Assessing flooding impact to riverine bridges: an integrated analysis

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We would like to thank once again the reviewers for their efforts and comments. Our hope is that we have sufficiently addressed these concerns for both the editorial team and the reviewers, and that we can move forward towards publication. It seems that at this stage the primary concern relates to the clarity of the objectives of this paper, which, from our standpoint, are to present a novel, multidisciplinary, multiphysics approach that considers the effects of a flooding hazard on a bridge and how that may impact the transportation network. This paper is objectively not a study of how bridge structures would generally respond to an extreme hazard, but how one may consider a local hazard in more detail and extend the analysis to the network at large. We feel that, at this point after four reviews, we have provided sufficient revision to this work to meet these objectives, and hope that we have resolved this disconnect. Further editorial changes related to specific physical response of specific individual bridge will not affect the primary objectives. Should a user want to refine their fluid modeling, structural modeling, or network modeling, that fits perfectly within the scope of what we present. Again, we thank the reviewer for their comments, which substantially improved the paper; and we hope that the editor can find that this paper is now suitable for publication.

No.	Comment	Answer
Reviewer #3 (reject)		
1.1	*The scientific contribution of the paper is still unclear.* *If the contribution is the development of a holistic framework for assessing susceptibility to flooding and relative consequences at systemic level, as discussed in response to the Reviewer's comments, then such a framework was already developed by others (see below a list of few).* *If the novel contribution is the analysis of a realistic case study, then there are too many simplifications and there is no link between hydrological and hydraulic analysis results and too many physically inconsistent assumptions in the fragility analysis.* *The authors could select one of these topics (overarching framework, bridge fragility analysis under hydrodynamic loads, impact of floods on traffic redistribution, analysis of the resilience of transport infrastructure of Carlisle to flood hazard) and provide much more information on it, making clear what is the improvement of the paper with respect to the state of art.*	The main contribution of the paper is the development of a holistic framework for assessing susceptibility to flooding and relative consequences at systemic level (L16-18) using CFD (Computational Fluid Dynamics) and FE (finite element) modelling. The analysis of a realistic case study is not the main focus, rather an example of application of the framework and proof-of-concept (L20-22). Assessing the consequences associated with flooding requires an understanding of the hazard and how infrastructure might respond to them. Although there are many ways to do this assessment, we argue that our approach is novel because it models hydrodynamic forces as demand on the bridge structure using CFD. While there are, admittedly, several other frameworks that have been developed for similar cases, this concept is not ubiquitous throughout the literature, and expanded computing power has resulted in more availability of these tools, and our hope is that we are providing an avenue for potential users to explore these multi-hazard approaches. This work obviously builds on existing literature, but moves this forward since: *(i)* it develops a multiphysics, multilevel approach that takes advantage of seemingly disparate physical models, never integrated before; *(ii)* it represents a first attempt to couple CFD analysis with both Finite Element (FE) and network analysis, in an effort to capture both the cause and effect of flooding (as parallel studies are doing for other hazards, e.g. Liu et al. (2021) for fire). The novelty of this work is grounded in how this fits within a multidisciplinary approach that could more broadly extend complex engineering analysis of hazard resilience into a practical network analysis. We would like also to specify differences from cited works. Gehl and D'Ayala (2018) presented a multi-hazard risk assessment using functionality loss curve; they did not include consequences at network level and applied the framework to an “ideal” bridge

		and a hypothetical road network only; no damage mechanism is specified, a bridge is considered closed when submerged. Kim et al. (2018)'s framework focused on traffic forecasting and related cost (no mention of direct costs); they adopted hydrological and hydraulic analysis to determine hazard information for 200/300/400-years return period. The work of Lamb et al. (2019) is about scour only and develops new fragility analysis; moreover, their consequences assessment was for railways bridges (in terms of passenger journey disruption); their study is the only UK-data-based work. Alabbad et al. (2021) proposed an interesting high-level framework where bridge closure is considered only (and based on comparing flood depth and deck height); no hydraulic or CFD modelling is included; it is also noted they use a 100- and 500-year return period as events. Missing works have been added in the manuscript and we thank the reviewer for the suggestion. The scope of this work is exactly not to adopt a silo-based approach (by selecting one topic), but to challenge the current *status-quo* with a holistic view of the matter. This is precisely the novel contribution. If we were keen to focus on one topic, we would have selected another journal (e.g., Eng. Structure for fragility analysis, Transportation Part B for traffic redistribution, etc.). Our choice of NHESS was about targeting an interdisciplinary journal interested on "natural hazards and their consequences", which embraces a "holistic Earth system science approach". NHESS serves a wide and diverse community of research scientists, practitioners, and decision makers (quite often "generalist" of the wider subject), which are looking to understand the potential practical consequences to infrastructure due to extreme flooding – in the remit of this study. The broader community (and two reviewers) has already positively engaged with this work (thanks to NHESS discussion and conference papers on preliminary parts of this study, see e.g. citation in Eidsvig et al. (2021)), and I am

