**SCOUR CONCERNS FOR SHORT-SPAN, MASONRY ARCH BRIDGES**

Brian Solan1, Robert Ettema2 M. ASCE, Donal Ryan3 and Gerard A. Hamill4

1Lecturer, Ulster University, Shore Road, Newtownabbey, Co Antrim, BT37 0QB U.K., b.solan@ulster.ac.uk

2Professor, Dept. of Civil & Environ. Eng., Colorado State University, 1372 Campus Delivery, Fort Collins, Colorado, USA 80526, Robert.Ettema@colostate.edu

3Senior Engineer, EDC Consulting Civil & Structural Engs., 43 Chapel View, Bellaghy, Magherafelt, BT45 8GZ, U.K., donal@edcconsulting.co.uk

4Professor, Queens University, School of Natural & Build Environment Architecture, Civil Engineering and Planning David Keir Building, Stranmillis Road Belfast, U.K., g.a.hamill@qub.ac.uk

**Abstract**

Short-span, masonry arch bridges constitute a significant proportion of the existing bridge inventory in the U.K., Ireland, Europe and northeastern USA. These old, historic structures are founded typically on relatively shallow footings of unknown depth and configuration, or on timber piles weakened by age and environmental exposure. Flume experiments used two common forms of short-span, masonry arch bridge and showed how local scour may readily undermine such structures. The experiments demonstrated that traditional, hydraulic adjustments do not significantly reduce scour depth: streamlining abutments with wing walls and using cutwaters on piers. The usefulness of stone armor placed around abutments and piers was proven, but such armoring may relocate scour downstream of the bridge. The findings emphasize the scour-countermeasure benefits of foundation strengthening, flow bypassing by means of relief culverts (where feasible), and the use of channel armoring and energy-dissipation structures downstream of the bridge.

**Key Words:** *abutments, bridges, scour, foundations, flooding*

**Introduction**

In recent years, increasing urbanization of watersheds has led to a growing number of scour-related failures of masonry arch bridges throughout the U.K., Ireland and Europe (e.g., DfI 2018, Wiggins et al. 2018, Zampieri et al. 2017). Many failures involved short-span bridges, most of which were built in the nineteenth century and traditionally have shallow footing foundations of unknown depth and condition (Wilmers 2012, O’Keefe and Simington, 2016). Fig. 1 shows a typical pier failure that occurred at a multi-span masonry-arch bridge located on the River Faughan, Northern Ireland (N.I.), U.K. This technical note, prompted by concerns raised by N.I.’s Department for Infrastructure (DfI), addresses the usefulness of standard hydraulics modifications to reduce scour at short-span masonry arch bridges. The modifications studied include streamlining the shape of pier noses, wingwall-angling of abutments, and armoring of the stream bed locally beneath a bridge. The DfI and other transportation agencies traditionally preferred these modifications to the more expensive alternative scour-countermeasures of foundation strengthening, flow bypassing or full channel armoring. Approximately half of the U.K.’s bridges are short-span masonry arch bridges (U.K. Government 2011). In many cases, such structures are over 100 years old, have protected status and cannot be replaced with new bridges (McKibbins et al. 2006).

Flume experiments were conducted to evaluate the extents to which traditional hydraulic modifications can mitigate scour, and to illuminate how scour develops at two common forms of short-span, masonry arch bridges: a single arch form extending to the stream bed, and a multi-arch bridge form that includes vertical walls extending a short distance above the bed. Fig. 2 illustrates the layouts and model dimensions of the two arch forms. The present note briefly summarizes the experiments, which included varying the invert level of arch footings because many old masonry bridges in the UK are supported by foundations of unknown depth and configuration. Foundation-invert levels were typically determined based on local custom, available resource, limited knowledge of regional geology, and involved no geotechnical design. A small number of experiments investigated the extent to which stone armoring of the bed arrested scour within the bridge entrance.

Masonry arch bridges comprise an arch barrel, confining spandrel walls, abutments, and possibly piers if multi spanning. Typical flow conditions observed during floods in the U.K. indicate that inlet control prevails with the crown of the archsubmerged and the outlet usually not submerged (Hamill 1999). As the flow elevation increases, the increment in cross-sectional area of flow decreases, thereby soon choking the approach flow. Such choking is typical of flow conditions leading to scour-related failure of short-span, masonry-arch bridges (Hamill 1999). In certain respects, masonry arch bridges have features similar to culverts, especially so-called bottomless culverts, prevalent in the USA and Canada (e.g., Kerenyi et al. 2003, 2007). Scour conditions in the U.K. typically involve either clear-water or live-bed scour, depending on the bridge site (DMRB 2012 & Kirby et al. 2015). For the purpose of the present study, only clear-water conditions of scour were considered.

