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Risk-based cost-benefit analysis for the retrofit of bridges exposed to extreme hydrologic events considering multiple failure modes

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ABSTRACT

Bridges exposed to flooding, hurricanes, tsunamis, and other extreme hydrologic events have been observed to fail due to deck dislodgement, pier failure, or foundation failure. However, the risk assessment and retrofit methodologies for these bridges have typically only been developed around a single failure mode. This paper addresses this gap by integrating the three observed failure modes for bridges vulnerable to extreme hydraulic events into a comprehensive risk assessment framework. Through the use of an event tree, the methodology accounts for the different consequences of failure associated with different failure modes. Bridge management strategies are investigated to determine the effectiveness of the retrofit actions with respect to their benefit (i.e. reduction in risk) and costs. An illustrative example for riverine bridges under various exposure scenarios is presented. The risk assessment and benefit-cost analysis elucidate the need to incorporate all pertinent failure modes of the structure by highlighting the competing nature of different failure modes. The illustrative example shows that the effective management of structures is site-specific and, that the intensity of the hazard at the bridge location affects which management strategy is preferred. The sensitivity to exposure level indicates that the optimal management of the structure should incorporate considerations for potential future changes in the intensity and frequency of the hazard.

1. Introduction

Managing bridges vulnerable to extreme natural hazards is driven by the need to preserve the functionality of the transportation network and mitigate the economic, environmental, and social impacts of bridge failures. Bridge failures such as the Schoharie Creek Bridge in New York due to flooding [1], the US-90 Biloxi-Ocean Springs Bridge due to Hurricane Katrina [2], and the Utastu Bridge during the tsunami following the 2011 Tohoku-Oki Earthquake [3] are a few examples where extreme hydrologic events have caused bridge failures. These failures do not imply that bridges are not designed considering hydraulic loads. Bridges are designed with respect to scour [4–7], hydraulic forces on bridge piers due to water pressure and debris [5,7,8], and uplift and transverse forces on the bridge deck [9,10]. However, floods, hurricanes, and tsunamis are low-probability high-consequence events that require a shift towards risk-based design and management methods.

Risk-based planning for the optimal retrofit of bridges vulnerable to extreme hydrologic hazards is complicated by the presence of multiple failure modes and their interdependencies. For flooding events, scour, and the resulting foundation failure, is the predominant failure mode [11–14]. However, in extreme cases, piers and decks may also fail as a result of the debris impact or extreme water pressures [1,11–16]. Coastal bridges vulnerable to hurricanes and coastal storms may fail due to wave and surge loading; typical structural damage includes deck unseating due to inadequate connections to the substructure. However, scour, debris impacts, and extreme hydraulic pressures may cause failures of the foundations and piers during these events as well [2,17–19]. The immense hydraulic loads stemming from tsunamis have dislodged bridge decks, damaged bridge piers, and have undermined pier foundations and abutments causing failure [3,20–22]. Thus, it has been observed that bridges may be rendered unpassable due to failures in their foundations, piers, and/or deck caused by extreme hydrologic hazards.

However, when it comes to risk assessment and management of bridges, there is a noticeable gap between observed failure modes and those included in risk assessment methodologies. For instance, the risk assessment of bridges exposed to flooding typically includes only scour [23–26]. Alternatively, some researchers have addressed the failure of decks during floods with respect to debris impact and flow blockage to asses bridge performance [16,27]. However, their optimal risk management strategies have typically been developed irrespective of considerations for debris impact on pier and deck failures; they have only

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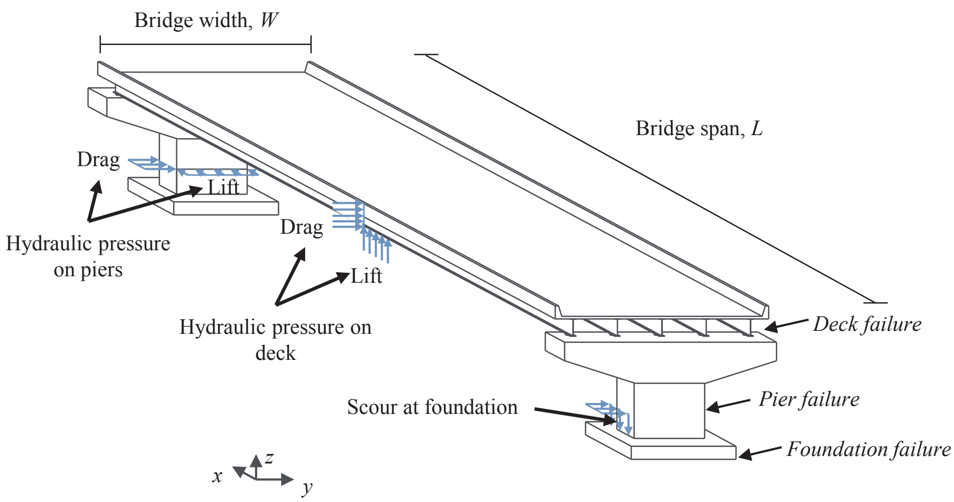

Fig. 1. Hydraulic pressures on the bridge deck and pier and scour at the foundation of bridges over water may cause deck failure, pier failure, and/or foundation failure rendering the bridge impassable.

included scour and the resulting foundation failure [24,25]. By doing so, the adverse effects that debris may have on the vulnerability of the bridge with respect to foundation failure (i.e. scour depths exacerbated by flow around debris) are systematically disregarded [8]. Current methodologies for assessing the life-cycle risk of bridges vulnerable to hurricanes include deck unseating and pier failure [28,29], while risk management strategies have focused on deck dislodgement [30]. It is important to note that foundation performance has been omitted from both risk assessment and management procedures in that research. For the tsunami hazard, risk assessment frameworks include bridge deck and pier failures, but omit scour and the performance of the foundation [3,31,32]. