Risk Assessment of Masonry Bridges under Flood Conditions: Hydrodynamic Effects of Debris Blockage and Scour

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Part 1: Previous Research and Track Record

Dr Slobodan Djordjevic (SD) is Professor of Hydraulic Engineering in the College of Engineering, Mathematics and Physical Sciences at the University of Exeter. He has been a PI/Co-I on a number of EPSRC [1-5], NERC [6], EU [7-8] and KTP projects on hydraulic modelling and various other aspects of flooding. He leads the FP7 multidisciplinary consortium CORFU [7] (COllaborative Research on Flood resilience in Urban areas, www.corfu7.eu). He has significant experience in experimental modelling in areas of relevance to this proposal including flooding [5, 9] and mass transport in open channel flow [10]. He has published four book chapters and many highly cited journal papers on urban flood modelling and is a recognised authority in that subject, frequently invited to lecture at conferences and deliver advanced courses in Europe and Asia. His multidisciplinary research on the influence of flood risk on house prices in London (on SWERVE project [3]) received the European Real Estate Society Best Paper Award in 2011.

Dr Gavin Tabor (GT) is a Senior Lecturer in the College of Engineering, Mathematics and Physical Sciences at the University of Exeter. He has been involved in numerous EPSRC and other projects (5 as PI), including the Flood Risk Management Research Consortium - 2 (FRMRC) [4] and a KTP [11] in the area of urban flood modelling. A specialist in computational fluid dynamics (CFD), he has contributed to the OpenFOAM open-source CFD project that will be used in this research and is an acknowledged expert in its use [12]. His research covers both the fundamental development of CFD methodologies (e.g. turbulence modelling [13]) and its application to various industrial and scientific flow problems [11, 14]. Recent research has focused on the application of CFD to Sustainable Drainage Systems (SuDS) problems (e.g. PhD funded by Fundacao para a Ciencia e a Tecnologia, Portugal on effects of turbulence on flood control devices), particularly in collaboration with the company Hydro International (through KTP-funded PhD [11] and EngD).

Dr Prakash Kripakaran (PK) is a Lecturer in Structural Engineering in the College of Engineering, Mathematics and Physical Sciences at the University of Exeter. Prior to this, during 2006-2009, he was a post-doctoral researcher in Prof. Ian Smith's internationally-reputed research group in structural system identification at Ecole Polytechnique Federale de Lausanne (EPFL), a university ranked consistently within the top 20 in the world for engineering. Of interest to this proposal is his work in the areas of bridge system identification [15-16], bridge capacity assessment [17] and structural performance monitoring [18-19]. His links with asset owners and stakeholder groups involved in bridge management are also vital for this research. His paper titled *Improving system identification using clustering* [15] received the 2008 best paper award from the Journal of Computing in Civil Engineering. His world-leading work on system identification is included as a case study in the ASCE state-of-the-art report [20] on structural identification of constructed facilities.

Dr Scott Arthur (SA) is a Senior Lecturer at Heriot-Watt University. His research essentially comprises work on all aspects of urban drainage systems from roof systems to urban watercourses and large sewer networks. Research undertaken as part of research consortium activities – FRMRC-2 & Strategic Alliance for integrated Water management Actions (SAWA), using internationally leading work studying the formation of blockages in sewers as a starting point [21], has resulted in Heriot-Watt being regarded as leaders in understanding the flood risk associated with debris in rivers [22]. The key research outcome has been to understand which land uses are most likely to generate natural and/or anthropogenic debris and which types of trash screen are most likely to suffer blockage [23-24]. Research outputs from laboratory [24] and field derived data led to Dr Arthur being invited to draft a high impact Technical Note for Construction Industry Research and Information Association (CIRIA) which will be incorporated in UK culvert design guidance [25].

Research team

This research brings together expertise from diverse engineering subjects such as computational fluid dynamics, hydraulics, flood resilience, watercourse management, experimental modelling and bridge assessment to address an engineering challenge of paramount importance to the country's transport infrastructure.

University of Exeter (UoE) will draw on expertise and experience from two major research groups within the College of Engineering, Mathematics and Physical Sciences that has expanded greatly in the past two years.