		currently discussing further application with a consultancy company which would like to use CFD for risk assessment. In this light, we are convinced that the article is worth publication, and eventual shortcomings will be challenged by the community.
1.2	*I respectfully disagree with the response to comment #2. The investigated bridge has very tall piers, and from simple calculations (just assume 2 kN/m2 of hydrodynamic load) one could immediately have an idea of the potential impact of hydrodynamic loads on the pier deflection and on the top displacement demand, which is strongly related to the performance of the bearings.*	The authors appreciate the reviewer's concern of the effects of fluid-structure interaction. The structural analysis results using the flood loads determined from the CFD analysis show that the lateral drift of the piers is sufficiently low: 0.053% of the pier height under only the most severe loading. Similarly, the maximum top rotation sustained by any of the piers is 0.00104 rad. The piers are tall, but they have substantial stiffness in the direction of flow that limits their deformation and the potential for significant fluid-structure interaction; therefore, the main vulnerability is judged to be in the superstructure for this particular bridge. It is noted that fluid-structure interaction may be important for other bridge geometries and flow conditions, but this again gets to the objectives of the paper, and it is quite common for these to include these and similar assumptions when modeling these types of problems.
1.3	*The case study bridge has not been changed. Even under a rare event such as the one considered (500 years return period), it is not expected to be flooded. The flow velocity of 3m/s at the deck level seems high, but no actual hydraulic analysis was carried out. A more realistic scenario should be analysed.*	The case study is an application of the framework and proof-of-concept. It was selected because all required data were available (as opposed to other bridges of the area), thanks to our collaboration with UK Highways Agency (formerly Highways England). The velocity of 3m/s was based on hydrodynamic simulation for the event of 500-year return period. Due to climate change, flood return periods are dramatically decreases, and a 500-year flood in 2021 could become a 271.6-year flood in the 2050s (Orton et al., 2016). Thus, for the design of e.g. bridge piers, return periods up to 500-year will be more and more justified (Rashidi et al., 2021); recent works has used similar return periods too (Alabbad et al., 2021). Highways Agency is supportive of the overall framework and expressed interest in investigating consequences due to extreme events for the M6 bridge in Carlisle (support letters available).

		The use of a coupled hydrodynamic and CFD analysis is part of the novelty of the work (rather a hydraulic analysis), since CFD has been suggested as a more sophisticated technique to be used for modelling flow depth and velocities at sites (Bento et al., 2021). This insight, again, gets to the objectives of this work.
1.4	*Figure 6 has been added, without no explanation of the results, which are not very clear. The obtained results should be explained and discussed.*	Discussion of obtained results have been provided in further depth preceding Figure 6 (L308-355). Moreover, also Fig. 5 was improved.
1.5	*The assumption of a coefficient of friction of 0.1 is not justifiable. If there is uncertainty in the friction, a Monte Carlo simulation should be carried out to investigate the effect of this uncertainty, or at least a sensitivity study should be performed to investigate the effect of the assumption*	The present study is not probabilistic in nature and thus a Monte Carlo simulation is beyond the scope of the work. Moreover, the discussion and use of 0.1 as a coefficient of friction is noted to be purely illustrative and admittedly highly conservative in the text (L412-413). The authors do not suggest a coefficient of friction of 0.1 is the true coefficient of friction, but it is based on (1) the suggested AASHTO Commentary design coefficient of friction of 0.2 and (2) the expectation that the coefficient of friction may be lower than expected in wet/submerged conditions. Further, the limiting coefficient of friction is defined as the AASHTO commentary suggestion of 0.2 in Figures 7a and 7b. To the authors' knowledge, there are no experimental data available to help overcome the epistemic uncertainty associated with these conditions.
	Alabbad, Y., Mount, J., Campbell, A. M. and Demir, I. (2021). Assessment of transportation system disruption and accessibility to critical amenities during flooding: Iowa case study. Science of The Total Environment, 148476 Bento, A.M. Viseu, T., Pêgo and J.P. Couto, L. (2021). Experimental Characterization of the Flow Field around Oblong Bridge Piers. Fluids, 6, 370. https://doi.org/10.3390/fluids6110370 Gehl, P. and D'ayala, D. (2018). System loss assessment of bridge networks accounting for multi-hazard interactions. Structure and Infrastructure Engineering, 14(10), 1355-1371. Eidsvig, U., Santamaría, M., Galvão, N., Tanasic, N., Piciullo, L., Hajdin, R., Nadim, F., Sousa, H.S. and Matos, J. (2021). Risk Assessment of Terrestrial Transportation Infrastructures Exposed to Extreme Events. Infrastructures 6(11): 163. https://doi.org/10.3390/infrastructures6110163 Kim, B., Shin, S. C. and Kim, D. Y. (2018). Scenario-based economic impact analysis for bridge closures due to flooding: A case study of North Gyeongsang Province, South Korea. Water, 10(8), 981. Lamb, R., Garside, P., Pant, R. and Hall, J. W. (2019). A probabilistic model of the economic risk to Britain's railway network from bridge scour during floods. Risk Analysis, 39(11), 2457–2478. https://doi.org/10.1111/risa.13370	

	Liu, Z., Silva, C.J.G., Huang, Q., Hasemi, Y., Huang, Y. and Guo Z. (2021). Coupled CFD–FEM Simulation Methodology for Fire-Exposed Bridges. J. Bridge Eng., 26(10): 04021074. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001770 Orton, P.M., Hall, T., Talke, S.A., Blumberg, A.F., Georgas, N. and Vinogradov, S. (2016). A validated tropical-extratropical flood hazard assessment for New York Harbor J. Geophys. Res. Oceans, 121: 8904–29 Rashid, M.M., Wahl, T. and Chamberset D.P. (2021). Environ. Res. Lett., 16: 024026	
	Reviewer #4 (accept as it is)	
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