An Assessment of the Suitability of Scour Estimation Methodologies for a Northern Ireland Scour Risk Assessment.

Pearce Braiden & Connor O'Higgins
School of Natural and Built Environment, Queens University Belfast, Northern Ireland

Myra Lydon
Lecturer, School of Engineering and Science, University of Galway, Ireland

Kristopher Campbell
Head of Highway Structure Unit, Department of Infrastructure, Northern Ireland

ABSTRACT: Scour risk estimation is a complex discipline given the inherent natural variability of watercourses and bed materials. The majority of risk assessments are based initially on qualitative measures followed by the estimation of maximum(equilibrium) scour depth using semi-empirical equations. The semi-empirical methods are limited by the flume conditions and associated limited scale they were developed in and the bed material that they simulated. The principal objective of this research is to provide an objective view on existing scour risk assessment methodologies with the intention of providing an easily practicable method of estimating scour risk that represents scour processes well in the context of Northern Ireland. The research will document the application and results of various existing methodologies on three Northern Irish bridges.

Fifty three percent of the Northern Ireland bridge stock are historic masonry arch bridges (Campbell et al, 2020). The combination of Northern Ireland's ageing bridge stock and limited infrastructure budget culminates in distinctive challenges for asset managers. Asset managers must effectively allocate resources and capital to bridges deemed to be of most critical concern. Asset managers are constrained by the fact that masonry arch bridges form an integral part of the aesthetic of many towns and therefore their replacement is prohibited by heritage conservation laws. (McKibbins et al, 2006). Of particular concern for historic bridges across watercourses is the impact that increased flood frequency and intensity will have upon the bridges. Global changes in climatic patterns are expected to have a profound impact upon existing river courses. Increased flow in rivers will inevitably lead to changes in the river channel including erosion of the bed material, otherwise known as scour. Scour is caused by shear stresses imposed on riverbeds and banks by changes in flow conditions or sediment transport. Scour undermines the integrity of bridges as it removes the soil that provides lateral pressure to the foundations.

Scour is the leading cause of bridge failures in the last 100 years in the UK (Network Rail, 2019). Scour has been blamed for many of the bridge failures, a notable failure in close proximity to Northern Ireland was the Malahide aqueduct collapse (2009). Historical bridges are particularly prone to scour failures as many are not documented well or the documentation is no longer available, making structural analysis difficult. Masonry arch bridges are considered at risk as many have shallow footing foundations of unknown depth and shape. Most masonry arch bridges were built to withstand considerably lower peak flows than those which have become common within the United Kingdom and Ireland. The combination of a lack of knowledge on the bridges and increasing forces on the riverbed, pose a significant level of uncertainty on bridge safety.

Scour risk estimation is a complex discipline given the inherent natural variability of watercourses and bed materials. The majority of risk assessments are based initially on qualitative measures followed by the estimation of maximum(equilibrium) scour depth using semi-empirical equations. The semi-empirical methods are limited by the flume conditions and associated limited scale they were developed in and the bed material that they simulated. Most methods are derived from flume testing using uniform quartz sands. When compared to reality most empirical relationships are known to over-predict scour by considerable margins (NCHRP, 2011).

Scour is a dynamic natural phenomenon that is well documented, however globally there is a lack of industry ready tools for the network wide assessment of scour and there is currently no framework for scour risk assessment in Northern Ireland.

The principal objective of this research is to provide an objective view on existing scour risk assessment methodologies with the intention of providing an easily practicable method of estimating scour risk that represents scour processes well in the context of Northern Ireland. The research will document the application and results of various existing methodologies on three Northern Irish bridges. To perform scour assessments the author completes exploratory field work to compile critical data and bridge properties. The analysis section of this research will focus on analysing the criticality of the parameters associated with scour assessment to ascertain which parameters should be of primary concern to asset managers.

1. BRIDGE SCOUR RISK METHODOLOGIES

Many risk assessment methodologies exist for the assessment of scour risk to bridges, primary examples include the method adopted by Highways England (BD97/12) and EX2502 adopted by Network rail (Sasidharan et al., 2021). No universal scour assessment exists and methods vary greatly by region and practitioner. Choosing which scour assessment to use can be especially difficult for multiple reasons, including the availability of accurate data and the lack of clarity regarding which methods are best suited to each case. The majority of scour risk assessments in literature and practice are comprised of an initial qualitative assessment followed by a quantitative assessment of expected maximum scour depth. A risk ranking is given at both stages commonly and only if a bridge is deemed scour susceptible in the qualitative assessment is it considered fruitful to complete a quantitative assessment.