- *The Centre for Water Systems (CWS)*: CWS has a strong international reputation for cross-disciplinary research into water management and hydroinformatics. It has been successful in completing projects funded by EPSRC, NERC, EU (5/6/7th Framework) and the industry, and in generating significant impact by transmitting findings into guidance. Its expertise includes hydraulics, hydrology, numerical modelling, simulation, optimisation, decision support systems, evolutionary computing, data mining and other methods. With a complement of 40+ personnel at any one time, it is the largest UK academic group in the field and one of the largest worldwide.
- *Structures and Dynamics Group (SDG)*: This group has recently been restructured and state-of-the-art equipped to

tackle a range of fundamental problems in infrastructure, aerospace, and biomedical systems. It was strengthened by a significant transfer from Sheffield (Professors Pavic, Brownjohn & Reynolds) in 2013 and has world-leading expertise in bridge and structural performance monitoring, and works actively with bridge operators and owners on issues related to structural management. The group has a strong track record of generating high-impact research with significant funding from EPSRC as well as excellent industrial links through Full-Scale Dynamics limited (FSDL), a university spin-off company that presents further opportunities for impact.

This research will also benefit from major investments the College has made in laboratory space and equipment. In particular, the experimental work in the proposal will benefit from (i) the availability of two full-time technicians in the fluids laboratory, (ii) a large-scale flume for hydraulic experiments that has recently been moved across the University from the sedimentation laboratory in Department of Geography to the fluids laboratory in Engineering with financial support from the College and (iii) state-of-the-art 3-D printing facilities in the Centre for Additive Layer Manufacturing (CALM) at the College. The College also strongly supports research co-creation with RCUK and other funding bodies, as proven by its recent success in securing EPSRC funding of over £10m to lead two CDTs, and is directly co-creating this proposal by funding a PhD studentship whose work will form an integral component of the proposed research.

Heriot-Watt University (HWU) led the Flood Risk Management Research Consortium (FRMRC) (2004-2012). Research activities are supported by a wide range of funders including: EPSRC; NERC; EU; Centre for Research Expertise in Waters (CREW); Rivers Agency (Northern Ireland); Office of Public Works (Ireland); Scottish Water; The Environmental and Clean Technologies Partnership; Indian Ministry of Earth Sciences (MOES); and, the Scottish Government. HWU has an excellent reputation for flood-risk research and end-user engagement is assured by the strong, established industry/stakeholder partnerships. The immediate researcher pool includes around 25 PhD students and 6 PDRAs working on debris and sediment transport research topics, as well as a significant number of wider collaborations.

In addition to the investigators from UoE and HWU, the project will also benefit from having ***Prof. Dusan Prodanovic*** from ***University of Belgrade (Serbia)*** as a visiting researcher. He is a noted expert in the field of experimental hydraulics and will act as an advisor to the research team on the experimental work planned in this research.

Industry consortium

The team has assembled a consortium of stakeholders as listed below:

- Jeremy Benn Associates (JBA)
- Mott MacDonald (MM)
- Cornwall Council
- Network Rail (NR)
- Bridge Owners Forum (BOF)
- Association of Directors of Environment, Economy Planning and Transport (ADEPT)
- Environment Agency (EA)
- Bill Harvey Associates (BHA)
- Devon County Council (DCC)
- Cumbria County Council
- Rail Safety and Standards Board (RSSB)
- UK Bridges Board (UKBB)
- Construction Industry Research and Information Association (CIRIA)

This consortium includes consultants (JBA, MM, BHA), asset owners (DCC, NR, Cornwall and Cumbria County Council), public agencies (EA), industry bodies (CIRIA, RSSB) and asset owner organizations (BOF, UKBB, ADEPT). A number of partners in the consortium have been or are involved in preparing guidance on evaluation and assessment of scour and hydraulic forces on bridges. Their experience and knowledge will help ensure that research outcomes are developed into methodologies that are suitable for integration within existing procedures for assessment and management of bridges.

References

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Part 2: Proposed Research

A. Introduction

The resilience of the UK's transport infrastructure to extreme weather events such as flooding is a major concern to the engineering community. Failure or reduction in service of bridges, which are vital links in the national transport network, can lead to loss of life and significant damage, hampers rescue and recovery efforts, and has severe knock-on effects on local and national economies. For example, 29 bridges, the majority being masonry bridges, collapsed or were severely damaged in the Cumbrian floods of 2009 [26]. The cost of repairing and replacing them was almost £34 million [27] excluding indirect economic and societal costs estimated to be at least an order of magnitude greater. The impact of the loss extended beyond the event and the replacement costs of the bridges as the unavailability of these bridges in the aftermath of the floods made journeys much longer for commuters. A one-mile trip was seen to become a 21-mile round trip in some cases while the travel time increased by as much as 2 hours at peak periods [28]. Additional costs to business due to increased travel time were estimated to be as much as £2m per week [28].

