Risk-informed asset management to tackle scouring on bridges across transport networks

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ABSTRACT
Scour is one of the main causes of bridge failures resulting in significant macro-economic impacts, often beyond the direct costs of infrastructure damage. Given the pressure to increase the resilience of transport networks, ageing bridge infrastructure, constrained budgets, variable knowledge of asset conditions and limited data, mixed ownership and operation of bridges, and concerns about the risks of climate change, there is a need to implement cost-effective monitoring and maintenance strategies. To this end, this study aims to set the scene for a risk-informed approach for tackling bridge scour, while considering the socio-economic impacts of disruptions due to bridge failures or closures. This study reviews the current practices in predicting, monitoring and managing bridge scour. It discusses the development of a risk-informed approach to aid the whole-life appraisal of bridges while considering the direct and indirect costs associated with bridge failure or closures. The approach provides a rational means to enable asset managers to evaluate the factors that affect bridge failure risk, select and prioritise appropriate mitigation measures, thereby improving the allocation of scarce monitoring and maintenance resources.

1. Introduction
A safe and efficient transport network is fundamental to connecting people, businesses and services and the associated infrastructure is often considered to be the largest publicly owned asset. Bridges are crucial points of connection within the transport network, underpinning economic vitality, social well-being and logistics of communities. Bridges also have strategic relevance, since they support access to emergency services (e.g. hospitals), utilities (e.g. water supplies) and connect rural communities to the major transport networks. However, they are exposed to natural hazards such as flooding, and disruption to their operation or their failure can have significant effects beyond the immediate local disruption, including undesirable health and safety, economic, environmental and political consequence. The recent flooding events in the UK namely, Londonderry (2017), Cumbria (2009), Gloucestershire (2007, 2009), Boscastle (2004) highlighted the need to ensure the resilience of the bridge infrastructure.

One of the important challenges facing the UK and many other countries is to make its critical transport infrastructure like bridges resilient to extreme weather events given a changing and uncertain climate (Lamb, Aspinall, Odbert, & Wagener, 2017). Nevertheless, the bridge asset management decisions are largely based on short-term, subjective criteria (due to a lack of data or the uncertainty of its accuracy) and consequent lack of understanding of bridge performance and its socio-economic and environmental impacts (Rashidi et al., 2016). For example, the UK has 160,000 bridges, 40% of which are considered to be historical assets, managed by different transport agencies under constrained budgets employing in-house management systems with various levels of sophistication (Pregnolato, 2019). The situation is exacerbated when asset managers often need to make decisions on basis of incomplete and uncertain information due to the lack of a robust and unified national bridge database or bridge management system (BMS) and inadequate information on the condition of the bridge due to lack of continuous monitoring (Dikanski, Imam, & Hagen-Zanker, 2018).

The foremost cause of bridge failure worldwide is scouring (Faulkner, Brownjohn, Wang, & Huseynov, 2020), with 6000 bridge failures in the USA and 140 UK rail bridge failures during 1846-2013 reported being scour-related (Prendergast & Gavin, 2014; van Leeuwen & Lamb, 2014). Scouring is defined as the removal of material from the bed and banks of a river by the action of water (May, Ackers, & Kirby, 2002). The stability of the bridge foundation may be endangered if the scour depth becomes significant, with a consequent risk of structural damage or failure. It is also identified to be the bridge management risk most likely to...
be impacted by climate change (Kallias & Imam, 2016). In 20 bridges in the UK is expected to be at high risk of failure due to climate change by 2080 (Dawson et al., 2018) and the scour risk mitigation expenditure alone is estimated to be €25-76 million annually for the period 2040–2100 (Nemry & Demirel, 2012). Scour occurs in three main forms (Kirby, Roca, Kitchen, Escarameia, & Chesterto, 2015; Pizarro, Manfreda, & Tubaldi, 2020):

i. **Natural scour** occurs due to long term changes to the river channel and includes the aggradation and degradation of the riverbed that may occur as a result of changes in the flow rate or changes in the quantity of sediment in the channel.

ii. **Contraction scour** occurs as a result of a reduction in the cross-sectional area of the river channel due to the construction of structures such as bridge piers and abutments. The narrowing of the channel results in higher velocities which in turn contributes to the movement of the materials from the riverbed and banks.

iii. **Local scour** is caused directly from the impact of the structure (i.e. individual piers or abutments) on the flow and occurs only near the structure. It is a function of the structure type and is superimposed on the natural and contraction scour.

The factors that contribute to the development of bridge scour can be characterised into structural (S), geotechnical (G), environmental (E), and induced by nature (N) or human (H) actions as presented in Table 1. These factors are subjected to high levels of uncertainty, due to extreme weather events brought about by climate change and limited availability of data. Moreover, bridge asset managers often use scour prediction models based on small-scale laboratory experiments whose accuracy may be low due to limited verification using field data (Dikanski et al., 2018). The problem is exacerbated by the lack of comprehensive asset data due to infrequent inspections, especially in the case of older bridges, where foundation conditions are often unknown and have to be assumed during scour assessments (Prendergast & Gavin, 2014).

Furthermore, the lack of an approach that allows a systematic means to prioritise and deploy resources toward those bridges that pose the greatest threat to safety, or higher socio-economic impacts, or disruption of vital services is detrimental to future-proofing critical transport infrastructures like bridges. To this end, this paper aims to set the scene for a risk-informed approach for tackling bridge scour, while considering the socio-economic impacts of scour-related bridge failures or closures. This study overviews the current practice of bridge management in general and scour in particular, framing it within a risk-informed approach. Finally, it discusses the development of such a conceptual approach that would aid the whole-life appraisal of bridges while considering the direct and indirect costs associated with transport disruptions.

