Hydraulics of scour in the vicinity of a FlexiArch bridge

Prabuddha Sathurusinghe, Gerard Hamill, Su Taylor, Desmond Robinson
Queen's University, Belfast, United Kingdom
sprabuddha01@qub.ac.uk, g.a.hamill@qub.ac.uk, s.e.taylor@qub.ac.uk, des.robinson@qub.ac.uk

ABSTRACT: Floods and scour are major causes of failure of bridges and with the increase in short-duration and high intensity rainfall events the occurrence of such failures is increasing. While standard free flow scour at bridge piers is an extensively researched area, the increased scour that occurs when the upstream water level is at or above the crown of an arch bridge (*pressure-flow scour*) is comparatively less well studied. As the frequency and magnitudes of floods increase, more bridges may be at a higher risk of being subject to pressure-flow scour.

A modern masonry arch bridge system called the 'FlexiArch', that does not involve any mortar or steel reinforcement and can be rapidly constructed on site, has been developed by Queen's University Belfast. The behaviour of the FlexiArch bridge system under developing scour has not been studied previously. This paper will present a series of experiments aimed at modelling pressure-flow on a scaled model of the FlexiArch bridge with a view to developing and understanding of the scour – bridge interactions.

KEY WORDS: pressure-flow scour; FlexiArch; scaled model; particle image velocimetry; ultimate scour.

1 INTRODUCTION

Serious consequences are associated with bridge failures, especially with collapse. For example, 59 fatalities occurred when the Hintze Ribeiro bridge at Entre-os-Rios, Portugal collapsed in 2001 [1]. 158 casualties were caused by the collapse of I-35W bridge in Minneapolis, USA in 2007 [2]. In the same year, the Tuojiang Bridge in Hunan, China collapsed resulting in 89 casualties [3]. These failures highlight the absolute importance given to safety in the design and maintenance of bridges. Better understanding of the action of the phenomena that can cause damage to bridges, such as bridge scour, can help inform the design process and the monitoring and maintenance of bridges.

Scouring, in the fluvial and estuarine environment, is the process of removing channel bed or bank material by channel flow. It deepens the channel in the vicinity of bridges and has the potential to compromise their stability via the removal of foundation support material. Scour can occur gradually over a long time or in a short duration during a flood event [4]. The failure of Hintze Ribeiro bridge and the collapse of part of Malahide viaduct in County Dublin in 2009 have been attributed to scour at bridge piers [1, 5]. In fact, floods and associated scour are the major causes of failure of bridges [6, 7]. 58% of 1502 reported bridge collapses in USA in the period 1966 – 2005 has been due to scour [8]. In the UK rail network there have been 138 recorded scour related bridge failures with 15 casualties in the period 1843 – 2013 [9]. The level of threat posed by scour on bridge safety has attracted much research towards understanding, estimating, monitoring and combating scour (Ref. [10-15] and therein). This has led to the development of scour manuals that provide guidance on those aspects [4, 16, 17]. Much of the work carried out on bridge scour has been on scour due to free flow conditions.

1.1 *Pressure-flow scour*

Greater depths of scour will occur in extreme flow cases where the upstream water surface is above the low chord of a bridge deck or the crown of a masonry arch bridge i.e. "pressure-flow" [18]. In this condition the flow is vertically contracted as it passes underneath the bridge, and the velocity and scour potential are increased. Two cases of pressure-flow are possible where the arch barrel may flow full (drowned orifice flow) or only partially full (sluice gate flow). Less work has been carried out on this type of scour [19] compared to free flow scour. Most studies that report on pressure-flow scour at bridges were scaled flume experiments with rectangular bridge openings spanning the flume width (flat-deck) and with [18, 20] or without piers [19, 21-23].