A major cause of bridge failure under hydraulic loading is debris in the watercourse. Research commissioned by the RSSB highlighted debris as the main factor in 20 out of 69 water-related failures of railway bridges [29]. In the US, drift or floating debris is cited as the primary cause for over one-third of bridge failures [30]. Debris can reduce conveyance capacity, enhance scour and increase hydrodynamic forces, which in turn may detrimentally affect bridge stability even under moderate flow rates. For example, in 2009, a masonry bridge owned by Network Rail at Feltham (Fig. 1) failed by subsidence at one of its abutments due to scour induced by debris although flow rates in the river were well below the levels required to trigger flood alerts [31]. The failure led to chaos on the south west train services with thousands stranded or facing lengthy commutes on replacement bus services.

Fig. 1: Debris accumulation at a masonry bridge (left); failure of Network rail's bridge at Feltham due to debris-induced scour (right)

Debris build-up can occur around any obstruction to water flow such as bridge piers. Masonry bridges, which constitute over 40% of the nation's bridge stock [32], are particularly susceptible to debris blockage due to their short spans and low clearances over water levels. While hydrodynamic effects due to debris are known to significantly heighten the chances of bridge failure by worsening pier scour and constricting flow, current guidance for design and assessment of bridges for hydraulic action [33-34] are highly inadequate for evaluating these risks. This was cited as one of the major reasons for bridge failures in Cumbria in the written evidence submitted by various stakeholders to the parliamentary transport committee that looked into the impact of the floods of 2009 on bridges and other transport infrastructure in the region [35]. This proposal will directly address this urgent and practical need for an approach to evaluate the risks from debris accumulation at bridges. ***It will investigate the hydrodynamic effects of floating debris in the watercourse during floods, and devise a systematic methodology to assess risks of debris blockage on masonry bridges and on bridge piers. The methodology, which will be built into existing CIRIA guidance [33] for assessment of bridges under hydraulic action, will enable optimal planning of interventions to effectively target bridges at risk to debris blockage and thereby improve resilience of the transport network and the rate of post-flood recovery.***

This research comprises of the following three key elements:

1. Froude-scale hydraulic experiments to depict effects of debris blockage on flow parameters and pier scour.
2. Numerical modelling to simulate flow under masonry bridges and around bridge piers with floating debris blockage.
3. Formulation of a risk-based strategy to assess the hydrodynamic effects of debris accumulation at bridges.

B. Background

Why are hydrodynamic effects of debris important in the context of bridge assessment?

Debris in the watercourse poses several threats to bridges. The force from debris impact can cause substantial damage to bridges yielding reduced service or even causing their collapse [36-37]. Large pieces of debris such as logs constrict flow, and further trap sediment [38] and other smaller pieces [39] thereby leading to massive debris build-up either around individual piers or covering full spans of bridges. Effects of debris blockage are similar to having a porous weir in the watercourse [33]. Debris obstructs flow, raises water levels and increases flow velocities immediately downstream [30]. These effects, in turn, influence scour and hydrodynamic forces on bridges. Scour is generally classified into three types – natural, contraction and local scour [33]. *Natural scour* is that due to channel and catchment characteristics regardless of the bridge. *Contraction scour* is caused by reduction of channel width such as from presence of piers in the riverbed. *Local scour* refers to scour in the immediate vicinity of specific obstructions to flow such as piers or dykes. Of these three types of scour, debris mainly affects contraction and local scour [30, 40]. If the blockage was to significantly increase water levels, it may also lead to large lateral and uplift forces on the bridge superstructure [33]. Masonry bridges are especially vulnerable since their capacity to resist imposed loads is derived from the self-weight effects of the masonry and fill, which may be fully or partially negated by buoyancy forces during flooding [33, 41]. High flow velocities due to debris blockage in combination with uplift forces can cause mortar scour in the arch ring and lead to catastrophic structural collapse [42]. Debris can also change angle of attack on piers thereby increasing local scour or even shifting flow around bridges [43]. Combinations of the above effects, yet to be fully investigated by research, were cited as causes for the bridge failures in Cumbria [35] and Boscastle [44]. *This work will fill this current knowledge gap that prevents evaluating bridge vulnerability to debris blockage, a concern raised by the bridge engineering community in the aftermath of recent floods [35] and a topic of increasing importance particularly with more frequent and clustered severe flood events such as in the winter of 2013/14 predicted due to climate change.*

