Response to Independent Reviewer Comments RC2

Comment: This paper examines the factor affecting bridge resilience and illustrates through literature research and the output of a recent workshop with major stakeholders in the sector possible actions to take based on the points individuated.
The paper is a welcome contribution given the importance of the infrastructure on the built environment and the future predicted impact of climate change, and present several important challenges and future opportunities. While the work is very comprehensive, there could be a few additional points of reflection that could be included:

Reply: We thank the Independent Reviewer for their appreciation of the merits of the work and for the suggestions for improvement.

Comment: In general, the text could be accompanied by more results from the literature, in particular of these could help highlight the elements of uncertainty.

Reply: Following the Reviewer's recommendation, we have added more references to the results in the literature, as discussed in detail in the responses to the following comments.

Comment: Line 135: One of the main factors of uncertainty in the scouring equation could be discussed further, examples include the definition of critical velocity (see Hamidifar et al 2021)

Reply: We agree with the Reviewer that empirical equations for scour assessment contains parameters such as the critical velocity whose definition is characterised by significant uncertainty. We have added the following sentences in the manuscript:

Artificial intelligence (in particular Machine Learning) is increasingly being used to produce more accurate multi-variate empirical predictors for scour (see e.g. Sharafi et al. 2016)…
..Another significant source of uncertainty affecting the estimation of the maximum scour depth is the evaluation of the flow critical velocity separating clear-water from live-bed conditions (Hamidifar et al. 2021).

The following references have been added:
Hamidifar, H., Zanganeh-Inaloo, F., & Carnacina, I. (2021). Hybrid scour depth prediction equations for reliable design of bridge piers. *Water*, *13*(15), 2019.

Sharafi, H., Ebtehaj, I., Bonakdari, H., & Zaji, A. H. (2016). Design of a support vector machine with different kernel functions to predict scour depth around bridge piers. *Natural Hazards*, *84*(3), 2145-2162.

Comment: Line 150: I would highlight also the first works by Oliveto and Hager 2002 and 2005, on temporal scour evolution

Reply: We agree with the Reviewer on the importance of the works of Oliveto and Hagers on the topic and have added them in the revised manuscript. The sentence:

"*Methods for time-dependent scour evaluations have been developed that can be applied for the assessment of scour under single (or multiple) flood events, opening the avenues for more accurate scour estimates. Additionally, and worthy of mentioning is the recent contributions for time-dependent scour modelling under non-stationary conditions. Among them, Pizarro et al. (2017a,b) and Link et al. (2017) proposed..*"

has been rewritten as follows:

"Methods for time-dependent scour evaluation have been developed that can be applied for the assessment of scour under single (or multiple) flood events, opening the avenues for more accurate scour estimates. The first studies on the topic considered the case of idealised hydrographs and clear-water conditions (see e.g. Oliveto and Hager 2002, Oliveto and Hager 2005), whereas more recent ones have also used more realistic hydrograph shapes. Recently, Pizarro et al. (2017a,b) and Link et al. (2017) proposed a model based on the dimensionless effective flow work, W*, for dealing with flood waves, and validated it against a wide range of unsteady conditions. Additionally, Link et al. (2020) proposed an extension of the model to consider the counter effects of erosion and deposition within the scour hole, which are typical of live-bed conditions."

The following references have been added:

Oliveto, G., Hager, W.H. (2002). Temporal evolution of clear-water pier and abutment scour. J. Hydraul. Eng. 128(9), 811–820.

Oliveto, G., Hager, W.H. (2005). Further results to time dependent local scour at bridge elements. J. Hydraul. Eng. 131(2), 97–105.

Comment: 175 -180 I would show some of the possible morphologies individuated from literature, which would help illustrate the point on important differences.

Reply: In general, morphologies are available for the simplified case of cylindrical piers. A recent work from Lee et al. (2020) has investigated more realistic pier and foundation shapes. The following text has been added in the manuscript:

"It is usually assumed that the shape of scour hole is indeed independent of the flow conditions and that it can be approximated by an inverted paraboloid with the upstream slope corresponding to the sediment's angle of repose, but these assumptions work well only for simple geometries such as cylindrical piers, as proven by Chreties et al. (2013), local scour conditions, and also for a flow direction perpendicular to the bridge longitudinal axis. Lee et al. (2021) have recently investigated experimentally the evolution of scour around piers and foundations with complex shape other than the cylindrical one, confirming that the maximum scour depth is attained upstream of the pier."

The following reference has been added:

Lee, S. O., Abid, I., & Hong, S. H. (2021). Effect of complex shape of pier foundation exposure on time development of scour. *Environmental Fluid Mechanics*, *21*(1), 103-127.