### 2. Bridge asset management

Assets are items with value and could be either tangible (such as bridges, buildings, equipment) or intangible (such as human capital, royalty). ISO 55000 defines asset management as ‘the coordinated activity of an organisation to realise value from assets’. Asset management policies thus cover social, economic and technical attributes of the asset, and is a process spanning across its service-life (Van Der Westhuizen & Grabe, 2013). When it comes to asset-centric industries like transportation, asset management is predominantly focused on the infrastructure involved (e.g. bridges, roads, railway track, signalling etc.). In principle, infrastructure asset management can be viewed as a decision-making process that aims to satisfy service and quality while minimising costs and effects. Setting priorities for maintenance and rehabilitation consumes most of the available funding for bridges and requires evaluation at both network level (i.e. which bridge within the network to maintain) and the
project level (i.e. which maintenance strategy to be adopted for a given bridge). The decision-making at the network level is governed by multiple bridge performance indicators such as structural health of the bridge, safety and security of users and workers, environmental impact, socio-economic impact on the users, and impact on agency’s reputation (Allah Bukhsh, Stipanovic, Klanfer, O’Connor, & Doree, 2019; Frangopol, Dong, & Sabatino, 2017; Yavuz, Attanayake, & Aktan, 2017).

The decision-making has been supported by academic research that employed different techniques to predict the bridge condition using Markov chains (Le & Andrews, 2013), Petri-net (Yianni, Rama, Neves, Andrews, & Castlo, 2017), analytical hierarchy process (Rashidi et al., 2016), Monte Carlo simulations (Frangopol, Kallen, & Noortwijk, 2004), Bayesian (Maroni et al., 2019) and normal regressions (Babanajad et al., 2018). Different BMSs are also employed to aid decision-makers to keep bridges in an acceptable level of service within the transport networks. E.g. PONTIS (Thompson, Small, Johnson, & Marshall, 1998) and BRIDGIT (Hawk & Small, 1998) systems are commonly employed in the US for reliability-based bridge management while considering agency and user costs. Other commercially available systems such as Canada’s QBMS, China’s CBMS, Denmark’s DANBRO, Germany’s GBMS, Japan’s RPIBMS, Korea’s KHBMS and Poland’s SZOK are also employed by transport agencies worldwide to determine optimal bridge maintenance strategies (Allah Bukhsh et al., 2019; Jeong, Kim, Lee, & Lee, 2018). While the BMSs of most of the countries have the capability of performing essential functions (e.g. data storage, asset condition prediction, cost modelling, optimisation), they often lack mechanisms for achieving trade-offs between cost-effective strategies and risk levels of bridge failure (Jeong et al., 2018).

A key part of the bridge scour management process is to identify those bridges that are most at risk of scouring and require further action. To identify vulnerable bridges, a quantitative (or at least a qualitative) risk assessment approach is required to predict the likelihood and consequence of bridge scouring and will provide a measure of the bridge’s performance during its life cycle. The most important bridges in a network can be identified by the use of the techniques available through network analysis (Alipour, 2017). Furthermore, the bridges can be weighted based on their importance to the system (e.g. bridges that provide access to critical facilities or major business regions could be weighted more heavily) and then ranked by the use of network performance indicators (Allah Bukhsh et al., 2019; Zanini, Faleschini, & Casas, 2019). This can not only aid in optimising inspection and maintenance budgets but also help in organising recovery and restoration actions in the case of regionally distributed extreme events such as floods that result in disasters. This means an effective understanding of the bridge asset is critical to be able to manage them successfully.

In the UK, multiple authorities are responsible for the bridges: with Highways England (HE), Transport Scotland (TS) and Welsh Assembly (WA) for the motorways and A-road bridges in England, Scotland and Wales respectively; Local Authorities (LA) for road bridges at the county level; and Network Rail (NR) for railway bridges. Even though there is a general bridge condition indicator, each authority has its approach to inspection and risk assessment resulting in variable knowledge of bridge condition (Department of Transport, 2014; Pregnolato, 2019). While the standards and guidance are effective in reducing the risk by prioritising maintenance and scour protection works, the combination of infrequent natural events (like floods), complex physical process and the challenges, costs and uncertainties associated with asset data make it difficult to quantify scour risks with confidence (Dikanski et al., 2018).

2.1. Predicting bridge scour

Bridge scour is a dynamic phenomenon that varies with many factors such as water depth, river flow angle and strength, pier and abutment shape and width, material properties of the sediments and vegetation growth (see Table 1) and poses obvious problems to the stability of bridge structures. Scour prediction is typically associated with a design hydrologic event that has a given likelihood of occurrence (e.g. the 200-year flood event). The limited understanding of the progressive deterioration of bridge scour due to infrequent inspections and the unavailability of data on the foundation depth often result in uncertainties within the risk assessment (Dikanski et al., 2018; Lamb et al., 2017; Pizarro & Tubaldi, 2019). Several studies have developed empirical equations to predict the scour depths and have often linked the depth and rate of scour development on a given structure to the position and type of the structure; water flow conditions including water depth, flow velocity and water kinematic viscosity (Pizarro et al., 2020) and the characteristics of the material forming the bed and banks of the channel (Kirby et al., 2015). A detailed comparison of widely used scour models can be found in the literature (Dikanski, Hagen-Zanker, Imam, & Avery, 2017; Pizarro et al., 2020; Pizarro & Tubaldi, 2019).

Generally, scour prediction models can be classified into (i) time-dependent and (ii) equilibrium. The equilibrium phase is when the erosion inside the scour hole is negligible and the scour depth reaches a temporary maximum (Kirby et al., 2015). The most commonly employed time-dependent and equilibrium scour prediction models are listed in Tables 2 and 3, respectively. For example, (Richardson & Davis, 2001) and (Sheppard, Melville, & Demir, 2014) are widely used in the USA and (Gao, Posada, & Nordin, 1993) is employed in China. While the equilibrium scour models are mainly used for design purposes, the time-dependent models are often employed to aid the risk assessment practices that inform maintenance interventions. The estimates of the scour depths at different times are also compared with the ones obtained by using equilibrium scour models and a peak of flood event corresponding to a return period.

The prediction of scouring risks due to extreme events induced by an increased risk of climate change from
screening generally combines generic information about the bridges requiring more detailed assessment. The initial with initial screening being applied to identify and prioritise consequences, both locally and nationally. The currently subsequent effect of scouring on the bridge magnitude; the effect of the said flood event on the scour; and the probability of occurrence of a flood event of a given magnitude.

The risk of bridge failure due to scouring is governed by the basis for risk-informed decision-making for the trans-

The United Kingdom Climate Change Projections 2009 (UKCP09) and 2018 (UKCP18) contain quantifications of the uncertainty associated with climate change and provide the basis for risk-informed decision-making for the transport networks (Dikansi et al., 2018).