How can one determine the size and rate of debris accumulation at bridges?
Debris at bridges can be from natural or man-made sources. Woody debris is common during floods since running water often picks up tree logs and branches in the *riparian zone* and transports them downstream due to the increased flow [45]. In urban areas, severe floods have been observed to even take cars and other vehicles in their flow [44]. Many studies have investigated debris accumulation in rivers and channels in non-structural contexts such as for flood risk [44] and ecological impacts [38, 46]. Of note is the work by EPSRC-funded FRMRC-2 that developed ways of characterizing the risk of debris blockage at structures as a function of catchment characteristics and rainfall patterns [21-24, 47-48]. While their work predominantly focused on debris formation at culverts, results are transferable to other structures such as bridges. Schmocker and Hager [49] used experimental studies to develop a systematic approach to determine the probability of debris blockage at the level of bridge decks from debris dimensions, flow parameters and bridge characteristics. Diehl [30] performed an in-depth study for the U.S. Geological Survey and devised a method to predict the maximum size of debris accumulation in a manner similar to FRMRC-2. This study showed that the risk of debris blockage is high for bridges with spans shorter than the design log length [29], which is the probable size of tree logs as evaluated from channel and catchment conditions. Thus, in reviewing the literature, it is clear that the knowledge for characterizing debris accumulation is readily available. However, this knowledge has not been utilized for bridge assessment due to a lack of research into understanding and predicting the hydrodynamic effects of debris blockage at bridges and, in particular, at masonry bridges, which are recognized as the most vulnerable to debris blockage and form the majority of the UK bridge stock. *This research thus aims to take forward recent research in the UK and abroad on debris blockage for the structural assessment of bridges under hydraulic action.*

How are effects of debris blockage currently evaluated for bridge assessment?
Hydrodynamic effects of debris mainly affect the following two factors: (1) scour and (2) lateral and uplift forces. While scour has long been recognized as a major cause of bridge failure, time varying hydrodynamic forces have received significant attention only after recent bridge failures due to extreme events such as from hurricane Katrina in the USA [50-51]. In the UK, CIRIA's C551 manual [33], which provides detailed guidance on evaluating scour depths and on scour protection and mitigation techniques, is the leading industry reference for scour risk assessment. Major asset owners such as Highways Agency (HA) and Network Rail (NR) [52] use risk-based approaches, which derive from or depend on the methodology in C551, for assessing bridges under hydraulic action. For example, HA's BD97 [34] offers a procedure to compute priority ratings of bridges based on their importance and susceptibility to damage due to scour. HA's BA59 [53] is the main reference for evaluating flood effects that are not scour-related such as lateral and uplift forces. While all these mention the importance of debris blockage to bridge safety, none except RSSB's T554 [52] offer an approach to evaluate the effects of debris blockage on scour and hydrodynamic forces at individual structures. A major reason for this is a lack of the scientific knowledge required for reliably predicting flow velocities downstream of debris. Even T554 [52] simplistically assumes that the hydrodynamic effects of debris blockage at a structure obstructing flow can be simulated by modelling an equivalent flow constriction. Hence it recommends evaluating scour due to debris blockage at a pier as the scour for a pier of the same type but with twice the width. This approach ignores effects of debris on factors related to downstream flow patterns such as the angle of attack at a pier, which can be significant as in the case of the bridge failure at Feltham [31]. Also, no reliable method is currently available to evaluate effects of debris

on hydrodynamic forces, which have been cited as an important factor in recent flood-related bridge failures [35, 54]. *This research will fill this key industry need for a reliable method to evaluate the risk of debris blockage at bridges by investigating and characterizing the fundamental hydrodynamic effects of debris blockage, and then transferring this knowledge into relevant guidance for practitioners.*

C. Aim and Objectives

This research will (i) *develop methods* to evaluate the hydrodynamic effects of debris accumulation underneath or upstream of masonry bridges and typical bridge piers under flooding scenarios, and (ii) *integrate findings* into a risk-based approach for assessment of bridges under hydraulic action. It is mainly concerned with assessment of scour at piers and abutments, and of lateral and uplift forces on the bridge due to *floating debris* blockage. The process of *debris formation* and forces from *debris impact* are not part of this investigation. The objectives of this research are as follows.

