Assessing flooding impact to riverine bridges: an integrated analysis

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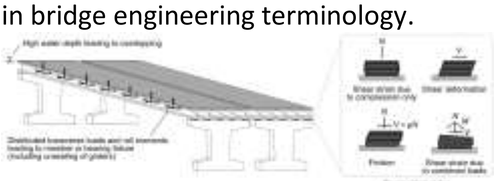
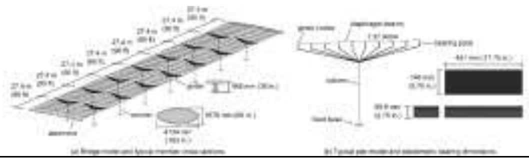
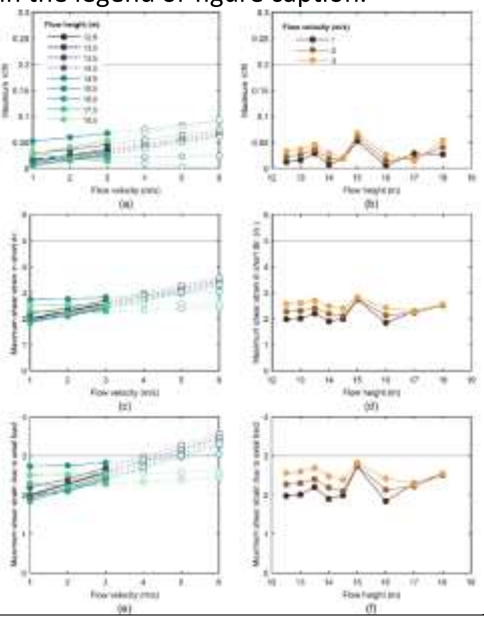
No.	**Comment**	**Answer**
Reviewer #1		
1.1	The manuscript presents an integrated framework for the assessment of flood impact on riverine bridges and the road network they connect, with the merit of including all the most relevant aspects of the problem, from the hydraulic to the structural and road network ones.	Authors appreciated the merit and complexity of the paper is highlighted by the reviewer.
1.2	The methodology is demonstrated on a UK case study, and it is intended to be applicable also elsewhere. Most of the various steps in the methodology are based on approaches that can be applied to a generality of cases, except the structural analysis step.	Authors appreciated the transferability of the method is highlighted by the reviewer. The structural analysis step will be made more general as suggested (see **Comment no. 1.3**).
1.3	The structural analysis is tailored to a very specific type of bridge, hence diminishing the overall generality of the methodology. The manuscript should be then improved by splitting the structural analysis in a more general part, possibly suitable for a large variety of bridges including old constructions, and a more specific part needed for the present case study.	The authors agree that the generality of the methodology should be preserved in the manuscript. To help clarify the distinction between the methodology and the case study, the text in Sec. 2.3 will be generalized to consider other types of bridges and the specific analysis details will be limited to Sec. 3.1.
1.4	Further improvement is needed in the analysis of the impact on the road network, where too simplistic assumptions are made. In particular, it is implicitly assumed that no parts of the network other than the bridge are impacted by the flood, and that the capacity of the alternative routes are not limited. These assumptions may bring to a strong underestimation of the impact, neglecting the possibility of severe traffic jamming on the alternative routes and the need to take even longer re-routing due to the unserviceability of the nearest ones.	We agree with the reviewer that assuming that no parts of the network other than the bridge are impacted by the flood (thus have reduced capacity) is an important simplification. We were aware of it, as stated in Sec. 4 (L379-382). This assumption is based on the following motivations. 1) This study is highly complex and multi-disciplinary; as such, its components needed to be kept at a low-complexity level in order to explore the combination of them (first of its kind). Nevertheless, all simplifications are

		clearly stated, and taken as points for future development (Sec. 4). 2) This study focused on riverine flooding, whose hazard footprint mainly affects bridges (Fig. 3b). For properly analysing the flooding impact to road networks, simulation of surface water flooding should be undertaken; this analysis would be a study on its own, and currently out of the scope of this piece of research. This will be better specified in Section 4. 3) This assumption implies an underestimation of the impact, and this point will be made clear. As stated in Sec. 4 (L373 and L383-4), the produced outputs are conceptual results and the importance of this work resides in the proof of concept of a new holistic methodology, rather than the quantitative results.
Reviewer #2		
2.1	The study combines a fluid dynamics model with a structural analysis model to assess the performance of an inundate bridge and then assess the impact on the functionality of the surrounding transport network.	-
2.2	The paper lacks of basic bridge engineering understanding and bridge modelling and therefore has inaccuracies and provides limited insights for bridges exposed to flood hazard. The novelty is not clear, although hydrodynamic modelling is included to study the bridge response under flood effects, several simplifications are made, while the description of the models is not adequate.	The authors appreciate the reviewer's expertise and insight in bridge engineering and will modify the manuscript to improve word use to ensure clarity. The novelty of the paper is the presentation of an interdisciplinary approach to evaluate performance of bridges subjected to flood loading and potential disruptions to transportation networks. In particular, very few studies have attempted to closely link computational fluid dynamics and structural analysis models. The reviewer suggests that the models employed in the present evaluation are inaccurate and provide limited insight. To be clear, the relatively simple case study models reflect the limited knowledge of the actual bridge and site conditions, and the authors are cognizant of the uncertainty in actual bridge performance due to the potential for other hydrodynamic conditions, structural limit states, or transportation network vulnerabilities that are excluded from the study. With these issues in mind, the authors will improve the descriptions of each of the