2.2. Risk assessment practices for bridge scour

The risk of bridge failure due to scouring is governed by the probability of occurrence of a flood event of a given magnitude; the effect of the said flood event on the scour; and the subsequent effect of scouring on the bridge’s stability. The severity of such a bridge failure can be assessed by the health and safety, economic, environmental and political consequences, both locally and nationally. The currently employed bridge scour risk assessment protocols are tiered, with initial screening being applied to identify and prioritise bridges requiring more detailed assessment. The initial screening generally combines generic information about the bridge and watercourse, such as dimensions, bed material, and vegetation, and its scour history. Different engineering standards and guidance, such as UK’s Design Manual for Roads and Bridges (DMRB or BD97/12) (DMRB, 2012) and EX2502 for rail bridges (Rail Safety & Standards Board, 2004), the USA’s National Bridge Inspection Standards (Arneson, Zevenbergen, Lagasse, & Clopper, 2012) are widely used in the scour assessment process and the common steps associated with it are summarised in Table 4. The following subsections give a brief insight into the scour risk assessment processes followed for bridges in the UK and USA.

2.2.1. Road bridges (UK)

The scour risk assessment of road bridges in the UK adopts a two-stage procedure for scouring risk rating (SRR) as elaborated within BD97/12. It takes into account the importance of the bridge (based on the type of road and traffic-flow) as well as an assessment of scouring concerning the foundation conditions (DMRB, 2012) (see Figure 1a). The Level-1 assessment is a screening method to identify the structures with a low risk of scour damage and involves qualitative rather than quantitative analysis. If the Level-1 assessment does not show that a bridge is adequate, the Level-2 scour assessment is carried out to estimate the relative scour depth corresponding to the assessment flow. The assessment is determined for the bridge site based on a statistical analysis of the available flood data, combined with tidal data where required. The ratio of the calculated total scour depth ($D_T$) to the depth of the foundation ($D_f$) is considered to be the main indicator of risk.

The constriction scour depth is calculated using Equation (13) (DMRB, 2012) while considering the surrounding terrain, type and size of bed material and location of the bridge concerning a sharp or moderate bend or straight reach of the river that informs the factor $F_i$ and original bed

Table 2. Commonly used time-dependent scour prediction models.

| Authors                  | Formula | Equation |
|--------------------------|---------|----------|
| (Melville & Chiew, 1999) | $z_e = \exp \left\{ -0.03 \left[ \frac{u}{u_c} \ln \left( \frac{u}{u_c} \right) \right]^{1.6} \right\}$ | (1) |
| (Hager & Unger, 2010)   | $Z_M(T_M) = |Q_M(T_M)|^{0.605} \log (\gamma T_M)$ | (2) |
| (Pizarro et al., 2017)  | $\dot{z} = \frac{1}{2} \ln \left\{ 1 + \frac{W}{\pi \bar{m}} \exp (s - 1) \right\}$ | (3) |
| (Link et al., 2017)     | $\dot{z} = c_1 \left( 1 - e^{-c_2 W^{c_3}} \right)$ | (4) |
| (Link et al., 2020)     | $\text{Dep} = \begin{cases} 0, & \text{if } \left| \frac{F_i}{\text{p}} \right| \leq g^I_i \\ \frac{\alpha}{\pi \bar{m}} \left( \frac{F_i}{\text{p}} - g^I_i \right) > 0, & \text{if } \left| \frac{F_i}{\text{p}} \right| > g^I_i \end{cases}$ | (5) |

Where $\text{Dep}$ is the sediment deposition over a time interval $\Delta t$, $g^I_i$ is the sediment transport capacity, $\text{p}$ is the soil porosity, $\text{P}_s$ is the sediment density, and $c_1, c_2$ and $c_3$ are model parameters.
Table 3. Commonly used equilibrium scour prediction models.

| Authors                  | Formula | Equation |
|--------------------------|---------|----------|
| (Froehlich, 1988)        | \( \Delta z = 0.32KpF_r^2 \left( \frac{d_o}{h} \right)^{0.62} \left( \frac{D}{D_p} \right)^{0.08} + 1 \) | (6) |
| (Melville, 1997)         | \( z = K_hK_dK_pK_u \) | (7) |
| (Gao et al., 1993)       | \( z = 0.46K'_0D^{0.40}h^{0.15}d^{0.07} \left( \frac{u_t - u_i}{u_t} \right)^{\eta} \) | (8) |
| (Richardson & Davis, 2001)| \( \Delta \theta = 2K_hK_dK_pK_u \left( \frac{d_o}{h} \right)^{0.35}F_r^{0.43} \) | (9) |
| (Sheppard et al., 2014)  | \( \Delta \theta = 2.5K_fF_r \) for \( 0.4 \leq \frac{d}{h} \leq 1.0 \) | (10) |
| (Williams, Bolisetti, &  | \( \Delta \theta = 1.01F_r^{0.28} \left( \frac{h}{D_p} \right)^{0.325} \left( \frac{D}{D_p} \right)^{0.059} \) | (11) |
| Balachandar, 2017)       |         |          |
| (Williams, Bolisetti, &  | \( \Delta \theta = 0.76k_i^{0.69} \left( \frac{D}{D_p} \right)^{0.32} \) | (12) |
| Balachandar, 2018)       |         |          |

where \( D_c, ave \) is the projected pier width, \( h \) is the flow depth, \( F_r \) is the Froude number, \( K_h \) is the factor for pier shape, \( K_d \) is the factor for the mode of sediment transport, \( K_p \) is a factor for the angle of attack, \( K_u \) is a factor for the density of the local scour at a pier, \( u_i \) is the incipient velocity for local scour at a pier, \( F_r \) is the ratio of bed material, \( F_r \) is a factor for average bed material, \( Z_{max} \) is the maximum scour depth at the pier, \( F_r \) is the ratio of the bed material, \( F_r \) is a factor for very wide piers, \( F_r \) is an importance factor based on road type, and \( V \) is importance factor based on 12-hour traffic flow.