**Flume Experiments**

The flume experiments, conducted at Ulster University, focused on scour at common forms of short-span, single- and double-arch bridges. Table 1 summarizes the full set of flume experiments, which were documented in a set of student theses (Ellis 2015, Stenson 2016, Colon 2016, Byrne 2016 and Watters 2017).

Two typical arch diameters were simulated at approximate scales of about 1:25. In the U.K., short-span arches have diameters ranging from about 2m to about 12m (DfI, McRobert personal communication 2015). As Fig. 2 indicates, the double-arch model differed in form from the single arch. The model single-arch bridge had a span of 0.38m, and the model double arch comprised two barrels of 0.18m diameter, with each barrel including vertical sidewalls and separated by a 0.11m-wide pier. The single arch equated to a 9.5m-diameter prototype arch, whereas each double arch equated to a 4.5m-diameter prototype arch (multi-arch bridges may vary in arch span). The streamwise width of the model arches was 0.3m, replicating a two-lane road (prototype width of about 7.5m) set between masonry parapets. In addition to no wing wall (0o), three wingwall angles were tested: 22.5o, 45.0o and 67.5o. A practical consideration was that wingwalls could be readily flared into roadway embankments, which in N.I. usually have a 2H:1V side slope.

Fig 2 indicates that the arches were modified by a sequence of adjustments: footing depths (single arch only), wing walls of variable attack angle were added to the abutments of the single arch. The double-span arch was fitted with an optimal angle (45o) of wing wall. The two cutwater sizes tested comprised triangular edges (or noses) extending to apex angles of 90o and 63o from the full 0.11m width of the pier in Fig 2b. Note that apex angle = 0o when no cutwater is used. This sequence aimed at establishing how orifice flow scour leads to failure of arch bridges, and then identifying how best to minimize scour for the more vulnerable bridges; i.e., those founded on shallow footings. An additional experiment was run with the central pier of the double-arch model treated as a solitary rectangular pier in a flow, where the approach velocity was comparable to the inlet velocity 50mm upstream (0.5 pier width) of the bridge opening of the double-arch bridge. This run sought to relate the scour depth at the central pier to that at an equivalent single pier. Fig. 3 indicates transects B-G, along which scour depths were measured through the arches. Also appraised was the scour depth development at front and back faces of the arches. In line with observations of flow conditions commonly associated with scour-related failure of short-span, arch bridges, the experiments simulated conditions of choked flow, whereby the bridge-created backwater caused supercritical flow through the bridge openings (Fig. 4).

The recirculating flume in which the data were collected was 10.0m long, 0.75m wide and 0.25m deep, and was set at a slope of 0.1%. Clearwater approach-flow conditions were simulated in all experiments. These conditions and arch configurations were suitable for evaluating the extents to which traditional hydraulic modifications can mitigate scour. A sediment recess (1.8m-long, 0.75m wide by 0.23m-deep) was placed downstream of the flume’s midpoint and, was filled with uniform, fine gravel. The median diameter and geometric standard deviation of the gravel were *D50*, = 2.54mm, and *σg* = *D84/D50* = 1.8, respectfully. This bed sediment was chosen as being representative of the coarse sediments (gravel-bed streams) typical of streams and small rivers in N.I. whose median size (*D50*) limits range from about 2mm to 256mm (Kirby et al 2015). Thus, the sediment used in the analysis is indicative of UK gravel-bed stream. Preliminary testing with choked-flow conditions confirmed (for this study) the utility of a bed formed of the fine gravel mentioned above.

Armor stone is sometimes placed to protect the bed through the arch barrel of a bridge (DfI, McRobert personal communication 2015). The stone-sizing relationship recommended by Lagasse et al. (2006) was used to estimate a lower limit of suitable stone size for an experiment run to investigate the extent to which scour could develop immediately downstream of a bed-armored arch bridge. The resulting median diameter of stone (specific gravity 2.65) selected for this experiment was 14mm, which corresponded to a 350mm-diameter prototype stone and to the “one-man stone” rule-of-thumb commonly used for armouring river beds in N.I. (DfI, McRobert personal communication, 2015). As done for actual bridges, the stone was placed as a, tightly packed single layer whose top aligned with the top of the bed through the bridge. A flow rate of 0.3m3/s was used for this experiment.