This research reviews three independent risk methodologies of completing quantitative scour risk assessments. The three methodologies are aptly named Design Manual for Roads and Bridges BD97/12 (BD97/12), Texas DOT SRICOS-EPA (TDOT) and Florida DOT Sheppard-Melville (FDOT) after their promoting authorities. The three methodologies aim to calculate the expected total scour depth at a bridge using geometry, bed material and flow characteristics. A notable omission is the guidance of EX2502 (HR Wallingford, 1992), the EX2502 guidance is similar to BD97/12 but was not deemed to be as suitable as BD97/12 as it required much greater volumes of inputs, especially more macro inputs relating to the river character, such as flashiness. EX2502 is also limited by a highly empirical scour depth calculation which may not reflect scour processes effectively when compared to other methods (NCHRP, 2011).

This research will focus on the key objective of specifying a methodology to help asset managers identify the most scour susceptible bridges using minimal on-site investigation and previous knowledge.

This research omits the important and invaluable work regarding the temporal variation of scour as it is still considered rudimentary and beyond the scope of a routine maintenance check. See (Pizarro et al., 2020) for an effective summary of the main time dependent scour depth prediction formulae. The estimation of scour depth with time is wrought with uncertainty, therefore is not practicable under the circumstances (NCHRP, 2011).This paper reviews three independent risk methodologies of completing quantitative scour risk assessments. The three methodologies are aptly named DMRB, TDOT and FDOT after their promoting authorities. The 3 methodologies aim to calculate the expected equilibrium scour depth at a bridge using geometry, bed material and flow characteristics. The three methodologies reviewed in this paper were chosen after a thorough review of existing literature on the topics of scour estimation and risk assessments. All three methodologies approach scour estimation in a different manner and this paper will outline the merits and limitations of each calculation sequence.

2. DMRB BD97/12

2.1. Overview

The Design Manual for Roads and Bridges (DMRB) advises the use of BD97/12 'The Assessment of Scour and Other Hydraulic Actions at Highway Structures' guidance for scour risk assessments in the UK. The DMRB methodology is widely implemented and regarded as the primary guidance in UK scour problems. BD97/12 is used commonly, however, is limited in its scope and is advised to be supplemented by the extensive CIRIA c742 guidance (Kirby et al., 2015). BD97/12 is based on assigning a risk rating to individual bridges. The risk rating is derived from a chart of relative scour depth vs a priority factor that accounts for bridge use, characteristics and topography.

A limitation of all the methods in this paper is the assumption that natural scour will have no net impact on the bed level. This is not realistic however limited literature is available on the topic and in the interest of keeping the guidance simple and practicable it is a fair assumption. Natural scour is poorly understood when compared to the constriction and local pier scour components which can be modelled in laboratory conditions. Natural scour is dependent on numerous factors from channel width to flow turbidity and bed material composition.

The impact of floodplains is difficult to quantify. This is problematic as the ratio of channel flow to floodplain flow is dependent on vegetation, topography and other site-specific factors. BD97/12 uses equations to apply factors to the upstream flow depth (Y_u) and velocity (V_u) to ascertain a representative flow depth (Y_{fp}) and velocity (V_{fp}) in a compound channel.

A considerable limitation of the BD97/12 method is the omission of riverbed properties, the riverbed geomaterials are of primary importance in scour problems. Having reviewed three independent calculation methodologies, it is obvious that the approach to scour estimation is as variable as the phenomena itself. Each methodology showed advantages over the others. The methods were primarily reviewed using two criteria; the ability of a calculation method to represent scour phenomena in an intuitive way, and the second, how practicable is the methodology to a bridge inspector. The following points highlight the benefits and limitations of each method in relation to the aforementioned criteria.