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Level \( D_{c,ave} \): The depth of local scour at piers is associated with the width and shape of the pier and the angle of attack of the water flow and is estimated using Equation (14) (DMRB, 2012). SRR is then determined based on the Relative Scour Depth (\( D_a \)) (see Equation (16)) and Priority factor (\( P \)) (see Equation (17)) and is assessed from the graph presented within Figure 1a to identify bridges with immediate risks (DMRB, 2012):

\[
D_c = F_cD_{c,ave} \quad (13)
\]
\[
D_{c,pier} = 1.5W_pf_rf_s\rho_b \rho_a \lambda y \quad (14)
\]
\[
D_{c,abutment} = \frac{1.5W_pf_rf_s\rho_b \rho_a \lambda y}{2} \quad (15)
\]
\[
D_R = D_TD_F \quad (16)
\]
\[
P = F*H*M*TR*V \quad (17)
\]

Additional weights are given to bridges with no suitable diversion route, a very long diversion route, or where the loss of bridge would result in unacceptable community severance. If the scour depth does not exceed the depth to the underside of the foundation for each pier and abutment, then the structure is designated as SRR 5 (5 is the lowest priority). Otherwise, it is allocated an SRR in the range of 1 to 4 (1 is the highest priority). An example of applying the BD97/12 manual for scouring risk assessment on A68 Galadae Bridge can be found within (Koursari & Wallace, 2020).
### 2.2.2. Road bridges (USA)

The USA’s Federal Highway Administration (FHWA) developed a risk-based methodology and software named HYRISK to evaluate the annual risk of scouring failure of an existing bridge in monetary value (Govindasamy et al., 2008) incorporating Equations (1) (6)-(7) and (9) presented in Table 3. The risk assessment process is three-tiered: Bridge Scour Assessment 1 (BSA1), Bridge Scour Assessment 2 (BSA2) and Bridge Scour Assessment 3 (BSA3) (see Figure 1b). By following the BSA 1 procedure (see Figure 1b), the scour depth corresponding to a specified future flood event is obtained through extrapolation charts that relate the scour depth ratio to the velocity ratio. BSA2 is carried out if a bridge is not found to have “minimal risk”, “immediate action required,” or “special action” at the end of BSA 1. BSA 2 determines the scour vulnerability based on the assumption that the bridge will experience the maximum possible scour depth within its lifetime.

The maximum total scour at the bridge is estimated to be the arithmetic sum of the three components of scouring, i.e. maximum pier, contraction and abutment scour. The scour vulnerability of a bridge depends on the comparison between the maximum total local scour depth and the allowable scour depth of the bridge. If BSA 2 does not conclude with a specific plan of action, the BSA 3 is carried out to calculate time-dependent scour depth. BSA 3 is valuable in the case of highly erosion-resistant riverbed materials such as clay and rocks, that do not achieve the maximum scour depth within the bridge’s lifetime. The vulnerability of a bridge to scour is then calculated by comparing the predicted scour depth with the allowable scour depth of the foundation. Examples of employing HYRISK for bridge scour risk assessment is given within Khelifa, Garrow, Higgins, and Meyer (2013).

### 2.2.3. Rail bridges (UK)

The scour assessment of railway bridges takes place at two stages: Stage 1 is a preliminary assessment which all riverine bridges are subjected to as dictated by EX2502 standard (HR Wallingford, 1992). Any bridge highlighted as being at risk is assessed at Stage 2 which includes a detailed hydrological and hydraulic assessment (Dikanski et al., 2018; Rail Safety & Standards Board, 2005). The depth of local scour at a railway bridge pier \(d_{pier}\) is estimated while considering the pier width \(D\), safety factor \(SF\) and different factors that take into account variables affecting the depth of scouring such as the angle of attack \(\beta\), the shape of the pier \(F_{shape}\), depth \(D\), velocity \(F_{velocity}\) and potential debris in the river \(F_{debris}\) (Equation 18)). The estimation of local scour at abutments \(d_{abutment}\) accounts for the depth of flow \(K_{abutment}\), angle of attack \(K_{a}\), abutment shape \(K_{S}\) and channel geometry \(K_{C}\) (Equation 19)). The contraction scour is estimated using (Kirby et al., 2015) and accounts for a range of factors, including dimensions of the structure, channel and floodplain, bed material grading and bends upstream of the bridge; however, variations in river flow are not accounted for. EX5202 assume the total scour depth \(D_{s}\) for a rail bridge structure to be a summation of contraction scour and local scour:
NR employs a ‘priority rating’ approach using the EX2502 standard to assign priority scores based on a ratio between foundation depth \( D_F \) and the predicted total depth of scouring \( D_T \) within a prescribed modelling approach (Rail Safety & Standards Board, 2004; van Leeuwen & Lamb, 2014). The Preliminary Priority Rating (PPR) is estimated by Equation (20) where the predicted total depth of scouring is that would occur following a 1:200-year flood event (HR Wallingford, 1992) (see Figure 2).

The PPR value is then adjusted for existing scour protection and other conditions in the river channel and floodplain such as river type \( (T_R) \) and the foundation material \( (F_M) \) to obtain the Final Priority Rating (FPR) given by Equation (21). The FPR score of different rail bridges thus obtained is classified as low, medium and high (see Table 5), thus, they can be prioritised for scour vulnerability and criticality:

\[
PPR = 15 + \ln \left( \frac{D_T}{D_F} \right) \tag{20}
\]
HR Wallingford (Roca & Whitehouse, 2012) introduced a new approach to assess the likelihood of scour risk on bridges while considering uncertainty and climate change within its decision-making process. The framework introduced a process of probabilistic scour risk assessment using fragility curves to account for uncertainty in input variables, prediction methods and performance of structures. The amount of scouring calculated for each event is compared with the depth of foundation and related to a probability of failure through a fragility curve.

### 2.3. Monitoring bridge scour

Currently, most countries are not able to identify bridges at higher risk of failure, due to the unavailability of high-quality data (e.g. bridge foundation depth, scour depth, etc.), the mixed ownership of the assets or the lack of an effective inspection regime (Jeong et al., 2018). The most efficient and cost-effective method of dealing with scour is to monitor its evolution over time and to accordingly implement maintenance or repair works (Prendergast & Gavín, 2014). The most commonly used bridge monitoring technique is visual inspections to detect cracking and scour. Divers are often employed to inspect the condition of foundation elements and to measure the scour depth using basic instrumentation. Such an approach is particularly at a disadvantage during flooding when the risk of scouring is the highest and diver inspections cannot be carried out due to health and safety considerations.