Of prime importance for the experiments was scour-depth and scour-location variation with geometric changes of arch: footing depth; wingwall angle; cutwater size; and stone armouring along arch openings. Both typical arch forms were subject to the same range of flow rates under clear-water approach conditions. An important similitude parameter was Shield’s number similitude, a non-dimensional form of bed [shear stress](https://en.wikipedia.org/wiki/Shear_stress) and the shear stress associated with the entrainment of uniform particles forming a bed surface (e.g., Pugh 2008). Approximate values of shear stress for uniform flow over the approach bed, *τo*, were estimated in terms of flow depth and flume slope associated with uniform flow along the flume and related to the critical value of bed shear stress, *τc*, for entrainment of the bed sediment in the sediment recess. The method suggested by Julien (2010) indicated a flume sidewall-effect correction of 5 to 8% for the lowest to highest discharges used. Using the Shields entrainment criterion (e.g., Julien 2010), *τc* for the *D50* mentioned above was estimated as 1.74N/m2. Accordingly, *τo*/*τc* = 0.80, 0.87 and 0.97 for uniform flow at the three discharges along the approach bed depths (no arch present). The threedischarges used were 0.03, 0.04 and 0.05m3/s, with corresponding uniform flow of 0.17, 0.19 and 0.21m. The values of Froude number for the equivalent uniform flow were 0.18, 0.25 and 0.28. The backwater effect caused by flow-choking at the arch models caused the water level to rise above the crown of the arch. The water level at the crown varied with discharge and was a maximum of about 0.025m for the largest flow and reduced to about 0.01m for the lowest flow. Reynolds number for the approach flow to the arches exceeded 105, indicating turbulent approach-flow conditions in the model as in typical field sites. Ryan et al. (2016) documented velocity measurements taken using an Acoustic Doppler Velocity meter with the bed fixed prior to the scour experiments. The hydrodynamic force on the bed was complicated locally by flow acceleration to and through the arch opening, and by flow separation and turbulence at the corners of the arches (Ettema et al. 2006). A further important parameter was the ratio of pier width, *B*, to median diameter of bed sediment, *D50*. For the experiments, this ratio was *B/D50* = 43, well above the lower limit of 25, which Raudkivi and Ettema (1983) indicate when relative coarseness of bed particles begins to reduce equilibrium scour depth.

**Results**

The results show how arch bridges can fail owing to foundation undermining and subsequent structural collapse, as Fig 1 illustrates. Deepest scour for the single arch occurred at the arch corners of transects B and D (Fig. 3). Scour at the double arch exhibited essentially the same morphology profile as at the single arch, except that substantial scour occurred at the pier joining the two arches; i.e., at transects D and E (Fig. 3). For the double arch, inclusion of wingwalls and cutwaters moved the location of deepest scour to the arch centre (transects C and F).

At the outset of each experiment, choking caused flow depth to increase to a maximum amount of about 25mm at the single arch for the largest discharge used (0.05m3/s). Larger values, up to about 30mm, were measured for the double arch, due to the slightly smaller opening cross-sectional area. As scour commenced and the cross-sectional area of flow into and under the arches increased due to sediment transportation, choking slightly eased, but remained a feature of the scour flow field. Sediment erosion was deepest a short distance (50 to 75mm) downstream from the entrance corners as expected, owing to maximum contraction and eddy shedding (separation secondary flow effects). This decreased along the center of the barrel and produced a depositional mound downstream of the barrel. Observations showed that the presence of wing walls at 45o significantly reduced eddy formation, but measurements indicated that peak velocity of flow though the barrel of the arch was not significantly reduced by the wing walls (Byrne 2016).

The flume experiments showed that scour undermined the upstream corner of the arch’s footings where the velocity magnitude was greatest. Kerenyi et al. (2003) concludes the same result for scour morphology at bottomless culverts. The region of deepest scour coincides with the region of greatest velocity in the barrel, and the presence of separation eddies at the sharp entrance to the arch opening. A feature of scour at the double-arch bridge (representative of multi-span arch bridges) was the formation of deepest scour at the pier joining two arches (apex angle = 0o). At this location, the proximity of arch corners, and the associated presence of higher velocities and turbulence structures, caused the deepest scour. This scour was on average about 32% deeper than at the other upstream corners (the abutment corners) of the arches. For multi-span arch bridges, the locations of deepest scour were typically at the piers linking arches.