The severe floods that the UK experienced in recent years caused collapse of or damage to many bridges – including bank erosion and other forms of damages [24-26]. Some of the extreme precipitation events and the resulting extreme river flows were among the highest recorded, especially the events in December 2015 which caused peak flows in many rivers and daily maxima in several regions to exceed their previous highest [27]. As the peak magnitude as well as the duration of a flood directly influences the severity of scour at bridges, the risk of scour could be exacerbated in the future as changes in climate are expected to result in increased frequency of intense precipitation in many areas of the world [28, 29] and higher discharge in rivers in some areas [30]. With a probable increase in the peak river flows of some rivers in the UK [29] expected as a consequence of climate change, the UK Climate Change Risk Assessment Evidence Report states that more research is needed to assess the impact of scour on bridges and pipelines due to altered peak discharge of future riverine floods [31]. Therefore, the risk of some bridges (such as short span arch bridges which constrict the flow more than flat-deck bridges) being subjected to pressure-flow scour could be increasing and warrants further investigation in to the effect of such flows on bridge structures.

1.2 FlexiArch Bridge system

The most common type of bridge in continental Europe, the UK and Ireland is the masonry arch bridge [32, 33]. About 40% of the bridges in UK's road and rail network are masonry arch bridges and most were built between the latter half of the 19th century and the start of the 20th century [34, 35]. The majority (80%) of the European railway arch bridge stock is short span (below 5m) [36]. These unreinforced structures are reported to be highly durable and require less maintenance compared to other types of bridges [37, 38]. But steel and reinforced concrete bridge construction led to a gradual decline of the masonry arch construction as the traditional construction of masonry arches consumed much more time.

The appealing attributes, such as durability and aesthetics of the unreinforced masonry arches led to the development of a modern masonry arch bridge system - 'FlexiArch' which has been implemented in the UK, Ireland [39, 40] and globally [41]. The system is similar in geometry to traditional masonry arch bridges but does not involve any mortar or steel reinforcement as employed in other modern arch bridge systems. The system consists of arch rings that arrive at the site as flat packs of precast concrete voussoirs connected by a flexible polymeric reinforcement. The rings naturally assume the designed arch shape (based upon the dimension of the voussoirs) once lifted and placed on skewbacks (or seating unit). Therefore, centering is not required in the construction of this system. Hence it requires much less labour and can be rapidly constructed on a site. The behaviour of this new type of bridge under scour has not been studied previously. The absence of mortar would mean that scour of mortar, which has been reported as a reason for some cases of masonry arch bridge failures [24], would not occur which means that the FlexiArch system is already more inherently safe from pressure-flow scour than standard masonry arch structures.

1.3 Pressure-flow scour at arch bridges

As there is a reduction in the width of the arch opening with rising stage, these bridges present larger obstructions to flow than flat-deck bridges that cause larger afflux and are hence susceptible to pressure-flow [42]. To the best of authors knowledge, no model to predict maximum scour from pressure flow conditions in arch bridges is to be found in literature.

Highlighting the lack of advice on pressure-flow scour in UK highway bridge design standards, Ryan et al. [43] carried out flume experiments on single span arch bridge models to understand the effects of pressure flow. They studied the velocity profile of the flow, the extent of scour and variation of maximum scour and afflux with time. The maximum scour was found to be in the upstream face of the abutments. This contrasts with scour under single span flat-deck bridges where maximum scour occurs downstream of the bridge opening [19]. Theoretical scour depth predicted by flat-deck bridge pressure-flow scour models were found to be unsatisfactory in estimating pressure-flow scour at arch bridges. It should be noted that contraction and local abutment scour appear not to be considered in the comparison. Even though the velocities were measured, no explanation for the causes of the scour nor reasons for the difference between measured and theoretical scour were conjectured as conclusions of the study.

To study the evolution of scour and evaluate the effectiveness of traditional hydraulics-based scour countermeasures against scour at short-span masonry arch bridges, Solan et al. [44] carried out clear water scour experiments on single and dual-span arch bridge models under pressure-flow conditions. The maximum scour for single arch was at the upstream arch corners while for dual span arch this was at the central pier. The upstream foundations were found to be undermined and that the maximum scour depth would increase with footing depth and flowrate. They also observed that introducing scour counter measures shifted the location of maximum scour.