3. REVIEW AND COMPARISON OF METHODS

3.1. DMRB BD97/12

- Simple approximations make this method easily practicable. This method makes no claim to be a highly accurate estimation but rather an indication, it fulfils this objective.
- The omission of riverbed material properties limits the reliability of results. The omission

of geomaterial erodibility leads to the conclusion that all soils scour to the same depth for given geometric and flow conditions. One would expect that highly erosion resistant soils would lead to much smaller maximum scour depths than soils with low erosion resistance. This is especially important given that the assessment flow is most likely going to occur in short durations.

- The use of a priority factor is valuable as it quantifies the importance and history of the bridge. **Error! Reference source not found.** Provides a simple and effective tool for practitioners.

3.2. TDOT

- The erodibility of geomaterials is well represented in easily understood charts. Briaud et al has focused on making a complex procedure simple through the use of extensive factors and charts.
- TDOT attempts to quantify abutment scour using a combination of pier and constriction scour principles in line with the recommendations of (Sturm et al., 2018).
- The method may be limited in its application to Northern Irish rivers as the method is validated for Texas rivers which are likely to be characteristically different. Northern Irish rivers are likely to exhibit different bed properties and likely older infrastructure among other differences.
- The methods are more difficult to understand, therefore may not be considered as practicable as the DMRB methods.

3.3. FDOT

- The FDOT method is widely regarded as a premium method that has focused on improving the limitations of previous formulae, while also making formulae that are easily adapted in the future.
- The Sheppard-Melville method isn’t constrained by the empirical formulae of other authors due to the use of non-dimensional parameters that reflect scour processes.
- The Sheppard-Melville method gives a good estimation of scour at wide piers (Ettema et al., 2017). This was a limitation of many prior methods.
- The methods tend to include more calculations than the DMRB methods, however, are considered more thorough and representative of scour processes (NCHRP, 2011).

The methodologies share common limitations that stem from the nature of semi-empirical equations as they are based on idealised conditions in flumes. The methods become limited in their capacity for accurate estimation of scour depth when extended beyond the parameters and data range upon which they are based (Choi, 2016).

Each methodology calculates the components of scour in varying ways, however, are mainly bounded on the same principles, that a threshold of motion exists. Some methods incorporate the threshold of motion into their calculations, while others assume the motion to have already began, thus warranting a scour assessment. Each scour calculation component provides different challenges and limitations.

3.4. General Limitations

Each methodology has its own limitations; however, some limitations are prevalent in all the methods. The first being the exclusion or limited knowledge of the armouring effect in which the larger grains protect the bed against shear, limiting scour. This problem is manifested well in flume tests that are exclusively reliant on uniform sediments (FDOT, 2005).

(Raudkivi, 1986) completed a series of test comparing scour at non uniform and uniform sediments, the results were that for both live-bed and clear-water scour, scour is considerably lower in non-uniform sediments. In live-bed conditions scour exhibited 30% lower equilibrium depth in non-uniform bed material.

Another limitation of most formulae is the use of clear-water conditions to simulate all conditions, this is not representative of reality. One concern when live bed sediment transport is neglected is the fact that studies have shown that in many cases the presence of suspended fine sediment reduces the drag force exerted on the bed by the flowing water. Increases in turbidity can greatly reduce the drag coefficient on the bed(Thompson et al., 2006). Studies by Sheppard (2006) determined that even small concentrations of suspended fine sediment cause reductions in bed shear stress and local scour depth.

A practical limitation of scour calculation is the omission of the effects of natural degradation and deposition in the channel. This is difficult to predict in low density soils.

When it comes to the applicability of the scour methodologies to Masonry Arch bridges, this cannot be confirmed given that no formulae have yet to account for the geometric characteristics of this type and shape of bridge (Solan et al., 2019). Naturally as flow depth increases at a masonry arch bridge, greater constriction is required to facilitate flows. A feature of masonry arch bridges is the occurrence of approach-flow choking which is brought about by the shape of the bridges (Solan et al., 2019). The duration of assessment flood flows creates uncertainty for the practitioner assessing a bridge for scour risk. Commonly the flood flow rates used to assess the risk to bridges are chosen based on the largest flood according to a growth curve. This approach may yield over estimation of scour risk as flood flows tend to be low duration events that are not long enough for the scour equilibrium depth to be reached (Choi, 2016).