Maximum scour depth at the upstream corners of the arch abutments escalated with increasing flow discharge as Fig. 5 indicates, irrespective of structural form. The single- and double-arch bridges tested had footing depths of 45mm and 75mm. As expected, because of its greater obstruction of flow, the deeper foundation produced the deeper scour for both bridges. This trend with discharge was the same for both bridges, for the flow range used and coincides with well-published findings for clear-water scour at bridge abutments and piers (e.g., Sturm et al. 2011). Scour depth increased with increased water discharge, which boosted magnitudes of flow velocity, bed shear stress and turbulence vorticity turbulence structures generated in the vicinity of arch corners.

Fig. 5 also indicates that the values of scour depth were comparable for the single- and the double-arch over the tested range of foundation depths. When the foundations were shallow (45mm), the entire structure was undermined irrespective of bridge form, and the scour patterns were similar for the two bridges. At higher flow rates, the double-arch with the deeper foundation (75mm) and slightly smaller opening area had the largest scour. Flow through each arch of the double arch created larger flow resistance (and thus caused more flow backwater) owing to the larger solid boundary associated with the double arch. It was observed that a substantial deposition mound formed of transported bed material at the exit downstream of each arch. The amplitude or height of the mound increased as discharge increased. Measurements taken during the tests indicated, though, that the mound slowly migrated downstream, once equilibrium scour depth was reached within the arch. During the testing, it was noted that the rate of flow influenced the rate of migration.

Over the range of footing depths tested, the deeper footings produced larger values of maximum depth scour as anticipated. Scour was deepest at the abutment corners for the single arch and at the pier for the double arch. Fig. 6 indicates the data trends for both the single and double arches for the same maximum rate of flow (0.05m3/sec). The trends for both arch forms are the same, with the double arch producing slightly deeper scour owing to pier presence. For the latter arch form, deepest scour typically occurred at the pier. The scour depths asymptote to the maximum depth of scour that occurred when footing depth exceeded the depth of scour. The depths are almost equivalent, with only slight difference. In the case of the double arch, all four depths of scour are plotted. Fig. 6 includes a scour depth measurement at a scaled isolated pier when it was placed, without the adjoining arches, in a flow having the same approach velocity at the model entrance for a flow rate of 0.05m3/s. The resulting scour depth at the pier was 84% of the depth when the pier formed part of the double arch. Scour was deeper when the pier was an integral part of a series of arches, because then flow contraction was greater around the pier, thereby producing slightly larger magnitudes of flow velocity under choked flow conditions (Arneson et al 1998 and 2013, DMRB 2012).

In Fig. 6 the maximum scour depth at the sides of the pier was about 16% larger than at the leading corners of the abutments of the double arch for the test configuration. The relative narrowness of the pier (compared to the arch span), and the shedding of turbulence structured from both sides of the piers, caused the scour to always be slightly deeper at the pier than at the abutment corners. Therefore, the scour depth for the double arch exceeded the scour depth at the single arch at the lower flow range. However, when the footing depth exceeded the scour depth, the two arch forms tend to the same final depth of scour. When the scour depth exceeded the footing depth, flow continued scouring sediment from beneath the leading edge of the footing and attained an equilibrium condition whereby more flow passed through the scour zone. For increased footing depth, the observed scour approached closer to its maximum equilibrium depth, which happened when the footings extended to the full depth of the flume’s sediment recess. Consequently, the additional scour that occurred when the scour depth exceeded the footing depth decreased as footing depth increased. In other words, the gap beneath the footing became smaller as the foundation depth increased. Fig. 7 shows the scour locations at the single arch for a footing depth of 150mm and flow rate of 0.05m3/s.

**Traditional, Scour Countermeasures**

The traditional scour countermeasures (pier cutwater and abutment wingwall) were practically ineffectual in substantially reducing scour. Armour-stone placement through the barrel of the arch inhibited scour in the arch, but enabled flow to jet through the arch and erode the bed downstream. In brief, flow-choking by raising flow depth above the barrel of an arch diminished the mitigating effects of streamlining flow entry into the arch.