The issue is exacerbated as the scour holes tend to be filled in as floodwater subsides and might go unnoticed during visual inspections, thereby misleading the real extent of the scour problem (Bridge et al., 2017). An effective alternative is to employ instruments such as accelerometers, sonars, fibre-bragg grating sensors and smart rocks etc (Prendergast & Gavín, 2014) to gather data related to scour depth and different factors that contribute to scour formation. These instruments can be broadly categorised as fixed and portable and the applications of some of the widely used instruments are discussed below and in Table 6.

(a) Fixed instrumentation

i. **Magnetic sliding collar**: These instruments work on the principle of a manual or automated gravity-based physical probe that rests on the riverbed and moves downwards as scour develops. They are widely used as they are considered to be relatively inexpensive, easy to install and operate. However, it is most effective only if

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**Table 5. Priority categories for scour protection of the UK’s railway bridges** (Rail Safety & Standards Board, 2004).

| Priority rating | Priority score | Priority category |
|-----------------|----------------|-------------------|
| 17.00-21.00     | Priority 1     | High              |
| 16.00-16.99     | Priority 2     | Medium            |
| 15.00-15.99     | Priority 3     | Medium            |
| 14.00-14.99     | Priority 4     | Medium            |
| 13.00-13.99     | Priority 5     | Low               |
| 10.00-12.99     | Priority 6     | Low               |
installed at a location of maximum scour and they are susceptible to ice and debris impact. Case studies of employing magnetic sliding collars for monitoring scour are available in Curtis et al. (2017).

ii. Movement sensors: Sensors such as tiltmeters and accelerometers measure tilting, vibration or acceleration of the bridge and allow for bridge or route managers to enforce bridge closures if necessary. Tiltmeters measure the relative rotation of a structural element and can be employed to measure differential settlement (Faulkner et al., 2020). Accelerometers are easy to install and measure the acceleration of a structural member in three directions and should ideally be installed alongside tiltmeters. While such movement sensors can be used to inform structural distress to the bridge engineers in real-time, they do not give a direct indication of scour depth. The accelerometers commonly contained in smartphones have been recently used for crowd-sensing bridge vibration data (Matarazzo, Vazifeh, Pakzad, Santi, & Ratti, 2017; Matarazzo et al., 2018).

iii. Float-out device: These are transmitters buried at different elevations that float to the river surface when exposed by scour. They emit a signal which is often received by a data logger installed on or near the bridge. Similar to magnetic sliding collars, these devices need to be installed in locations where maximum scour depth is expected. However, they do not indicate the scour level beyond the depth of installation and installation is considered to be expensive due to drilling. They are more suitable for bridges which are under construction due to the ease of installation at that stage. Examples of using float-out devices are given in Curtis et al. (2017).

iv. Time-domain reflectometry (TDR): This radar-based monitoring technique involves sending an electromagnetic pulse down a pipe buried vertically in the riverbed at the location where maximum scour is predicted to occur. TDR is advantageous if there is a continuous and long-term scour monitoring exercise (Yu, Zhang, Tao, & Yu, 2013). However, variation in temperature and salinity can affect the accuracy of the measurements from TDR (Fisher, Atamturktur, & Khan, 2013).

v. Fibre-bragg grating (FBG) sensors: The method involves the installation of sensors arranged on fibre and mounted on a cantilevered beam or plate. The bending strain induced on the exposed beam or plate due to flowing water around the pier or abutment is detected by the sensors. The bending detected by the FBG sensors reveals that the rod plate or beam is exposed or free which invariably is the detected scour depth. They are relatively cheap to fabricate (Prendergast & Gavin, 2014) and can be used to monitor changes in scour depth on installed piers or abutments over a long time frame. However, the installation requires specialised training, is susceptible to destruction and is highly sensitive to vibrations occurring due to flowing water or traffic (Ekuje, 2018). Further information on employing FBG sensors for bridge scour monitoring is provided in Kirby et al. (2015) and Zhou, Huang, Huang, Ou, and Chen (2011).

vi. Smart rocks: This novel technology is gathering interest due to its real-time monitoring capability of bridge scour. The embedded electronics within the ‘rocks’ functions as a source of a magnetic field and is designed to automatically roll down to the bottom of the scour hole. Once placed around a bridge pier in a scour critical zone, the change in the magnetic field near the
bridge pier can be measured during a flood event. The location of the maximum scour depth will correspond to the location of the smart rock. While they are immune to noise, debris, salinity, temperature variations and extreme flood events (Bao & Liu, 2017), the effectiveness of the monitoring technique is dependent on the measurement accuracy of the magnetometer and the selection of measurement points. Examples of employing smart rocks for bridge scour monitoring are given in Chen, Tang, Li, Chen, and Tang (2018), Tang, Chen, Guo, et al. (2019) and Tang, Chen, Li, et al. (2019).

(b) Portable instrumentation

i. Sonar: It is considered to be a robust and reliable instrument for scour monitoring and has been widely used due to its ease of installation when compared to other techniques (Fisher et al., 2013). They record the scour depth by measuring the time taken for an acoustic signal to travel to the river bed and back. Sonars can be designed to collect information at prescribed intervals ranging from 15 minutes to bi-weekly and is also able to measure scour refills (Ekuje, 2018). However, high turbidity, sediment transport and debris may affect the effective reading of scour depth. Further information and case studies of using sonar for scour monitoring is given in Topczewski, Ciesla, Mikołajewski, Adamski, and Markowski (2016) and Zheng, Xu, Cheng, Wang, and Lu.

ii. Ground Penetrating Radar (GPR): The scour depths are obtained by determining the water-sediment interface through this radar-based device. Functionally similar to the TDRs, the GPR consist of a pulse generator, cable and a transmitter that floats on the water surface to capture measurements of the river bed. While GPRs have the advantage of giving accurate and continuous measurements of the river bed conditions, they require specialised training for operation and are difficult to operate during heavy flooding (Prendergast & Gavin, 2014). More information and case studies for using GPR for scour monitoring is given in Anderson, Ismael, and Thitimakorn (2007) and Park, Lee, and Cho (2004).