Ebrahimi et al. [45], conducted clear-water pressure flow experiments on arch bridge models and measured the final scour and variation of hydrodynamic pressure on the faces of the abutments. While the location of maximum scour is in line with those of Ryan et al. [43], comparing the measured maximum scour with the sum of theoretical pressure-flow scour with contraction and local scour at abutments (which were not included in Ryan et al. [43]), they suggest that the total scour at an arch bridge may be higher than at a flat-deck bridge.

1.4 Aims and Objectives

Better understanding of the hydraulics behind pressure-flow scour phenomena and the structural response of bridges to developing scour would be critical input in the assessment or design of masonry arch or FlexiArch bridges. In real bridges, the developing scour and the structural response would interact, and the consequent nature of this interaction is what would instigate failure. To date, all previous experimental work has separated the scour phenomena from the structural behaviour of the bridge [43-46]. Therefore, research is underway at Queen's University Belfast with the overall aim to conduct a holistic study of pressure-flow scour and bridge response of FlexiArch bridges to address this gap in knowledge. This will be achieved by developing the outcomes from the following objectives:

- The extent and causes of bed scour at a FlexiArch bridge will be investigated using experimental modelling.
- The influence of pressurised flow on the FlexiArch bridge systems, and the additional scour resulting from that flow will be determined.
- The structural response to scour will be investigated using both numerical modelling and laboratory investigations.
- Measurements of scour and structural response will be achieved using laser and digital image analysis systems.

2 METHODOLOGY

This research is using enhanced monitoring of the development of pressure-flow scour under single span FlexiArch bridges.

The experiments are carried out in the 18.8 m long, 0.75m wide and 0.75 deep flume in Hydraulics lab in Queen's University Belfast. The horizontal stainless-steel flume has a test section with a clear side in the middle. The test section as seen in Figure 1 shows the test set-up with a uniform sediment bed spanning the whole width of the flume and is truncated by uPVC false beds on either side along the flow direction. The sediment bed supports the FlexiArch bridge model at the centre of the flume and can extend sufficiently to either side of the model as be representative of a typical bridge.

The flume is equipped with a pump that can pump up to 45 l/s. The flowrate is controlled manually and is measured using an electromagnetic flow meter with a resolution of 0.01 l/s. The flow depth is controlled by a tailgate. The pump is not capable of recirculating sediments and a sediment trap downstream of the false bed would capture the sediments that would not settle within the test section.

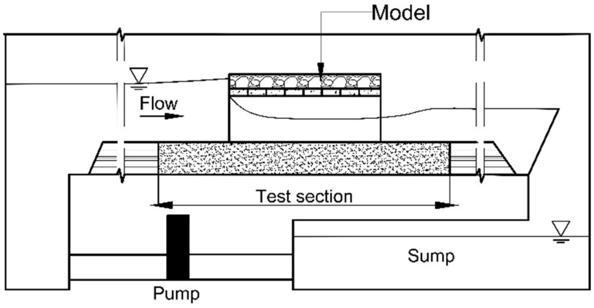

Figure 1. Schematic of the flume and test setup (not to scale) and instrumentation not shown

2.1 *Bridge model*

The experiments are based on a 1:10 scaled model of a typical FlexiArch bridge (as seen in schematic in Figure 2 and in Figure 3) with a span of 5 m and a rise of 2 m. Unlike earlier pressure-flow scour research the arch rings and the skewbacks are made of a 1:10 scaled concrete while the backfill will also be a 1:10 scaled version of Type 3 (open graded) Unbound Mixture [47]. The spandrels are represented as Perspex so that the movements of the backfill can be observed. This research aims to assess the fundamental fluid/structure interaction of this bridge in its most vulnerable scenario. This will occur when the foundations are either shallow or are undermined so that no vertical reactions or thrust is carried by them. Therefore, the initial testing is with the FlexiArch supported only on the skewback foundation. The authors acknowledge that foundations will both influence the scour at the bridge as well as its structural behaviour. Therefore, to compare the behaviour under this critical scenario with a real implementation, foundations will be studied at a later stage in the research. In all of the tests conducted the bridge model will be placed perpendicular to the flow.