4. DATA COLLECTION METHODS

Every bridge has a different geometric profile and velocity distribution for a given flow rate. Without an understanding of how the flow distributes in a channel, it is not possible to do a scour risk assessment. To complete a scour assessment a variety of inputs are required, primarily depths and velocities of flow upstream of the bridge. This subsection highlights potential ways to obtain input parameters for scour risk assessments.

Scour assessments are completed under the assumption that the relationships of flow rate to depth and velocity for a bridge are valid for high floods. This is potentially not realistic however it is deemed dangerous to collect field data during high floods, thus limited research is available on alternative depth-velocity relationships incorporating floodplains. To complete the scour assessment methodologies reviewed previously and summarised above, field investigation and desk-based data acquisition was required. The collection of data enables an equilibrium scour depth to be projected for each individually assessed bridge using the observed flow depth and velocity relationship and bridge characteristics.

This section details the essential parameters that are needed in each of the reviewed scour assessment methodologies (TDOT, FDOT, BD97/12). The methods employed were chosen with both simplicity and practicability in mind. A method statement was created with both the practitioner’s safety and time in mind.

Flow depth, channel and floodplain width were physically measured on site. Flow measurements were taken with an electromagnetic current meter which was validated to be within 4% of flow rate measured at the Drumiller gauging station as shown in Figure 1. Length and peri measurement were obtained from existing drawings and confirmed on site. the flow was considered to be contacting the pier nose straight-on. The median grain size (D_{50})was determined from Riverbed soil samples taken at the upstream side of each bridge and brought to Queens University Geotechnics laboratory to undergo a grain size distribution analysis.

5. CASE STUDIES

To assess which scour calculation methodology (TDOT, FDOT, BD97/12) is best equipped to provide a representative and practicable approach to scour risk, three Northern Irish bridges were chosen to apply the methodologies to, as shown in Figure 1. For each bridge, key bridge characteristics are described in this section and followed up with a scour risk assessment using the BD97/12, TDOT and FDOT methods. The end result is a scour risk rating in accordance with the BD97/12 approach. The three chosen bridges were selected as they are located close to the source of the River Lagan, a regionally important river in Northern Ireland. The Lagan's source is located at Slieve Croob mountain 14km from the town of Dromore from which the bridges are centred around. Choosing bridges that were close to the river lagan's source was significant as it enabled easy data collection as flow rates and depths are less in these areas as compared to downstream reaches of the river which receive greater runoff and recharge.

When selecting bridges, Regent bridge was an important choice given that it exhibited a rectangular river profile and was bounded by high walls. This allowed the application of the scour depth estimation methodologies to be completed using a simplistic ideal profile. In contrast to this, the other bridges were selected as they exhibited floodplains which require a different approach to the estimation of the relationship between flow velocity and depth in the channels.

The three selected bridges are located at Irish Grid References:

- Regent Bridge:
  E 320050 N 353306
- BlackBog Bridge:
  E 315893 N 354036
- Thorneyford Bridge:
  E 325143 N 351617

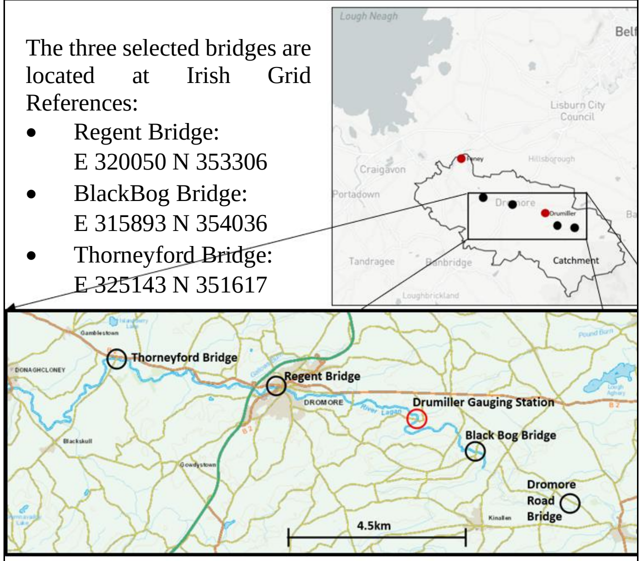

Figure 2- Bridge locations (Daera, 2021) (UK Centre for Ecology and Hydrology, 2021).