1. Perform a series of hydraulic experiments in laboratory flumes using scale models of potential obstructions to determine the hydrodynamic effects due to debris blocking water flow.
2. Create numerical models for simulating fluid flow and scour around masonry bridges and bridge piers with debris accumulation, and validate these models using results from flume experiments.
3. Employ numerical models to generate the empirical relationships between flow characteristics, hydraulic conditions and structural geometry in order to create the knowledge required for methodology development.
4. Develop a *risk-based approach*, compatible with existing risk-based methods of assessing flood risk to bridges, to predict the hydrodynamic effects on a masonry bridge or bridge pier suffering from debris blockage during floods.
5. Incorporate approach into existing CIRIA guidance [32] on scour at bridges and other hydraulic structures, and illustrate its application to a set of key bridges in collaboration with industry partners.

D. Programme and Methodology

D.1. Research Methodology

This research consists of three work packages (Fig. 2), which will be completed by two post-doctoral research assistants (PDRA1/PDRA2) and one UoE-funded PhD student. WP1 and WP2 aim to study and characterize the interactions between various parameters related to scour and hydrodynamic forces at bridges. Froude-scale hydraulic experiments conducted with prototypes of a masonry bridge and typical bridge piers in WP1 will inform and support development of computational fluid dynamics (CFD) models in WP2. WP2 will have two strands of work to estimate the two main parameters of interest for structural assessment during floods: (i) scour and (ii) hydrodynamic pressures. WP3 will incorporate the gained knowledge in a strategy to evaluate individual bridges for the risks due to debris blockage.

D.2. Work Packages

<u>*WP1: Hydraulic experiments (Lead: Slobodan Djordjevic, CI: Scott Arthur & Researcher: PDRA1)*</u>

The objective in this work package (Fig. 2) is to use laboratory experiments to help understand how debris in the watercourse changes flow characteristics and thereby influences scour and forces on bridges. The team will use a large rectangular flume that is 0.6m wide, 0.7m deep and 14m long to perform a series of hydraulic experiments to capture the interactions between channel, flow and debris-related parameters. Choosing an appropriate scale for modelling is critical to get reliable results from flume experiments. Initial calculations considering constraints on flume sizes and flow rates with facilities at UoE have shown that Froude-compatible experiments with 1:10 length-scale models of short-span masonry bridges (< 6m spans) with flow rates up to 200 litres/sec are viable. Multi-span bridges and those with longer spans may require modelling at smaller scales. Experiments on several models of various kinds of masonry bridges in real-life scenarios are also practically infeasible due to cost and time constraints. Hence we will first evaluate debris effects using a prototype of a chosen short-span bridge. The understanding from laboratory experiments will then help calibrate CFD models that are capable of simulating results for a broader set of scenarios in WP2. Dart Bridge, which is a masonry arch bridge over the Dart river in Bickleigh near Exeter and is currently managed by a project partner (DCC), has been selected as the prototype for this research. In addition to Dart Bridge, we will

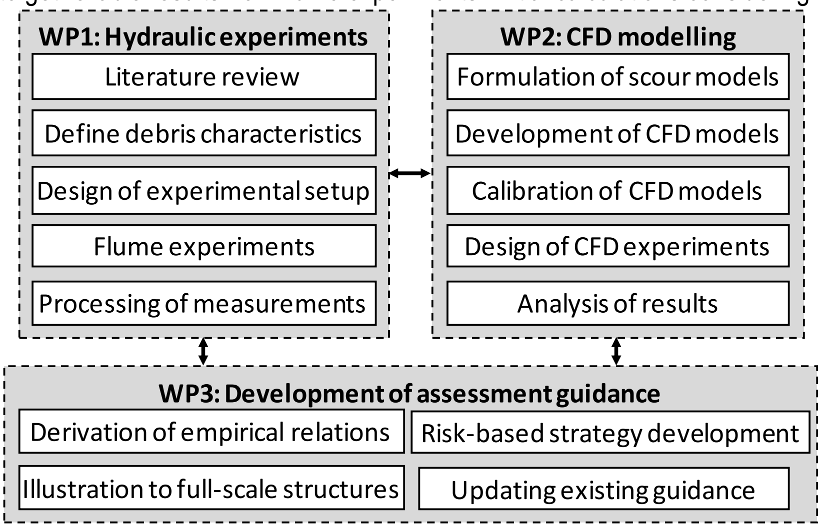

Fig. 2: Work-packages in proposal

create prototypes of typical bridge piers susceptible to debris blockage and experimentally investigate flow around such structures. Material similar to river sand sediment (non-cohesive) will be used to study scour. We will use collected measurements to also compare against current practice of assessing debris-induced scour by increasing pier sizes [52].