iii. Sounding rods: Vertically supported sounding roads have been used for scour monitoring since the early 19th century to determine the riverbed level. The setup comprises of a vertical or non-vertical metal rod connected to the bridge structure with a base plate resting on the river bed. As the scour develops, the rod slides downwards and the difference in river bed level is measured. Though it is simple to install and considered to be the cheapest form of scour monitoring, the measurements are susceptible to debris and hydrodynamic forces (Kirby et al., 2015).

iv. Remote sensing systems: Drones (Jalinoos, Amjadian, Agrawal, Brooks, & Banach, 2020) and satellites (Selvakumaran, Plank, Geiß, Rossi, & Middleton, 2018) are recently gathering attention for their capability to collect and measure real-time spatial data over a large area, including information on the bridge and the riverbank. Such systems can also be used to measure bridge movements (directly or indirectly related to scour) including rotation and settlement and used to inform analytical models. The high-resolution imagery (limited to above-water features) of a bridge and its surroundings collected by the remote sensing systems can also be used to create a 3D reconstruction to determine the safety and vulnerability of the bridge. It can also be used for the post-scour assessment of bridges. However, one of the key challenges observed for drones is that the images must be taken at the same incidence angle, polarisation and direction for precision.

Recently published literature (Bao & Liu, 2017; Pizarro et al., 2020; Prendergast & Gavin, 2014) provides further insights into the capabilities and relative costs associated with different scour monitoring techniques. The application of the existing methodologies, however, has been limited considering issues on the complexity and cost-effectiveness, resolution, capability for providing repeated and reliable information, installation, and rigour in data retrieval and processing. Moreover, there is a lack of a business case for monitoring, as the risks of bridge failure and associated costs are not well understood, and there are no systematic frameworks for addressing the same. Whence, a risk-informed asset management framework could aid decision-makers to identify cost-effective and value-based monitoring strategies for a bridge infrastructure for a given level of risk of failure.

3. Risk-informed asset management of bridge scour

Given the value of critical infrastructure such as the bridge within the transport system, it is also important to be able to predict the consequence of closures or failures for each bridge across the system. In the view of different challenges associated with budget allocation and future impacts of climate change, a risk-informed approach that prioritises the monitoring and subsequently maintenance of bridges while systematically considering structural, functional, operational and environmental conditions might prove to be a transparent, cost-effective and risk-averse approach to bridge asset management. The HYRISK model developed by the USA’s FHWA (Khelifa et al., 2013) and the scour risk assessment approach employed by the UK’s Highways England (DMRB, 2012) are probably the closest to a whole-life risk-informed
asset management approach for bridges in general and scour in particular.

However, despite the significance of the macroeconomic costs of bridge closure or failure, neither of them considers it within the decision-making. To assess and maintain the bridges effectively, it is clear that good quality information about their condition and a sound understanding of the direct and indirect costs associated with transport disruptions is vital. A combination of improved data, multiple-scale modelling and better-designed monitoring will provide a high-quality database of information and add to the tools required for decision making (Vagnoli, Remenyte-Prescott, & Andrews, 2018). However, of equal importance is how this information is managed and used to make critical investments to maintain or improve the value of the transport network (Srinivasan & Parlikad, 2017). Indeed, this is the definition of effective asset management as defined in ISO 55000 the national 'standard' for asset management. To this end, a risk-informed asset management approach is fundamental to control and manage bridge infrastructures at the network level (Pregnolato, 2019).

This paper introduces a conceptual framework (see Figure 3) for such a risk-informed approach and shows conceptually how risk management and information quality levels can effectively support bridge scour management planning at both network and project level. The business policies define what the transport infrastructure agency is aiming to achieve and are usually governed by stakeholder expectations, budgets, performance indicators and other targets. Strategy defines mechanisms by which these policies are translated into operational decisions based on their risk levels and thereafter implementation of works programmes. E.g. bridges categorised as high scour risk, require scour protection works and/or monitoring, warning and community preparedness as necessary.

On the other hand, medium or low scour risk bridges might need to be monitored for changes to the bridge, river and catchment area. The strategy selection would ideally be informed by time-dependent deterioration models discussed in Table 2 to predict the scour depth and life cycle costs of the bridge infrastructure over its service life. The risk management takes a holistic view of infrastructure that requires consideration of several key elements beyond just the physical bridge infrastructure. The significance of risk depends on the combination of the likelihood of scouring and its consequence. While the likelihood of scouring is governed by different contributing factors (see Table 1), the magnitude of the consequences is often mediated by the macroeconomic costs or impacts of related bridge closure or failure.

The scour risks of individual bridges could also be amalgamated for an entire network or route, to yield a measure of overall bridge network performance. The scour risk will also influence the management of existing transport assets such as roads, railways or bridges and the prioritisation of resources between competing demands. By quantifying the performance of individual bridges, investment in scour maintenance and monitoring can be targeted to those sections with the greatest failure probability and consequences and works programmes designed accordingly. Such an approach would also aid in making a business case for investing in predictive and preventive asset management regimes. This would inform decision-making on the need for installing a scour monitoring system (or not) on a given bridge and to select appropriate monitoring options (from Table 6) if proven beneficial (relative to the absence of such information). To this end, the value of information models (Giordano, Prendergast, & Limongelli, 2020; Klerk, Schweckendiek, Den Heijer, & Kok, 2019) can be employed to quantify the benefits (or not) of such decisions.
However, to be effective, the strategies designed to improve the reliability and resilience of the bridge assets need to account for uncertainties associated with predicting the performance and condition of the asset (see Section 3.1). The World Bank concept of information quality levels (IQL) has been used to suggest the data requirements for different levels of bridge asset management shown in Figure 3 (Paterson & Scullion, 1990). The IQL concept acknowledges that different qualities of data are required for these levels and it provides a standard for acquiring and using data when carrying out any management activity. This enables a sufficient amount and quality of data to be collected for the task in hand, thereby reducing unnecessary data collection and processing costs (Robinson, 2008).

Overall, the key objectives of the risk-informed framework presented herein are to determine the likelihood of scouring and consequence of bridge failure or closures and make optimal risk-informed decisions related to inspection, maintenance and replacement, while dealing with uncertainty associated with the unavailability of data. The presented conceptual approach can, therefore, be used by bridge infrastructure managers and senior decision-makers for:

- Preparing a network-level bridge asset management plan while considering the user requirements and risk of disruptions.
- Identifying value-based asset management practices for given levels of risk and budget
- Producing annual business policies for the network.
- Reviewing and auditing to seek improvement in the planning approach.