By applying the methodologies to both constrained and unconstrained channels the reader can gain a greater understanding of the assessment methodologies. All three bridge are under the management of the Department for Infrastructure and are regularly inspected for condition monitoring, As part of the assessment scour defects are noted. Each of the three chosen bridges are recorded to have experienced scouring in the past.

- Black Bog Bridge had four historical records of apron scour, the latest in 2017.
- Regent Bridge had four historical records of pier scour, the latest in 2017.
- Thorneyford Bridge had six historical records of pier scour, the latest in 2019. The records include an undermining in which some of the masonry that made up a pier collapsed.

The application of the scour methodologies (TDOT, FDOT, BD97/12) are completed with the historical scour records in mind. It would be expected that given the history of scour at these bridges, the methodologies would affirm their risk of scour.

5.1. Case study 1 - Regent Bridge

The first bridge assessed was Regent Bridge which is situated in Dromore, County Down, NI. Regent bridge is a listed historic three-span masonry arch bridge. The bridge is located 25m upstream of a skewed rock weir structure that leads to a natural channel contraction. The river edges are bounded by concrete aprons and vertical masonry walls enabling the cross-section to remain constant with the exception of depth for all flow rates. The bridge approach flow is approximately perpendicular with the bridge parapet. Regent Bridge exhibits a common feature of medium to large masonry arch bridges, a redundant flood arch that is offset from the principal channel and only is active during high water levels. The presence of redundant arches is important for bridge maintenance access but also limits potential river contraction at the bridge.

5.1.1. Assessment Results

Using the priority factor approach of BD97/12, Regent Bridge could be assigned a rating of four **(low risk)** for most of the conditions assessed. The results of the TDOT assessment display a risk rating of three (Medium risk). The individual results of each methodology are displayed on Figure 3 and Table 1 which shows the approximate risk rating of each of the methodologies for a 50m^3/s flow rate. The TDOT scour depths are greater as they are increased by a disproportionately high constriction scour depth. Overall, it can be concluded that Regent Bridge is expected to not be a bridge at considerable risk of scour related failure. The bridge may experience scouring but high-risk ratings signal impending bridge collapse, thus the low-risk rating may be expected as Regent Bridge from observation is a safe and effective bridge. Regent Bridge has a higher priority rating when compared to the other case studies, which is because it supports a road of greater traffic volume. Note that Dscour = Drelative in Table as the foundation depth has been assumed to be equal to 1m when unknown in accordance with the guidance of EX2502 (Network Rail, 2018)

Table 1- Regent Bridge relative scour depth (Constriction + Pier).

Dscour = Drelative	Q (m3/s)	FDOT	TDOT	BD97/12 &TDOT RE
	50	2.78	3.5	2.7
	12.9	1.4	1.38	1.2

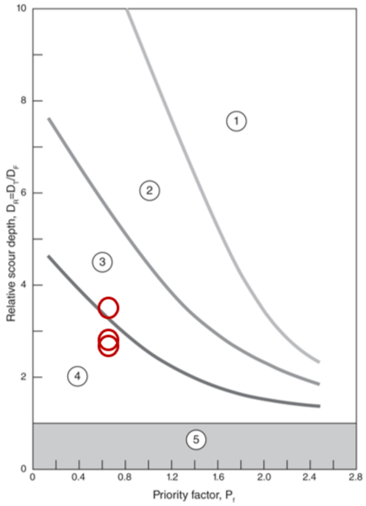

Figure 3- Priority risk rating chart- Regent Bridge.