Comment: 210 Scouring on deck by Carnacina et al with debris accumulation also illustrate the potential increased scouring as well as flow acceleration (Carnacina et al. 2019)

Reply: We agree with the Reviewer that this is a topic of extreme interest, as also emerged in a meeting between few authors of this study and Mark Pooley (Highways England). The following text and references have been added:

Another topic that is receiving considerable attention by researchers is the pressure-flow scour due to vertical contraction, which takes place in the case of submerged bridge deck (Carnacina et al. 2019). A recent review paper (Majid and Tripathi 2021) discusses the many research needs in this field.

The following references have been added:

Carnacina, I., Pagliara, S., & Leonardi, N. (2019). Bridge pier scour under pressure flow conditions. *River Research and Applications*, *35*(7), 844-854.

Majid, S. A., & Tripathi, S. (2021). Pressure-Flow Scour Due to Vertical Contraction: A Review. *Journal of Hydraulic Engineering*, *147*(12), 03121002.

Comment: 220 Would be nice to have a comparison of various literature fragility curves, again as an illustration of the vast uncertainty existing around their determination also in line 265

Reply: Unfortunately, there are very few fragility curves available in the literature, and these cannot be compared because they refer to different bridge typologies and also they are based on different intensity measures. The problem of the definition of appropriate intensity measures is discussed in the paper in Section "2.3. Vulnerability of various bridge typologies" and research needs are highlighted in Table 1.

Comment: Line 410 the reference to Bayesian Networks is not fully clear? It seems an important challenge but the expected outcome could be extended further, how this could merge the data?

Reply: The text in the original manuscript:

"*One way to overcome the cost limitation is to install monitoring systems only at critical locations, by extending the information gained at these locations to the other assets through the use of Bayesian Networks. Criticality could be defined operationally, by asset owners, or take account of wider analysis of the number of users who may be directly or indirectly disrupted by the failure of physically interdependent infrastructures (see Thacker et al., 2017). This approach has been developed originally by Maroni et al. (2020) considering the problem of scour risk assessment, using data from scour probes (Figure 4a) and gauging stations. It has been subsequently extended to include observations from inclinometers or GPS receivers (Tubaldi et al., 2021), which may also be useful for assessing the bridge state. A further extension of the developed Bayesian Networks is required to allow merging information with different temporal resolutions, such as bathymetry observations obtained during inspections (every few years) and continuous measurements of flow height or surface velocity. Such an extension would also allow accounting for the results of inspections. Methodologies are also needed for using sensor data to support decision-making and for quantifying the benefit, in terms of better-informed decision making, of the information provided by sensors.*

Concepts such as the value-of-information and the reduction of relative entropy could be used for this purpose (Giordano et al., 2020, Tubaldi et al., 2021), whereas theories such as expected utility

(Cappello et al., 2016) and multi-criteria decision making (Triantaphyllou, 2020) could help to set sensor reading thresholds and configure alert settings."

has been rewritten as follows:

"One way to overcome the cost limitation is to install monitoring systems only at critical locations, by extending the information gained at these locations to the other assets through the use of Bayesian Networks (BNs) (see e.g. Maroni et al. 2020). These probabilistic tools provide a graphical representation of the various variables involved in a problem (e.g. scour risk assessment for a set of bridges in a network), and of their conditional dependencies. BNs can be used to efficiently spreading inside the network the information from sensors, which is usually limited to few variables (i.e. nodes). Maroni et al. (2020) developed a BN-based framework for evaluating the scour risk for three bridges crossing the river Nith in Scotland, exploiting data from scour probes installed at a bridge (Figure 4a) and gauging stations. The framework has been subsequently extended to include observations from inclinometers or GPS receivers (Tubaldi et al., 2021), which may also be useful for assessing the bridge state. A further extension of the developed BNs is required to allow merging information with different temporal resolutions, such as bathymetry observations obtained during inspections (every few years) and continuous measurements of flow height or surface velocity. Such an extension would also allow accounting for the results of inspections. Methodologies are also needed for using sensor data to support decision-making and for quantifying the benefit, in terms of better-informed decision making, of the information provided by sensors. Concepts such as the value-of-information and the reduction of relative entropy could be used for this purpose (Giordano et al., 2020, Tubaldi et al., 2021), whereas theories such as expected utility (Cappello et al., 2016) and multi-criteria decision making (Triantaphyllou, 2020) could help to set sensor reading thresholds and configure alert settings. The criteria could be defined operationally, by asset owners, or through wider analysis of the number of users who may be directly or indirectly disrupted by the failure of physically interdependent infrastructures (see Thacker et al., 2017)."

Comment: Other general comments include:

Plots with the cause of failure of bridges as a percentage of mechanism, given the breadth of the stakeholders this statistic would be very welcomed

Reply: We agree with the Reviewer that this piece of information would be very important, but unfortunately, such statistics are not available. We have added this as a gap/need in Table 1 "List of actions and next steps for improving bridge resilience to flooding":

"- Statistics of the principal causes of failure and collapse mechanisms for various bridge typologies."