To consider the types of debris for simulation in the flume, we have had (i) consultations with industry partners (including JBA who are leading an ongoing EA-funded project [55] on blockage and debris modelling guidance), (ii) have examined previous research on characterizing debris accumulation in channels and bridges, and (iii) have as a project partner, the investigator for the recent FRMRC-2 research in the UK [21-24,47-48] and related work abroad [25,30,40]. These have helped define the common types of debris blockage at bridges and piers during floods. Debris types are largely dependent on catchment conditions and can be classified under the following geometries: (i) cylindrical shapes for wooden logs, (ii) rectangular blocks to simulate large debris from trees that cover full bridge spans and cars resembling debris in urban areas and (iii) triangular wedges to simulate debris accumulating at piers. Debris models will be created from a polymer called PEEK using 3D printing at UoE with an internal structure that will be manipulated to match the density of real debris. A geometrically exact model of typical coarse wooden debris (e.g. a tree trunk with branches) will also be created to experimentally assess the reliability of using regular geometrical shapes for approximating real-life debris. Models of Dart Bridge and bridge piers will be created in Perspex to a scale of 1:10. The bridge model will be designed to hold pressure transducers to measure pressure distributions upstream and underneath the bridge.

The bridge and debris models will be placed in the flume, which will be equipped with ultrasonic Doppler flow meters for collecting flow velocity measurements and SONAR-based fathometers for scour depth measurements. Flow conditions for simulation will be determined from C551 [32] and FRMRC-2 outputs [47] to match the flow characteristics for bridge assessment during floods. Flow rates in the flume will be scaled appropriately to have Froude compatibility with actual flow regimes. Lateral and uplift forces on the bridge model will be measured using a system of load cells between the bridge model and rigid steel frames mounted downstream of and above the model. Design of this experimental setup for collecting measurements in the flume will be a challenging task. Significant prior experience in field and laboratory hydraulic measurements will be helpful in ensuring that experimental simulations are representative of real-life situations. The team will therefore be assisted in this phase of the project by a visiting researcher - *Prof. Dusan Prodanovic* from University of Belgrade, who is an internationally-recognized expert in experimental hydraulics. The designed setup will support a series of experiments that vary systematically the combinations of flow conditions, debris types and positions, pier types and bridge orientation. This will be done to capture the interactions between channel, flow and debris-related parameters, with carefully chosen lengths upstream and downstream from the bridge model. For each combination, scour depths, flow velocities near piers/abutments, and forces on the bridge will be measured and stored.

WP2: Computational modelling (Lead: Gavin Tabor, Researchers: PhD, PDRA2)

WP2 (Fig. 2) will focus on the application of CFD to predict hydrodynamic effects of debris blockage for a broad range of bridges. For reasons of computational efficiency, Reynolds-Averaged Navier-Stokes (RANS) modelling with the k-ω model will be used to represent turbulence. Free surface flow will be treated using the standard Volume of Fluid (VOF) method to capture the interface. Parameters in the CFD models will include channel dimensions, bed conditions, flow rates and geometries of bridge and debris. The debris will be modelled as static solids obstructing flow in the channel, with shapes matching the three main types specified in WP1 above (cylinders, rectangular blocks, triangular wedges). Geometry development and meshing will be carried out using the commercial code Pointwise, whilst the open source code OpenFOAM, which already implements the necessary VOF modelling, will be used for the CFD simulations. The inlet flow rates on the upstream side will be provided as boundary conditions.