Two sizes of uniformly graded (coefficient of uniformity, *Cu* < 3) silica sand will be used in the study. The particle size distribution analysis of the sediments is being carried out.

The dominant factors that cause the pressurised scour to occur will be investigated by observing velocity profile in the vicinity of the arch inlet using laser particle image velocimetry. A laser rangefinder with a manufacturer stated accuracy of ±1 mm will be assessed for the purpose of monitor the maximum scour under developing scour.

2.2 *Planned experiments*

Through a series of tests in which flow rate, flow depth through the arch and sediment sizes are controlled and the resulting velocity distributions at the arch inlet measured using laser particle image velocimetry (PIV), the relationship between scour and flow conditions and the dominant factors that cause the pressure-flow scour to occur will be investigated.

The maximum scour occurring over different free flow and pressure-flow conditions will be monitored through a laser distance measurement sensor and ultimate scour profile measured through digital image analysis systems to study the relationship between free flow and pressure-flow scour.

Ultimately, the effect of the developing scour on the structural behaviour of the bridge will be investigated through monitoring the displacements of the arch through vision based displacement measurement [48] under both flow and varying load conditions to simulate vehicle loading capacity.

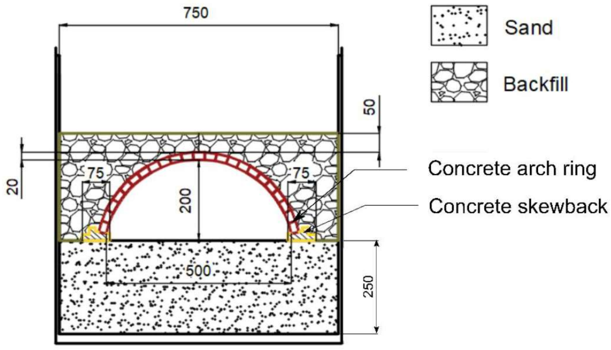

Figure 2. Cross-sectional schematic of the single span FlexiArch bridge model (dimensions in millimetres)

Figure 3. Arch ring of the 1:10 scale model (Photo by Evdokia Gyftaki)

3 CONCLUSIONS

Pressure-flow scour at a FlexiArch bridge, and the bridge response to the developing scour, will be investigated in this study. The relationship between scour and flow conditions and the dominant factors that cause the pressurised scour to occur, and their impact, will be investigated. Also, relationships will be developed to predict the increased scour due to pressurized flow compared to normal river flow. In the long run, the structural response of FlexiArch bridge to scour will be investigated using both numerical modelling and laboratory investigations. It is expected that the outcomes of this study would provide basic understanding of the hydraulics of scour at FlexiArch bridge and the structures response to the developing scour. Such an understanding would allow to identify when critical levels of scour has occurred as well as to identify suitable countermeasures to scour.

ACKNOWLEDGMENTS

The first author acknowledges the funding from the UK's Engineering and Physical Sciences Research Council (EPSRC) under grant EP/R513118/1. Special thanks are due to Queen University's Mr. Desmond Hill for his workmanship and Ms. Evdokia Gyftaki for the work on the scaled voussoirs.

REFERENCES

[1] J. J. Sousa and L. Bastos, *Natural Hazards and Earth System Sciences*, 13, 3, 659-667, 2013.

[2] S. Hao, *Journal of Bridge Engineering*, 15, 5, 608-614, 2010.

[3] F. Y. Xu, M. J. Zhang, L. Wang, and J. R. Zhang, *Journal of Performance of Constructed Facilities*, 30, 5, 04016030, 2016.

[4] A. M. Kirby, M. Roca, A. Kitchen, M. Escarameia, and O. J. Chesterton, *Manual on Scour at Bridges and Other Hydraulic Structures*, 2nd ed. CIRIA, 2015.

[5] RAIU (Railway Accident Investigation Unit), 'Malahide Viaduct Collapse on the Dublin to Belfast Line, on the 21st August 2009', RAIU, Blackrock, Ireland, 2010–R004, 2010.