Comment: In the table and based on a high-level cost/opportunity analysis, which action should be taken first or prioritized, together with a desired temporal framework.

Reply: It is difficult to establish priorities and timeframes, since the research needs and challenges refer to various areas, where different experts and stakeholders should be involved (e.g. from hydrologists to structural engineers and bridge managers and inspectors). Thus, the various actions should and could be carried out in parallel. Moreover, timescales can be very uncertain and strongly affected by governmental choices and allocation of resources for research and risk mitigation. For these reasons, rather than adding an estimate of the timeframe in the table, we have added a list of actions aimed at filling research gaps and addressing the identified needs and challenges.
The revised Table 1 is attached at the end of this document.

Comment: Protections are generally overlocked, but several older bridges have been protected with rip-raps gabions, block ramps or similar structures.

Reply: We agree that protections have not been sufficiently described in the manuscript. However, we feel this is out of the scope of the Invited Perspectives article, which does not aim to provide an exhaustive review of available techniques. The CIRIA Manual provides a good overview of techniques and good references.
We have clarified this in the revised manuscript by rewriting the sentence:

"*This framework could be used to identify cost-effective solutions for bridge scour management and risk mitigation.*"

as follows:

“This framework could be used to identify cost-effective solutions for bridge scour risk management and mitigation. It could also be extended to allow selecting the most appropriate scour protection measure among the many available (see e.g. Kirby et al. 2015).”

Comment: I can’t find Cantero-Chinchilla and de Almeida, 2021 in the list of references, which should illustrate the literature on debris impact on scouring. Other references on the topic exist that show the impact of debris accumulation on scouring, the impact on scouring protection that highlight important results on scouring temporal evolutions and morphologies (see for example the early work by Melville and Dongol 1992 but also Lagasse et al 2006, Pagliara and Carnacina 2010, Carnacina et al 2019)

Reply: We apologise with the Reviewer for the missing reference, which has been added in the revised manuscript:

Cantero-Chinchilla, F. N., de Almeida, G. A. M., & Manes, C. (2021). Temporal Evolution of Clear-Water Local Scour at Bridge Piers with Flow-Dependent Debris Accumulations. *Journal of Hydraulic Engineering*, *147*(10), 06021013.

The sentence in the original manuscript:
“*The effects of debris on scour evolution are also a topic of extreme interest that has been subject of significant research efforts in the last decades. Cantero-Chinchilla et al. (2021) lists the most important studies on the topic and presents an assessment of the influence of flow intensity, blockage area ratio, and depth ratio on the development of local scour with flow-dependent debris accumulation. Debris accumulations can increase local scour depths by a factor of two or more compared to local scour depth without accumulations. The increase in scour depth that results from debris accumulations depends critically on the characteristics of debris accumulations (e.g. size and shape, which mainly determine their influence on scour) that will form at a given location, which is difficult to predict. Experiments by Panici and de Almeida (2018, 2020, Figure 1) provide methods to estimate the maximum dimensions possibly formed under given flow and debris conditions. However, additional experimental research is needed to extend the range of applicability of existing methods and approaches, and to characterize the likelihood of accumulation of debris at bridge piers*.”

has been rewritten and extended as follows:

"The effects of debris on scour evolution are also a topic of extreme interest that has been subject of significant research efforts for many decades, since the early qualitative studies of Laursen and Toch (1956). Cantero-Chinchilla et al. (2021) lists the most important studies on the topic and presents an assessment of the influence of flow intensity, blockage area ratio, depth ratio on the development of local scour with flow-dependent debris accumulation. These parameters were found to be the most important ones also in other studies on the topic (e.g. Pagliara and Carnacina 2010), whereas the debris permeability, which affects significantly hydrodynamic forces, has a minor influence on local scour (see also Lagasse et al. 2010). Debris accumulations can increase local scour depths by a factor of two or more compared to local scour depth without accumulations. The increase in scour depth that results from debris accumulations depends critically on the characteristics of debris accumulations (e.g. size and shape, which mainly determine their influence on scour) that will form at a given location, which is difficult to predict. Experiments by Panici and de Almeida (2018, 2020, Figure 1) provide methods to estimate the maximum dimensions possibly formed under given flow and debris conditions. However, additional experimental research is needed to extend the range of applicability of existing methods and approaches, and to characterize the likelihood of accumulation of debris at bridge piers. Another topic that is receiving considerable attention by researchers is the pressure-flow scour due to vertical contraction, which takes place in the case of submerged bridge deck (Carnacina et al. 2019). A recent review paper (Majid and Tripathi 2021) discusses the many research needs in this field."