Notably, only a few studies till date have been conducted to determine the socio-economic impacts incurred due to bridge closures or failure (Frangopol et al., 2017; Kim, Shin, & Kim, 2018; Lamb et al., 2019; Marsden et al., 2020; Yavuz et al., 2017) possibly due to the difficulty of collecting data. Considering the macroeconomic costs within the decision-making will aid the transport agencies to identify feasible actions to prevent, mitigate or recover from future disruptions and the costs associated with these. This, in turn, would make it possible to manage the level of vulnerability or risks in the system, while considering the costs and benefits of different asset management strategies and resource allocations. Similar approaches have been successfully adopted globally for managing other transport infrastructures such as roads (Qiao, Dawson, Parry, & Flintsch, 2015) and railways (Sasidharan, Burrow, & Ghatora, 2020; Sasidharan & Torbaghan, 2020).

The different macroeconomic costs or impacts associated with bridge closure or failure considered within the proposed framework are highlighted in the sequence:

i. Safety: Safety concerns are paramount, motivating intensified inspection, speed restrictions, and bridge closures during extreme flood events. These practices incur some economic losses for passengers and freight even in the absence of bridge failures. For example, the risk of structural collapse of a rail bridge across the UK due to scour leading to passenger train derailment is estimated to be $9.43 \times 10^{-3}$ fatalities and weighted injuries (FWIs) annually (Lamb et al., 2019). The bridge collapse would be highly consequential while considering the significant legal processes and infrastructure damages.

ii. Service disruption: The partial or full closure of a bridge disrupts traffic flow and direct customer access to surrounding businesses and produce a risk of social exclusion to the communities affected. The change in the regular flow of customers could result in either an increase in revenue or loss for businesses. Even though the loss in business revenue is temporary, the negative impacts are a major concern because it may lead to the closure of some businesses (Yavuz et al., 2017). The business revenue loss and social exclusion may directly be linked to the number of households or users without direct access during the mobility impact time, average expenditure and income per household and the frequency of visits for work, leisure and living (Marsden et al., 2020).

iii. Re-routing of traffic: The different modes of bridge failure attributable to scour may cause different amounts of structural damage and can significantly reduce the traffic capacity of the road and railway link. The impacts of bridge service reduction on traffic and travel behaviour depend on the alternatives available such as the rerouting of traffic within the network or a shift to other modes of transport. For example, the closure of Forth Road Bridge in the UK resulted in 42% of car users and 46% of bus users shifting to railways to travel for work, and additional rail services were introduced to account for the traffic demand (Marsden et al., 2020). On the other hand, disrupted journeys on the railway network will usually be replaced using bus services and lorries, resulting in additional road traffic, and an increase in environmental emissions and accident risks on the road networks. While the rerouting due to the collapse of a road bridge in the USA costs $400,000 per day (Zhu & Levinson, 2010), the scour related railway passenger journey disruptions in the UK is estimated to cost £165,000 per day (Lamb et al., 2019). In the case of extreme events like bridge collapse, flooding or damage to bridges, the unplanned loss of transport capacity could necessitate traffic redistribution for a prolonged time. This could potentially generate significant user costs due to longer travel distance; higher levels of congestion, delays, vehicle operating costs, emissions and accident risks; and the resulting opportunity losses (Yavuz et al., 2017). The existing literature that deals with modelling the impacts of disruptions (Lamb et al., 2019; Marsden et al., 2020) indicates that both the scale and variety of traffic redistribution and travel behaviour during bridge closures or failure is larger.
than that considered in traditional transport disruptions (e.g. road closure).

iv. **Environmental impacts:** The collapse of bridges causes debris and spillages which contaminate the watershed which in turn can be harmful to human health, and can harm or kill wildlife. The failure can also release excessive dust and suspended particulates which in turn impacts the surrounding air quality and reduces visibility (Zanini et al., 2019).

v. **Third-party damage:** The bridge failure and the debris resulting from it often causes damage to agricultural land, private properties and goods and forestry (Yavuz et al., 2019). The bridge owning organisation responsible could be sued and fines that may be levied by government agencies.

vi. **Reputation:** The impact of transport agency’s reputation due to disruption results in loss of consumers (Srinivasan & Parlikad, 2017) and investor confidence that may follow an accident, particularly when the transport agency is found to be negligent or liable.

### 3.1. Uncertainties

While considering the macroeconomic impacts or costs of scour related bridge disruption or failure within the decision making, there are some challenges concerning the lack of data associated with costs, impacts, benefits, the depths of scour holes and bridge foundations, giving rise to uncertainties. The risk of scouring may also change over time due to changes in hydraulic conditions at the structure because of climate change, land-use change, construction of flood defences or channel migration, or changes in the catchment or watercourse upstream or downstream such as dredging or removal of a structure leading to bed degradation (Kirby et al., 2015).

Risk assessment techniques such as Monte Carlo simulations, Bayesian, Fuzzy logic and Petri nets are recommended to deal with such uncertainties (Rama & Andrews, 2016; Sasidharan & Torbaghan, 2020; Zhang & Wang, 2014). Majority of these techniques use historical data and probability judgements, and conclusions on the acceptability of the solutions are often made directly based on derived probabilities and confidence levels. However, in some instances, it might be difficult to deal with uncertainty using probabilistic risk assessment techniques due to the lack of data. Expert opinion is often suggested as a means of overcoming such issues (Sasidharan, Burrow, Ghataora, & Torbaghan, 2017).

### 4. Discussion

The continuous increase in demand on the transport networks creates a need for a risk-informed infrastructure management strategy, particularly for bridges as they are critical elements within the transport infrastructure. To improve the safety and availability of the transport network within constrained budgets, innovative methods that can continuously monitor the bridges are required to provide rapid and reliable information to the decision-makers, to schedule current and future inspection and maintenance strategies. The distributed guidance about inspection regimes and scour risk assessment for bridges has resulted in variable knowledge about the condition and performance of bridges across the transportation networks in the UK. For a given section of road or railway, choices need to be made by HE, NR or LAs, between alternative maintenance strategies. This situation is exacerbated when there are limited maintenance budgets and competition between different infrastructure systems (road, rail, drainage, signalling, bridges etc.) in terms of their monitoring and maintenance needs. While deferring inspection or maintenance intervention for a short term is an easy solution, it can be expensive in the long term as it increases maintenance and user costs, safety risks and environmental impacts.