***Wingwalls***

At the lower flow rates, the maximum depth of scour reduced as abutment wall angle of the single arch increased from 0o to 67.5o, as Fig. 8 presents. This reduction in scour depth is largely attributable to the reduction in the maximum diameter and vorticity of the turbulence structures developed at the upstream corners of the arch. The reduction was observed and recorded with photographs (with dye injection) during testing. For wingwalls set at 22.5o and 45o, the scour-reduction effect was modest, with practically no effect for the two highest discharges. For the wing wall setting of 67.5o, wing wall mitigation of scour diminished from about 36% to 10% over the discharge range. The rapidly decreasing effectiveness of wingwalls at the higher discharges, for which choking increased, was due to the increased submergence of the arch crown. Submergence caused more flow to enter the arch barrel from above the wingwalls. These trends occurred also for the double-arch, whose data Fig. 9 presents. A repeat experiment conducted to check the variability of results (for the arch fitted with 45o wingwalls and subject to 0.05m3/s) produced essentially the same result for maximum scour depth (at location B) though the depth at center barrel (location C) was about 6mm deeper.

***Pier Cutwaters***

Observations showed that a pier cutwater streamlined the flow around a pier linking two arches, and thereby reduced the strength of turbulence structures formed as flow passed. Fig. 9 indicates for a pier, with footing depth of 75mm, that the use of the large cutwater markedly reduced scour depth at a single pier exposed to the two smaller flow rates. The maximum reduction in scour depth was about 45% for the big cutwater when the flow rate was 0.03m3/s. The smaller cutwater had essentially no effect in reducing scour depth. Also, as water discharge increased, the effect of the larger cutwater diminished. This finding agrees with the outcome of tests done with other footing depths for the pier (Fig. 6). The influence of pier streamlining diminished over the range of discharges tested because the greater choking of approach flow at the higher discharges (especially at 0.05m3/s) further raised the water elevation at the arch entrance. Crown submergence greatly diminished the utility of cutwater streamlining, because more water was drawn from the water-depth region directly above the arches. For the highest discharge, 0.05m3/s, the large cutwater reduced scour depth by only 3%.

***Armor Stone***

Though only one experiment was conducted, it showed that the armor stone prevented scour at the entrance corners of the double arch and inhibited scour along the barrel of each arch. This finding concurs with Kerenyi et al. (2007), who showed that stone armouring substantially reduces scour at the entrance and within bottomless culverts. However, the present experiment also showed that flow issuing from the arches scoured the bed downstream of the double arch. A form of head-cutting scour began at the downstream end of the armor stone and caused the layer of armor stone to successively fall apart. Field experience during 2015 (DfI, McRobert personal communication, 2015) involving the failure of armour stone downstream of a masonry arch bridge corroborates this finding and shows that stone immediately downstream of the bridge must be sufficiently large to withstand the high-velocity flow passing through the bridge opening for the choked flow condition.

**Conclusions and Recommendations**

Masonry arch bridges on shallow footings are highly vulnerable to scour under extreme weather events, thus prompting the need to consider effective scour countermeasures. This technical note, summarizing a more extensive study, shows thattraditional wing walls and pier cutwaters (flow streamlining) have only a moderate effect in reducing the maximum depth of scour at arch bridges subject to choked approach flow. Furthermore, armoring of the bed through the bridge opening shifts the scour problem downstream of the bridge.

To preserve the masonry arch bridges, the writers recommend that bridges be strengthened by underpinning foundation footings. Underpinning involves the transfer of the foundation bearing stresses to a deeper stratum, which will not be impacted by bed scour under choked-flow conditions. This approach is feasible when suitably strong foundation material, such as rock, can be economically reached; e.g., as Fig. 1 illustrates. Sheet-piling can be driven around the foundation of an arch to protect the foundation when suitably bearing stratum is located at depth. However, issues with headroom clearance can be significant in applying this method, as can vibration weakening of pilings (DfI, McRobert personal communication 2015). At sites where the local terrain is suitable, bridge owners should explore flow-bypassing by means of relief culverts. Flow by-passing involves using relief culverts to divert part of flood flows and sized to prevent flow from over-topping the bridge. Should bridge openings be armored, the channel downstream of the bridge must be armored and some form of energy dissipation structure possibly added downstream of the bridge to prevent erosion and possible head-cutting of the channel downstream of the bridge. Fig. 10 illustrates a waterway failure where inadequate attention was given to armoring downstream of an arch bridge.

**DATA AVAILABILITY STATEMENT**

Some or all data, models, or code generated or used during the study are available from the corresponding author by request. (Scour depths, flow depths and velocities, sediment size).

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