		models and identify specific limitations of the approaches that may be addressed in future work.
2.3	The authors do not explain the loads used on the bridge. Are these code-based loads, which design situation/combination has been considered and for which elements?	Since the paper describes a general methodology for evaluating performance under flood loading, a specific bridge design code or standard is not used in this study. Moreover, the loading considered here applies to structures with inadequate freeboard and/or structures subject to orifice flow and inundation. Flow characteristics for such conditions may be well established in the literature, but forcing on the superstructure is not. Therefore, the bridge loads are determined directly from the computational fluid dynamics model of the superstructure considering different combinations of flow heights and velocities that are possible at the site. The forces and moments on the bridge superstructure based on the computational fluid dynamics model results are the loads indicated in Fig. 2. These forces and moments are applied as distributed loads over the length of each girder and then transmitted to the other structural components (bearings, piers, etc.). An improved description of this procedure will be added to the manuscript, and the authors will also note how the methodology can be applied.
2.4	The loads shown in Fig. 2 have no relevance to bridge engineering, while there are errors in bridge engineering terminology. 	These loads on the superstructure are relevant for high water flow leading to orifice flow conditions or inundation of the deck; consideration of these types of loads is not unique to this study (e.g., see Mondoro and Frangopol 2018).
2.5	The deformations shown in Fig. 2 for bearings are basic, described with wrong terminology and not relevant to the paper. Not correct bearing modelling/bearing failures are shown. Elastomeric bearings are usually deteriorated on isolated bridges, while their connections to the super/substructure are very critical and not discussed in the paper at all (a contact-like connection is insinuated through friction). Instead based on line 280 of the manuscript "These bearing elements were connected to rigid links, which simulated cap beams: : :" i.e. a fully rigid connection. Furthermore, it is	The authors disagree that these bearing deformations are irrelevant in view of the large forces modeled on the bridge superstructure. Complex nonlinear modeling of the bearing response including deterioration due to environmental exposure is not performed, but this is not the focus of the paper (the focus is on the methodology that links computational fluid dynamics, structural analysis, and transportation network evaluation). The reviewer refers to L280 of the manuscript to suggest that the bearings in

	not clear if uplift of the deck from the isolators is modelled in Opensees, and if this was done it should be further explained.	the model are modeled as rigid elements; however, the bearings are not modeled as rigid elements. “Rigid links” on this line refers to the condition between the cap beam and pier; this will be clarified in the revised manuscript. It is also understood that this is still a modeling simplification, and this will be noted. Uplift of the deck was not modeled in *OpenSees*, since this would imply significant movement of the superstructure that would invalidate the computational fluid dynamics model; instead, uplift and unseating (overcoming the assumed frictional resistance between the girder and bearing) is evaluated in post-processing.
2.6	Figure 4 indicates ‘abutment’, but no abutment is shown here. 	The abutments are not explicitly modeled; rather, the abutment locations are used as boundary conditions in the model. Figure 4 will be modified to clarify.
2.7	Foundation is shown fully fixed. This is not an acceptable assumption especially for a river crossing bridge. Foundation and SSI effects are activated under dynamic loads, like flooding.	This study focuses on the performance of bridge superstructures subjected to high water flow; therefore, soil-structure-interaction (SSI) has not been modeled. The authors are aware of this limitation, as stated in Sec. 3.1 (L323), and agree that detailed investigation of the foundation and SSI under this loading would be of significant interest. However, it is beyond the scope of the present paper.
2.8	Yielding of the girders or piers is considered (line 125), however, it is not clear if non-linearities of the bridge elements were considered in the model, and if this is the case then it is not sufficiently explained; for example, how the nonlinearity of the deck or reinforcement has been included in the model.	The manuscript will be updated to expand the description of the finite-element model. The girders and piers were modeled as fiber-based line elements with nonlinear constitutive models for the concrete and reinforcing steel within their respective cross sections. In addition, geometric nonlinearity was modeled (P-Delta effects), though significant influence of geometric nonlinearity would imply deformation that invalidates the computational fluid dynamics model (this was not observed).
2.9	Opensees is an advanced software to simulate the performance of structural systems subjected to earthquakes. It is not clear, why this software was selected for an oversimplified bridge model, and in particular, if a linear elastic simulation has	The authors suggest that a multitude of different software packages may be able to adequately characterize flood loading on the superstructure. The authors have never suggested that *OpenSees* is the only suitable option structural analysis within this methodology. However, this software was

