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Towards integrating modelling of flood-induced bridge failures

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Abstract

This study investigated the impact of fluvial flooding on bridges. A high-resolution flood model is coupled with damage and transport modelling, to assess structural vulnerability and critical functionality of bridges subjected to flooding. The study involves integrated investigation of riverine bridges, devises a systematic methodology and practical implementation in computer-based decision support tools. The research draws on the principles of a risk-based approach to assess the hydrodynamic effects of floods at bridges, and moves these forward by advancing a deep analysis over the whole UK territory. This research will fill the gap of current guidance for design and assessment of bridges relevance within the overall transport system, highly inadequate for evaluating these risks in light of the increasing external pressures.

1 Introduction

The service provided by transport infrastructure ensures connection within and among urban areas. Flood events are the most frequent cause of damage to infrastructure compared to any other natural hazard (Brown et al., 2014). A failed connection can endanger emergency response and recovery, as well as the overall economy. Although bridges and roads have been designed to last long, they were not designed to cope with changing climate, population increase and economic austerity. Therefore, in the UK, many strategic bridges have been built without any particular flooding protection criteria, and their frequency of use has out-stripped their design specification. The risks to bridges from fluvial flooding have been recognised as crucial at global level (Dawson et al., 2016). Nevertheless, in contrast to extensive research on the seismic fragility analysis for civil infrastructure, relatively little attention has been devoted to the flood-related assessment of these structures (Lee et al., 2016).

[*] Led and did the work
[†] Created the first draft of this paper
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This research draws on the principles of a risk-based approach to assess the hydrodynamic effects of floods at bridges and moves these forward by advancing a deeper analysis for a case study in the UK.

1.1 Background and motivation

Since past times, towns and cities have been settled and grown up alongside or around rivers. When a city developed, the river became a critical crossing point and bridge fundamental elements of connection. Recent failures have underlined the need of placing resilience measure to mitigate the consequence of the adverse weather events, especially in a context of climatic changes.

Flooding is a constant threat whose impact disrupts people lives and for industrial/manufacturing areas. Local transport networks play a crucial role in modern communities for economic vitality, social well-being and logistic. In particular, bridges have social and economic importance, since they can provide access to important service (schools, hospital) and also carry utilities (pipes and cables); indeed, they are key for accessibility but also for vital public utilities such as power, water supply, gas, electricity, and communication.

All riverine bridges are subjected to the risk of flooding, as naturally located upon rivers. Different consequences arise from floods depending from the hazard and the vulnerability of the bridge. The vulnerability does not come from the type of structure alone (e.g. masonry, steel or concrete bridges), but a range of influential factors are involved in assessing the bridge vulnerability, such as the catchment or demand type. A risk approach is the most appropriate, since it allows to deal with the three elements of the risk: hazard, exposure and vulnerability (Grossi et al., 2005). The hazard component deals with magnitude and frequency of the event (e.g. rainfall intensity, return period); the exposure contains details of the "asset at risk" location and characteristics (i.e. bridge type, catchment). The vulnerability component is concerned with the susceptibility to damage of the exposed elements due to the hazard impact, assessed by using vulnerability or damage functions.

Current knowledge is incomplete regarding the vulnerability of critical infrastructure to flooding (Pitt, 2008). This research aim to fill this gap in regards to the flood impact on riverine bridges

2 Method

This study aims to understand bridge performance during floods by (i) developing an infrastructure inventory for the UK's road bridges; (ii) characterizing the flood hazard for a range of flood events; and (iii) describing the bridge performance and serviceability as a function of flood hazard loading using damage functions.

2D simulations were undertaken to produce timeseries of flood depth and velocity. CityCAT (City Catchment Analysis Tool) is the advanced hydrological model) (Glenis et al., 2013) that computed the movement of the floodwater influenced by the natural elevation of the terrain and by land use properties (including factors such as the location of streets, buildings and permeability). CityCAT is a software developed at Newcastle University and solves the shallow water equations using the method of finite volumes with shock-capturing schemes and a uniform propagation of the rainfall time-series (Figure 1). The software can be applied for pluvial and fluvial flooding at catchment-level, as well as for large areas using the Microsoft Azure Cloud platform.

The high resolution of the flood model (0.5-1 m of resolution) allows to integrate its output with (i) bridge damage models, to investigate the failure mechanism of the structure; and (ii) transport models, to investigate how bridges and nearby road links are affected by flooding in terms of traffic disruption and accessibility.

A probabilistic measure of the structural performance is typically expressed as a fragility curve relating hazard loading (considering intensity measures, like flood depth, flow velocity, debris and scour) to the probability of failure or damage. This involves: (i) identification of the failure modes induced by IMs; (ii) development of appropriate process models to represent each failure mode; and (iii) generation of fragility curves for different degrees of serviceability. The serviceability analysis is directly fed into a traffic model for the computation of induced delays and the optimization of restoration strategies (Pregnolato et al., 2016).