[6] K. Wardhana and F. C. Hadipriono, *Journal of Performance of Constructed Facilities*, 17, 3, 144-150, 2003.

[7] L. Deng, W. Wang, and Y. Yu, *Journal of Performance of Constructed Facilities*, 30, 2, 1-13, 2016.

[8] J. L. Briaud, L. Brandimarte, J. Wang, and P. D'Odorico, *Georisk*, 1, 2, 77-88, 2007.

[9] Rail Safety & Standards Board, 'Impact of scour and flood risk on railway structures', 2004.

[10] B. W. Melville and S. E. Coleman, *Bridge scour*. Water Resources Publication, Highlands, Ranch, Colorado, USA, 2000.

[11] R. Ettema, B. W. Melville, and G. Constantinescu, *Evaluation of Bridge Scour Research: Pier Scour Processes and Predictions*. The National Academies Press, Washington, D.C., 2011.

[12] T. W. Sturm, R. Ettema, and B. W. Melville, *Evaluation of Bridge-Scour Research: Abutment and Contraction Scour Processes and Prediction*. The National Academies Press, Washington, DC, 2011.

[13] J. Briaud *et al.*, "Summary report: The Sricos–EFA Method," ed: College Station: Texas A&M University, 2011.

[14] J.-L. Briaud *et al.*, 'Realtime monitoring of bridge scour using remote monitoring technology', Texas Transportation Institute, 2011.

[15] L. Deng and C. S. Cai, *Practice Periodical on Structural Design and Construction*, 15, 2, 125-134, 2010.

[16] L. A. Arneson, L. W. Zevenbergen, P. F. Lagasse, and P. E. Clopper, 'Evaluating Scour at Bridges', Federal Highway Administration, U.S. Department of Transportation, FHWA-HIF-12-003 HEC-18, 2012.

[17] P. Lagasse *et al.*, 'Bridge scour and stream instability countermeasures: experience, selection, and design guidance: Volume 1', National Highway Institute (US), 2009.

[18] L. A. Arneson and S. R. Abt, *Transportation Research Record*, 1647, 1, 10-17, 1998.

[19] B. W. Melville, 'Pressure-flow scour at bridges', in *Scour and Erosion: Proceedings of the 7th International Conference on Scour and Erosion*, Perth, Australia, 2015.

[20] I. Carnacina, S. Pagliara, and N. Leonardi, *River Research and Applications*, 35, 7, 844-854, 2019.

[21] D. A. Lyn, *Journal of Hydraulic Engineering*, 134, 7, 1015-1020, 2008.

[22] E. R. Umbrell, G. K. Young, S. M. Stein, and J. S. Jones, *Journal of Hydraulic Engineering*, 124, 2, 236-240, 1998.

[23] S. Y. Kumcu, *Canadian Journal of Civil Engineering*, 43, 4, 334-342, 2016.

[24] J. Collins, M. Steele, D. Wilkes, D. Ashurst, and B. Harvey, 'Investigation into highway bridge damage and failures during the November 2009 Cumbria flood', in *Forensic Engineering: Informing the Future with Lessons from the Past: Proceedings of the Fifth International Conference on Forensic Engineering organised by the Institution of Civil Engineers and held in London, UK, 16-17 Apr*, London, United Kingdom, 2013.

[25] R. Mathews and M. Hardman, *Proceedings of the Institution of Civil Engineers-Forensic Engineering*, 170, 4, 165-178, 2017.

[26] Department for Infrastructure, 'Review of North West Flooding August 2017', 2018.

[27] T. Marsh, C. Kirby, K. Muchan, L. Barker, E. Henderson, and J. Hannaford, *The winter floods of 2015/2016 in the UK-a review*. Centre for Ecology & Hydrology, Wallingford, United Kingdom, 2016.

[28] Z. W. Kundzewicz *et al.*, *Hydrological Sciences Journal*, 59, 1, 1-28, 2014.

[29] K. Humphrey *et al.*, 'UK Climate Change Risk Assessment Evidence Report: Chapter 1, Introduction', Report prepared for the Adaptation Sub-Committee of the Committee on Climate Change, London, 2016.