Since scouring damage accounts for the majority of bridge failures, and the given the higher cost of repairs and the macroeconomic impacts of closure or failure of bridges, it is of critical importance to adopt a robust real-time monitoring strategy that can detect the development and presence of scouring. While different guidelines and standards exist for the scour risk assessment of road and rail bridges, the lack of a mechanism to share best practices has resulted in distributed and costly management of the country’s bridges. For example, unlike the road bridges standard of BD97/12, NR does not consider the consequences of scouring risks (operational impacts, safety etc.) within its risk assessment process. The operational impacts of scouring risks can be assessed by considering the loss of utility associated with disruption to passenger journeys and freight movement.

Furthermore, other factors such as route importance or disruption to railway passenger journeys and freight movement can also be considered within the decision-making process. Neither of the agencies accounts for the indirect costs associated with transport disruption due to bridge failure or closures, namely congestion and risk of accidents due to mode-shifts, risk of business closures and social exclusion, and downstream environmental impacts. This suggests that bridge owners and transport authorities need to consider the macroeconomic impacts associated with the failure or closure of critical infrastructure within their scour risk assessment processes alongside environmental and safety implications, i.e. to adopt a whole-life approach (Lamb et al., 2019; Vagnoli et al., 2018).

An effective inspection regime that includes bed measurement and engineering analysis can find indications of developing scour before the situation becomes critical (Lamb et al., 2017). While Highways England or Transport Scotland might be able to inspect all of its bridges, as envisaged by the DMRB or BD97/12, it is unlikely for many Local Authorities (LAs) who own more bridges of a wide variety of construction and age to do the same. For instance, LAs in England (outside London) control approximately 53,000 bridges with a span of 1.5 metres or more. In comparison, HE, TS and WA together own approximately 15,887 bridges that are mostly relatively modern in design
and construction. Moreover, LAs operate on constrained annual budgets that are often used for maintenance activities such as pothole repairs while considering the local pressures and circumstances.

For example, with a current bridge maintenance backlog of £590 million, LAs currently anticipate necessary maintenance work to be carried out on approximately 14% of 3000 sub-standard road bridges in the UK during the next five years due to budget constraints (Pregnolato, 2019). Most of the UK’s railway bridges were built in the 19th century and the foundation depths of these bridges are unknown (Rail Safety & Standards Board, 2004). NR’s standard for the management of existing bridges and culverts (RT/CE/S/080) states that all riverine bridges at risk of scouring are subjected to preliminary assessments once every 3 years (van Leeuwen & Lamb, 2014). In reality, since 2000 approximately 83% of bridges have only had two inspections, 16% had three inspections and only a limited number of structures (approximately 1.5%) have had 4–6 inspections due to an inherent asset defect (Yianni et al., 2017). While the commonly employed visual inspection results in less accuracy, continuous monitoring using sensors enables smarter and proactive asset management of bridges and increases the resilience and value of the transportation system (Srinivasan & Parlakad, 2017).

Considering that climate change is projected to increase the frequency and intensity of some extreme events such as floods, the importance of having resilient bridges that can maintain functionality during these events and quickly recover afterwards is of great significance. Taking into account the fact that bridges have a considerably longer service life, sometimes surpassing 100 years, it is of direct relevance to ascertain their condition and capacity against climate-change risks. Despite all these considerations, to account the fact that bridges have a considerably longer service life, sometimes surpassing 100 years, it is of direct relevance to ascertain their condition and capacity against climate-change risks. Despite all these considerations, to date, only a few studies have addressed the potential impacts of climate change on bridge infrastructure. Consequently, there is a need to extend current risk-based asset management systems to incorporate the effects of climate change and the associated time-dependent risk of bridge failures due to scour action.

5. Conclusions

The conceptual risk-informed approach introduced within this paper, unlike the scour management frameworks currently employed by transport authorities worldwide, considers the direct and indirect consequences associated with closure or failure of bridges due to scouring within the decision making. Such an approach will enable the economic appraisal using a whole-life asset management approach to inform inspection regimes, prioritise preventive maintenance of bridges in vulnerable areas of greatest failure risk, and identify cost-effective strategies to monitor and reduce risk. The latter may include, for example, the use of more initially expensive inspection techniques such as sensors but which have a lower risk of failure due to timely maintenance. If such an informed inspection regime is followed up with well-designed remedial works considering their whole-life value, undermining of the structure may be prevented even in extreme conditions.

As discussed above, data plays an essential role in the proposed approach since it is used to estimate the likelihood of scour formation and the consequences of subsequent bridge closure/failure. Integrating the proposed approach within a network-level asset management system could enable data stored within the databases of such systems to be easily accessed and interrogated. The customisation of the databases of typical network-level asset management systems should include provision for data relating to the climate, historical flood events and geological information in addition to the more typical data associated with inventory, scour depth, maintenance history and bridge usage. Some of these additional data may need to be provided by expert opinion. This can present a challenge for organisations not used to risk-informed asset management approaches. Bridge asset owners should therefore be encouraged to: (i) identify the bridges that are likely to be vulnerable to scouring, (ii) evaluate the physical characteristics of bridge infrastructure to understand the exposure to climate change or extreme events, and (iii) consider the macroeconomic impacts associated with bridge closure or failure while budgeting for monitoring and maintenance strategies. Furthermore, a robust and unified bridge management system would go a long way in establishing a holistic asset management culture.

In terms of future research, it would be particularly interesting to apply the risk-informed asset management approach introduced in this paper to identifying cost-effective inspection, monitoring and maintenance regimes. Although concurrent failures of multiple bridges across a transport network are rare, it would be interesting to study the impact of such low-probability, high consequence events. Moreover, the likelihood of such concurrent failures will increase if the increasingly frequent and intense storm and flood events occur as a result of climate change. Given that the end product of such a study may influence transport agency decisions, it would be appropriate to assess the relative effectiveness of different asset management strategies against impacts of climate change and budget constraints.

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