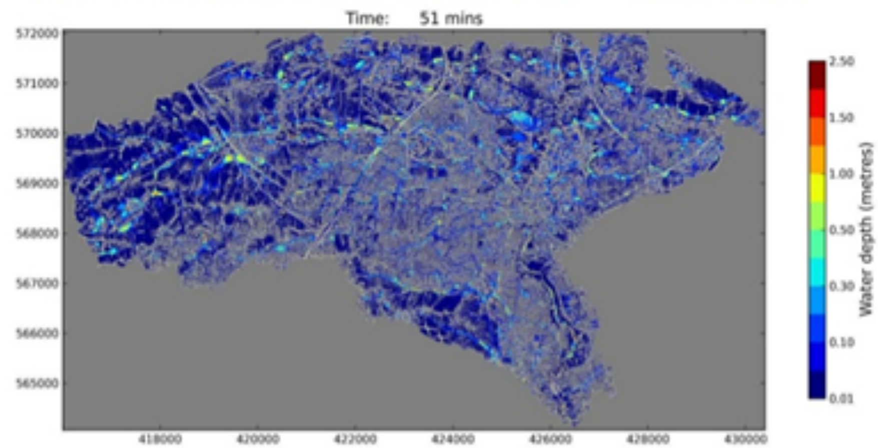

Figure 1. Example of an output obtained from the CityCAT, based on the solution of shallow water equations. This is a water depth map for the Ouseburn catchment (UK).

2.1 Assessing risk and resilience at national level (UK)

Many of the national strategic bridges have been built without any particular flooding protection criteria, and their frequency of use has outstripped their design specification. Whilst monitoring and structural analysis can help identify bridges that are susceptible to failure, it is also necessary to understand the implications of their failure on the wider transport network to enable risk-based decision-making and prioritisation of limited funds for maintenance and enhancing national resilience.

The UK can be seen as a system of interconnected cities along rivers; England only has around 58,000 bridges, of which 50% of them are masonry and >100 years old (Sarhosis et al, 2015). An increase demand, climatic changes and asset aging are likely to lead to a national infrastructural shock, if no methods are developed in order to constantly and systematically assess the infrastructure conditions and performance By working with key stakeholders (e.g. Department for Transport, Arup), this research is developing a co-designed model as screening tool for infrastructure risk management.

At this stage, data have been collected from several local agencies (such as Cumbria County Council) and a pilot of a national bridge inventory has been designed. Site-specific failure modes and fragility curves will be developed using approaches such as a finite and discrete element models (Sarhosis et al, 2015) based on the structural design of the bridge, considering detailed asset information and knowledge of maximum loads and speeds. In addition to repair costs, considered functionality loss metrics will include the number of closed lanes and the speed limit reduction. Evaluation of the flood risk associated with different serviceability levels include (i) limit state failure (e.g. collapse); (ii) no practicable service; and (iii) reduced practicable service. Integration of the hazard and fragility information will provide a bridge risk classification.

3 Results and discussion

This study is facing the challenge to couple a high-resolution flood model (CityCAT) to an integrated analysis of bridge performance. At the current stage, the bridge exposure has been analysed at national (Figure 2) and regional (e.g. Cumbria region) level. A taxonomy of bridges has been identified, including the following characteristics: location (geo-referenced), bridge type, foundation type, material, age, catchment/river, carried utilities, owner. Discrepancies are present in the methods of collecting data of the different agencies and this did not allow to fully complete the pilot of the inventory.

Some bridges are far more important than others because of the volume of traffic they carry, or the criticality of the services they connect (e.g. ambulance route to a hospital). Investments should be directed towards those, in order to maintain good connections between two sides of a city even during hazardous events. Decision-makers and risk analysts will benefit from this study by understanding the impact of bridge disruption across the transport sys-tem. This research is ultimately relevant to current guidance for design and assessment of bridges

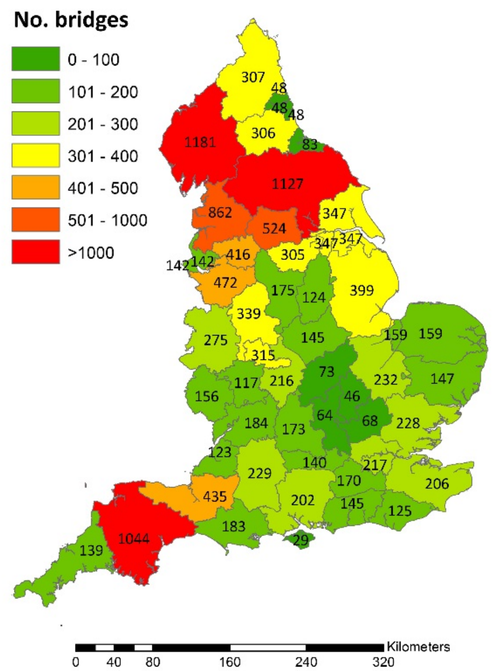

Figure 2. Bridge stock analysis at regional (county) level in England.

4 Conclusion and future research

This study investigated an integrated method to analyse the impact of fluvial flooding on bridge performance. It will demonstrate a comprehensive approach to risk analysis associated with urban infrastructure and develop tools for authorities, enabling independent analysis of the transport network. A high-resolution flood model is coupled with damage and transport modelling, to assess structural vulnerability and critical functionality of bridges subjected to flooding.

As future stages of this research, protocols and criteria of data collection will be drawn to uniform the asset exposure information, as a basis of best-practice of bridge management. Appropriate bridge characteristics will be selected from the inventory, and such data will be used to define fragility functions describing bridge performance and serviceability as a function of flood hazard loading.

Acknowledgement

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