In WP2 we will evaluate computationally the two main hydrodynamic effects on a bridge, namely *scour* and *pressures*. Two distinct approaches to modelling scour will be investigated and later compared for their effectiveness. In the first approach, sediment transport will not be modelled explicitly in CFD; instead, scour will be estimated from flow velocities predicted by the models. The predicted velocity distributions will be used in combination with the depth-averaged critical threshold velocity computed using procedures given in C551 to determine the maximum scour depth. This will represent a simple but robust approach to identify areas where scour may be significant. In the second approach, we will develop and implement a novel scour model allowing the development of scour holes using the mesh adaptation and morphing capabilities available in OpenFOAM. Bed load transport will be represented with empirical models based on the bed shear stress and suspended load using a concentration obeying a standard transport equation. Erosion will be simulated by moving the boundary points perpendicular to the bed in regions where the shear stress exceeds a critical value at a rate governed by empirically-determined relations [56]. Mesh motion techniques in OpenFOAM include techniques for interior grid relaxation, which will help maintain adequate quality meshes for the simulations. Pressure distributions, which are a direct output from CFD simulations, can easily be evaluated on surfaces representing the bridge structures.

Validation of CFD parameters such as mesh resolution is crucial to ensure that models represent real flow conditions reliably. Initial validation of the modelling techniques and of the scour model will be compared against literature data for simple cases e.g. surface piercing cylinder [57]. Having validated the methodology for these cases, we will use results from the laboratory experiments in WP1 to further test the CFD models. We will generate CFD models of Dart Bridge and that of piers in the channel with flow conditions as modelled in the experiments in WP1, and compare against measured values of velocity, pressures and scour. The validation process will be aware of the uncertainties and errors in flume experiments and models. While full-scale CFD models match both Reynolds and Froude numbers at real situations, flume experiments at a reduced scale meet only Froude criteria. Previous research has shown that results from flume experiments often overestimate scour and forces [43]. Our approach will be to calibrate the CFD modelling against lab-scale models and then scale up computationally to investigate the full scale correctly. Accuracy and computational costs of the two distinct approaches for scour prediction and modelling will be assessed to determine the most suitable approach for the next stage of the project.

Scour depths (*D*) will be empirically related to flow velocities (*U*) near piers or abutments based on results from the scour modelling approach identified as the most suitable for scour prediction. We will then use full scale CFD simulations to predict debris effects for a diverse set of debris and bridge scenarios. Since preparation and processing of CFD models incurs significant time and resource costs, obtaining results for every scenario that may be encountered in practice is infeasible. This research will employ a *fractional factorial design* to evaluate the interactions between model parameters that largely determine the two quantities of interest – flow velocities (*U*) and pressures (*P*). The experimental parameters are: (1) area of channel cross-section after accounting for debris blockage, (2) flow rates, (3) bridge orientation to channel, (4) debris location in terms of its distance upstream of bridge, (5) geometry of masonry arch defined in terms of its height and span length, (6) number of bridge spans and (7) shape of bridge pier. Results from WP1 will help make informed choices on the initial range of values for the first four parameters. They will also provide an indication of the nonlinearity in the relationships between these model parameters and the two quantities of interest. Therefore, experiments will first capture the influence of these four parameters on *U* and *P*. Subsequently, the effect of bridge geometry will be studied by varying the height to span ratio of the bridge; this is expected to mainly have an impact on the uplift pressures on the structure. The effect of debris blockage at multi-span bridges will then be examined. Scour at intermediate piers and at abutments due to debris accumulation at an individual pier or due to blockage of an entire span will be investigated. Results from the models, which will include flow velocities around piers and abutments, and pressure distributions on the bridge superstructure, will be compiled for use in WP3.

WP3: Assessment guidance development (Lead: Prakash Kripakaran, CI: Scott Arthur, & Researcher: PDRA2)
This work-package will focus on the development of a risk-based methodology, which integrates with current approaches for assessing bridges under hydraulic action [33], for evaluating debris-induced scour and hydrodynamic forces at a given masonry bridge or a bridge pier. This methodology, which will use results from WP2, will have the following steps:

Step 1: Assess the potential for debris accumulation at given bridge. This step will integrate knowledge gained in WP1 in choosing debris models with the experience of project partners (ADEPT, BOF, UKBB, NR) and Co-I (SA) in managing debris at assets. This will be used to devise a strategy to predict the maximum size, type and geometry of debris build-up at individual bridges or piers based on catchment and channel characteristics. This will draw directly on work being undertaken by Co-I (SA) as part of the Blue Green Cities project (EP/K013661/1) to develop an end user focused model to predict the risk of debris arrival at individual river structures. It will also use findings from an EA-funded project to produce blockage and debris modelling guidance being led by partner (JBA) and expected to finish in 2014.