We have also added the recommended references:

Lagasse, P. F., Clopper, P. E., Zevenbergen, L. W., Spitz, W. J., and Girard, L. G. (2010). Effects of debris on bridge pier scour. *National Cooperative Highway Research Program 254 (NCHRP) Rep. No. 653*, Transportation Research Board, Washington, DC.

Pagliara, S., & Carnacina, I. (2010). Temporal scour evolution at bridge piers: Effect of wood debris roughness and porosity. *Journal of Hydraulic Research*, *48*(1), 3-13.

Carnacina, I., Pagliara, S., & Leonardi, N. (2019). Bridge pier scour under pressure flow conditions. *River Research and Applications*, *35*(7), 844-854.

Laursen, *E. M. and Toch*, A. (1956). Scour around bridge piers and abutments, Bulletin No. 4, Iowa Highways Research Board, Ames, Iowa.

Table 1. List of research areas, challenges & needs, and actions for improving bridge resilience to flooding.

Area	Research challenges & needs	Actions
Hazard assessment and mitigation	- Characterization of likelihood of debris accumulation at bridge piers. - Critical evaluation of the effectiveness of technical solutions for mitigating hydrodynamic forces for bridges at risk of inundation. - Extension of current flood forecast and warning capabilities to longer lead times and uncertainty characterization. - More accurate modelling of the impact of climate change on frequency and intensity of flooding.	(1)-(5)
Hydraulic actions modelling	- Additional field research, data collection and analyses also needed to characterize the interrelated flood actions and validate models. - Characterization of the temporal evolution of scour under the influence of time-varying intervening variables characteristic of flow and debris, with further experiments extending the range of applicability of developed approaches. - Characterization of the effect of bridge pier and foundation geometries on the development of scour and on the scour hole shape. -Development of models for establishing the relationships between measured river parameters (flow height, surface water velocity) and parameters controlling scour and hydraulic actions (e.g. depth averaged velocity).	(1)-(5)
Vulnerability assessment and reduction	- Identification of optimal intensity measures to be used in fragility analyses for describing the joint effect of various flood actions on bridges. - Definition of methodologies for evaluating the vulnerability of various bridge types to concurrent flood-induced actions, accounting for cumulative effects (e.g. scour accumulated in previous floods) and the effects of debris through advanced modelling of water-soil-bridge assets. - Statistics of the principal causes of failure and collapse mechanisms for various bridge typologies. - Cost-benefit analysis of alternative solutions for mitigating the risk of different bridge components (e.g. deck unseating and uplift).	(1)-(6)
Risk management	- Development of decision support tools to aid bridge managers to identify optimal actions for emergency/long-term flood risk management (including restoration and/or adaptation measures to climate change). These should take into account the bridge fragility and the consequences of bridge failure.	(2),(4)-(8)

	- Identification of actions that could be taken in the short term to mitigate the impact of forecasted floods (e.g. removal of debris accumulated at piers). - More explicit considerations of structural vulnerability indicators and consequences in risk rating procedures. - Improvement of response and recovery procedures that are kept up to date with the most recent technologies.	
Impact-based forecasting	- Tools enabling the paradigm shift from flood hydrograph to impact-based forecasting, so that mitigation measures can be better planned and justified using cost-benefit criteria. This could contribute to an increased awareness of the actual risk of bridges and a better acceptance of mitigation measures by affected communities.	(2)-(5)
Monitoring	- Evaluation of the metrological effectiveness of sensors for monitoring the effects of floods on structures. - Development of approaches for fusing information from numerical models and heterogeneous sensing systems, providing observations and measurements of different parameters involved in the risk assessment. - Incorporation of monitoring technologies into risk management procedures.	(2)-(8)
Value of information of data	- Quantification of the benefits, in terms of cost savings to bridge operators and ultimately to communities, of data and information from sensors. This requires the development of a methodology for comparing the value of information from systems characterized by different measured quantities, accuracy, and spatiotemporal resolution. This effort could help to increase the adoption of sensors for monitoring bridges and rivers by bridge managers and operators. - Cost-benefit analysis of risk mitigation measures (rip-rap) vis-a-vis bathymetric surveys and accurate foundation depth evaluations for identifying the most effective scour management strategies in case of unknown foundation depths.	(2)-(8)
Resilience quantification	- Restoration models for different types of bridges and different operators (masonry arch bridges vs. multi-span concrete bridges, road or railway bridges). - Life-cycle resilience metrics for multiple flood scenarios including climate projections	(4),(5),(6),(7)

Actions: (1) Laboratory and in-field experiments; (2) Development of models and techniques; (3) Numerical analyses; (4) Pilot case studies; (5) Data collection (through monitoring or desk studies); (6) Academic-industry workshops and engagement events; (7) Engagement with general public; (8) Training of experts, inspectors, recovery teams.