5.2. Case Study 2 – Black Bog Bridge

The bridge in Case Study 2 is located on the Black Bog Road, 1.8km North of the town of Kinallen, NI. For ease, this bridge will be described as Black Bog Bridge throughout the paper. The bridge is a historic three span masonry arch bridge. The bridge approach flow is approximately perpendicular with the bridge parapet. The bridge has a documented scour history and is situated at the downstream end of a meander and exhibits a redundant flood arch. The Drumiller gauging station is approximately 3.2 km downstream of this bridge and Regent Bridge is located 7.9km downstream

5.2.1. Assessment Results

Using the priority factor approach of BD97/12, , Black Bog Bridge could be assigned a rating of four **(low risk)** for the majority of the conditions assessed. The individual results of each methodology are displayed on Figure and Table 2, which shows the approximate risk rating of each of the methodologies for a 30m^3/s flow rate. The results of the TDOT and BD97/12 assessment display a risk rating of three (medium risk). The TDOT and BD97/12 results are increased by a disproportionately high constriction scour depth. Overall, it can be concluded that Black Bog Bridge is expected to not be a bridge at considerable risk of scour related failure. This can be further confirmed by the presence of bedrock that is likely below the granular riverbed. If the bridge can be confirmed as being founded on rock, a risk assessment like the one completed would not be required as the bridge would be deemed ‘no risk’ by both the BD97/12 and TDOT level 1 assessments. It is important to note that the assessment flow of 50m^3/s has been replaced by a 30m^3/s value for this bridge and Thorneyford Bridge. The reason for this is that flows above 30m^3/s enter the extended larger floodplains around the bridge which are much more difficult to assess in relation to their impact on scour.

Table 2- Black Bog Bridge relative scour depth (Constriction + Pier).

Dscour = Drelative	Q (m^3/s)	FDOT	TDOT	BD97/12 &TDOT RE

	30	2.4	4.6	4
	12.9	1.88	2.15	1.6

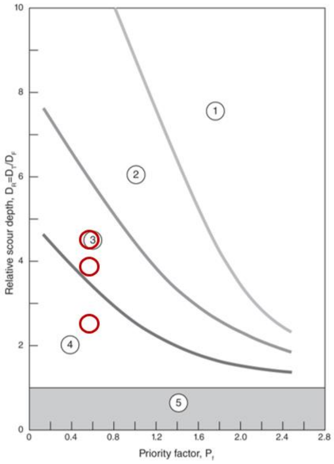

Figure 4- Priority risk rating chart- Black Bog Bridge.

5.3. Case Study 3 – Thorneyford Bridge

Case study three is based upon Thorneyford bridge, a historic four span masonry arch bridge which is located on the Blackskull road, 2.8km Northeast of Donaghcloney town, NI. The bridge is approximately 300m downstream of a ninety-degree river bend that evolves into a meander upon which the bridge sits on. Thorneyford Bridge is located approximately 11km downstream of Drumiller gauging station and 6.3km downstream of Regent Bridge. The bridge is believed to have been constructed between 1760-1779 (OSNI, 2021). Thorneyford Bridge has a detailed history of scour, having undergone scour related repair in 2020. Repair was required following the face collapse of one of the piers due to scour undermining and some masonry loss on the other pier.

5.3.1. Assessment Results

Error! Reference source not found. shows that the majority of the conditions assessed display a bridge with scour risk rating of four, (**low risk)**. The results of the BD97/12 & TDOT RE assessment for a flow rate of 12.9 m3/s display a level five rating, (no risk). It can be concluded that Thorneyford bridge is expected to be a bridge at limited risk of scour failure. The individual results of each methodology are displayed on Figure which shows the approximate risk rating of each of the methodologies for a 30m^3/s flow rate

This conclusion is interesting given the fact that Thorneyford Bridge was the bridge that had a history of scour failure and yet is the lowest risk according to the scour assessments. The most likely explanation of the pier face failure is the presence of large obstructions that had been placed across the channel on the front edge of the pier, which have not been explicitly modelled. It would be anticipated that one particular impact that would be seen if the obstructions were modelled as extensions of the piers is that the peir nose shape factor would increase as a result of the square nose, thus increase expected equilibrium pier scour depth. There are many potential reasons why the pier face failed that can’t be modelled using the methodologies including potential large debris accumulation.

Table 3- Black Bog Bridge relative scour depth (Constriction + Pier).

	Q (m^3/s)	FDOT	TDOT	BD97/12 &TDOT RE
Dscour = Drelative	30	1.62	2.03	1.05
	12.9	0.95	1.05	0.85

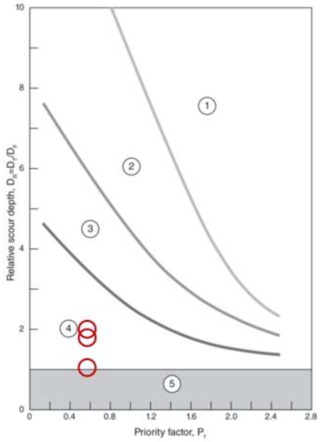

Figure 5- Priority risk rating chart- Thorneyford Bridge.