Step 2: Evaluate vulnerability of bridge to debris effects from its potential for debris blockage and based on channel and bridge parameters. The following two-stage process that depends on the structure's exposure to debris effects will be developed: (i) rating of bridge according to its vulnerability to debris effects and (ii) evaluation of scour depths and forces if bridge is classified as vulnerable to the hydrodynamic effects of debris. The first stage will employ a strategy to identify and prioritise assets that may be exposed to damage from debris effects. It will help identify bridges that require further examination in the second stage using a more detailed and systematic approach to evaluate debris-induced lateral/uplift forces and scour. Results collected in WP2 will help in the development of the approaches for these two stages. We will first analyze the data to define threshold criteria based on the range of values for debris, channel and bridge parameters for which debris effects are important. These criteria will be used to set vulnerability thresholds. Building on this, model predictions from WP2 will be generalized so that they are applicable to all masonry bridges and bridge piers, and re-formulated as empirical relations in the form of graphs and charts for embedment within the second stage of this step. The goal will be to predict depth-averaged flow velocities and uplift/lateral pressures from flow, channel, debris and bridge-related parameters. Flow velocities will then be related to scour depths using the approach derived in WP2 after the calibration process. Pressures can be converted into equivalent lateral and uplift forces, which may then be considered in combination with the bridge's self-weight and structural configuration to determine the risks these forces may pose to structural stability.

The team will lastly illustrate application of the developed methodology to analyse a number of masonry bridges, which have been chosen to cover a range of scenarios from those that failed due to debris blockage during floods to those that suffered only minor damage. These bridges are (1) Feltham bridge over river Crane, (2) Calva bridge and (3) Northside bridge over river Derwent in Cumbria, (4) B3263 bridge over river Valency in Cornwall, (5) Rothern bridge over river Torridge in Devon and (6) the Lower Ashenbottom viaduct over river Irwell in Lancashire. Relevant data for their assessment will be provided by industry partners (County Councils, NR, JBA and EA). Illustration on these structures will help validate the methodology and also form examples for practitioners as part of an updated CIRIA guidance [33].

E. Project Management

This project will require two PDRAs and one UoE-funded PhD to complete the work. Duration of the two PDRAs has been staggered to suit the project (see workplan). PDRA1 with a PhD in scour/hydraulic engineering and background in experimental work is needed for two years and will focus on WP1. The UoE-funded PhD will investigate computational modelling of debris-induced scour (WP2). PDRA2 with a PhD in CFD modelling will commence work in the second year of the project. PDRA2 will work alongside the PhD on calibration of CFD models and complete the rest of the tasks in the project including development of a risk-based approach (WP3). This post will be for 30 months. UoE investigators SD, GT and PK will lead WP1, WP2 and WP3 respectively. SD will have overall responsibility for managing the project. SA from HWU will contribute primarily to WP1 and WP2. An industry Steering Committee with members from various stakeholders will oversee the project. It will be chaired by Richard Fish of BOF and will formally meet every six months with the first at the start of the project. PK will coordinate project meetings and communication with partners.

F. Timeliness, Novelty and National Importance

Proposed research is very timely given recent flooding events such as those of winter 2013/14 in the South-West, where the collapse of sea wall in Dawlish caused major disruptions to rail traffic west of Exeter for nearly two months and cost the local economy of Plymouth over £240m [58]. The recent ICE's state-of-the-nation report [59] on infrastructure also stresses the need for greater resilience to flooding in the UK's transport sector and urges investments toward improving asset management procedures of structural assets, an expected impact of the guidance produced by this research.

The project is novel as no scientific approach is currently available to evaluate how debris in the watercourse affects the structural performance of bridges. This significantly limits the level of assessment and protection measures offered to bridges against flood-related damage, and also limits assessment of the resilience of our transport networks.

This research falls within EPSRC's strategy on global uncertainties and living under environmental change themes. It will address a specific request made by various stakeholders to the UK government's transport committee, in the aftermath of the Cumbria floods, for further research into debris effects on bridges [35]. It will also provide solutions to challenges highlighted by the UK government toward creating a climate resilient infrastructure [60]. Lastly, masonry bridges are not only important elements of our transport infrastructure, but many of them are also part of our national heritage and cannot be subject to replacement. This research will enable us to better preserve them for future generations.

H. References

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