[30] H. Madsen, D. Lawrence, M. Lang, M. Martinkova, and T. R. Kjeldsen, *Journal of Hydrology*, 519, 3634-3650, 2014.

[31] R. J. Dawson *et al.*, 'UK Climate Change Risk Assessment Evidence Report: Chapter 4, Infrastructure', Report prepared for the Adaptation Sub-Committee of the Committee on Climate Change, London, 2016.

[32] C. Melbourne, J. Wang, and A. K. Tomor, *Proceedings of the Institution of Civil Engineers: Bridge Engineering*, 160, 2, 81-87, 2007.

[33] Z. Orbán, 'UIC Project on assessment, inspection and maintenance of masonry arch railway bridges', in *Proceedings of the 5th International Conference on Arch Bridges*, Madeira, Portugal, 2007.

[34] J. Page, *A guide to repair and strengthening of masonry arch bridges*. Transport Research Laboratory, 1996.

[35] R. J. Bridle and F. Sims, *Proceedings of the Institution of Civil Engineers - Engineering History and Heritage*, 162, 1, 39-49, 2009.

[36] Z. Orbán, 'Assessment, reliability and maintenance of masonry arch railway bridges in Europe', in *Proceedings of Arch Bridges IV–Advances in Assessment, Structural Design and Construction*, Barcelona, Spain, vol. 2004.

[37] L. D. McKibbins, C. Melbourne, N. Sawar, and C. S. Gailard, *Masonry arch bridges: condition appraisal and remedial treatment*. CIRIA, London.

[38] Highways England, 'CD 376 - Unreinforced masonry arch bridges', *Design Manual for Roads and Bridges, Volume 2, Section 2*, 2020.

[39] S. E. Taylor, D. Robinson, A. E. Long, and A. Gupta, 'Testing of a novel flexible concrete arch system', in *Innovations in Bridge Engineering Technology : Selected Papers, 3rd NYC Bridge Conf., 27-28 August 2007, New York, USA*, K. Mahmoud Ed., Taylor & Francis, Leiden, 2007.

[40] A. E. Long, D. McPolin, J. Kirkpatrick, A. Gupta, and D. Courtenay, FlexiArch: from concept to practical applications, *The Structural Engineer*, 10-15, 2014.

[41] Macrete Ireland Ltd. 'FlexiArch Projects', http://www.macrete.com/flexiarch-flexiarch-projects/ (accessed 08 May, 2020).

[42] D. Ryan, R. Ettema, B. Solan, G. Hamill, and J. McRobert, 'Stability of short-span bridges subject to overtopping during floods: case studies from UK/Ireland and the USA', in *E-proceedings of the 36th IAHR World Congress*, The Hague, Netherlands, 2015.

[43] D. Ryan, G. A. Hamill, J. McRobert, and W. Smith, 'The hydraulics and resulting bed scour within the vicinity of Submerged Single Span Arch Bridges', in *Proceedings of the Civil Engineering Research in Ireland*, Belfast, United Kingdom, 2014.

[44] B. Solan, R. Ettema, D. Ryan, and G. A. Hamill, *Journal of Hydraulic Engineering*, 146, 2, 06019019, 2020.

[45] M. Ebrahimi *et al.*, 'Experimental investigation of scour and pressures on a single span arch bridge under inundation', in *Proceedings of the 7th IAHR International Symposium on Hydraulic Structures, ISHS 2018*, Aachen, Germany, 2018.

[46] P. Zampieri, F. Faleschini, M. A. Zanini, and N. Simoncello, *Engineering Structures*, 156, 363-374, 2018.

[47] Highways England, 'Series 800 Road Pavements — Other Hydraulically Bound Mixtures', *Manual for Contract Documents for Highwayworks Volume 1*, 2016.

[48] D. Lydon, M. Lydon, S. Taylor, J. M. Del Rincon, D. Hester, and J. Brownjohn, *Mechanical Systems and Signal Processing*, 121, 343-358, 2019.