6. CONCLUSIONS

This research has summarised three of the most prominent quantitative scour risk assessment methodologies and provided a review of each in the context of Northern Irish Bridges. Each assessment type is different and works on different principles, each with specific merits. The research applied each of the methodologies to three Northern Irish bridges and assigned an individual risk rating based on the anticipated pier and constriction equilibrium scour depth. Each bridge achieved a risk rating of four – 'low risk' for 100-year flood events. The conclusion that each bridge is low risk is intriguing given that each bridge has a recorded history of scour. This could be attributed to multiple reasons namely; the BD97/12 chart isn't calibrated to the use of the less conservative FDOT calculations, the bridge scour was caused by debris, or vertical contraction is caused by the masonry arch shape. A solution to this that would require much greater research effort would be to create a BD97/12 chart that is calibrated to the FDOT methods. This would require extensive field observations of many bridges over long periods of time. Following the application of each methodology to the selected bridges and subsequent analysis of variables. The suggestion is to make use of the simplistic and intuitive BD97/12 priority risk rating chart and method of obtaining input parameters. The scour depth calculations are most advisably completed using the FDOT methods which utilise the Sheppard-Melville pier scour equation and the Laursen constriction scour equations. The FDOT method was deemed of greatest benefit and effectiveness through a culmination of ease of understanding and representation of proven processes.

The understanding of scour processes has come a great way over the past 100 years however, scour calculations are likely to remain non-universal and drastically different by region. This is easily understood when the nature of the process is considered, a single fallen tree can create greater scour effects on a pier than 100 years of intermittent flooding. Scour is inherently a natural phenomenon and the way in which it will impact each bridge is as individual as the bridge itself. The author hopes that this research has highlighted both the benefits and limitations of scour calculation methods while also demonstrating how the methodologies can be applied to bridges in Northern Ireland.

7. CONCLUSIONS

Campbell, K., Lydon, M., Stevens, N.-A., Neeson, T., Taylor, S., 2020. A review of the data held on 3,437 masonry arch bridges in Northern Ireland.

Choi, S.U., 2016. Water and Environment Journal 30, 14–21.

Ettema, R., Constantinescu, G., Melville, B.W., 2017. Journal of Hydraulic Engineering 143, 03117006.

Kirby et al., 2015. Manual on scour at bridges and other hydraulic structures.

McKibbins, L.D., Construction Industry Research and Information Association., Great Britain. Department for Transport., Network Rail (Firm), 2006. Masonry arch bridges : condition appraisal and remedial treatment. CIRIA.

Network Rail, 2018. Scour prevention and management. Available at: https://cdn.networkrail.co.uk/wp-content/uploads/2019/06/Challenge-Statement-Bridges-Scour-prevention-and-management.pdf. [Accessed 16th November 2021].

NCHRP, 2011. Evaluation of Bridge-Scour Research: Abutment and Contraction Scour Processes and Prediction. Transportation Research Board, Washington, D.C.

NCHRP, 2011. Evaluation of Bridge Scour Research: Pier Scour Processes and Predictions. Transportation Research Board, Washington, D.C.

Pizarro, A., Manfreda, S., Tubaldi, E., 2020. The science behind scour at bridge foundations: A review..

Sheppard, D. M., and Miller, W. 2006. "Live-bed local pier scour experiments," Journal of Hydraulic Engineering-ASCE, Vol. 132, No. 7, 635-642.

Solan, B., Nowroozpour, A., Clopper, P., Watters, C., Ettema, R., 2019. Scour-Induced Failure Of Masonry Arch Bridges: Causes And Countermeasures.

Sturm, T., Abid, I., Melville, B., Xiong, X., Stoesser, T., Bugallo, B.F., Chua, K.V., Abt, S., Hong, S., 2018. Combining Individual Scour Components to Determine Total Scour. Transportation Research Board, Washington, D.C.