for the acceleration of the water under the bridge, where the increase in velocity is significant as the flow enters and exits the arch. Further work is underway to investigate the length of the abutment and how it may affect the under bridge flow velocities.

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