	been adopted. Also, validation of the models is not provided.	selected for use in the case study in order to simulate potential nonlinear response in the girders and piers under the hydraulic loading. Alternative software will be mentioned as possible options in Sec. 2. The reviewer's observation that no validation of the models is provided is well-taken. The authors recognize that this is limitation of the study, however, there is a dearth of data available to support validation. The authors note that the methods employed by the authors have been used in prior studies.
2.10	The bridge deck and girders are modelled as rigid bodies, however, this is an oversimplified approach. Also, shear, flexural, and axial stiffness properties of the deck are not provided. In line 195, it is mentioned that "The bridge deck and girders are modelled as a rigid cross section (i.e. in 2D)"; this is confusing as a 3D model is shown in Figure 4.	The authors agree that the original language is too confusing and will clarify that the bridge superstructure is rigid in the computational fluid dynamics model (an important simplification to ensure the feasibility of the study) but not in the finite-element model; to that end, the authors can also provide the stiffness parameters from the finite-element model. Figure 4 shows the finite-element model only.
2.11	It is not clear if the CFD model accounts for the river-bed and river channel characteristics, the model input is not explained sufficiently, and no information of the model are given. It is not clear what is the output of the hydrodynamic model (e.g. time-histories of the hydrodynamic force?) and how then this output is imposed in the Opensees model.	The CFD model assumes a constant value of the section, calculated as possible from available data. Model input are listed in Table 2 and explained in Sec. 3 (L260-272). The output of the hydrodynamic model includes water velocity and depth (1-in-a-500-year flood event). The values were extracted in proximity of the bridge, and also validated with historical data and inspection reports. The statistics for the velocity (both in its actual flood flow direction and also normal to the bridge) were computed from the LISFLOOD-LP velocity vectors Vx/Vy data and the maximum water depth, for both considering maximum values over the whole flood simulation. These values provide the initial data for the CFD model; in fact, the OpenFOAM model was set to simulate a range of flow velocity and depth values above and below the calculated 500-year flood results in order to assess how varying the depth and velocity affected the resulting bridge performance (see L260-8). The 500-year return period flood showed velocity values up to roughly 3.5 m/s and max flood depth up to 17 m near the M6 Bridge. These statistics motivates using a range of steady-

		state velocities of 1-3 m/s and inundation heights of 12.5-18 m above datum (14.8 m above river bottom) respectively, with the bottom of the bridge's lowest girders at approximately 12.375 m and the top at 14.425 m above +3.2 m datum.
2.12	In section 2.3, the authors provide relevant literature for the definition of slight, moderate, extensive, and complete damage states, however, it is not clear which thresholds values have been used for the damage assessment of each bridge component, e.g. piers, bearings, deck in section 3.1.	The authors have inferred damage states based on the most probable failure modes examined in Fig. 5. The manuscript will be revised to explicitly relate the analysis results to the damage states. The connection between Sec. 2.3 and Sec. 3.1 will be better defined, by connecting Sec.3.1 and Fig.5, with Table 1.
2.13	The framework includes a reliability analysis; however, no such analysis is conducted, which by definition is based on failure probabilities of the structure under study.	We agree with this note and thank the reviewer for the comment. It is correct that no statistical distribution of flood intensity was considered, therefore the term "reliability analysis" was substitute by "performance evaluation".
2.14	The horizontal lines in Fig. 5 are not defined in the legend or figure caption. 	Figure 5 will be amended to indicate the limit state thresholds plotted in grey. Relevant equations from the literature will be included to the manuscript to show how these values are computed.
2.15	Recent papers that study the vulnerability of bridges to flood effects are not included in the literature review, e.g.: • Kim, H., Sim, S. H., Lee, J., Lee, Y. J., & Kim, J. M. (2017). Flood fragility analysis for bridges with multiple failure modes. Advances in Mechanical Engineering, 9(3), 1687814017696415. • Ahamed, T., Duan, J. G., & Jo, H. (2020). Flood-fragility analysis of instream bridges–consideration of flow hydraulics, geotechnical uncertainties,	These references have been reviewed and will be included in the paper.

	and variable scour depth. Structure and Infrastructure Engineering, 1-14. • Hung, C. C., & Yau, W. G. (2017). Vulnerability evaluation of scoured bridges under floods. Engineering Structures, 132, 288-299.	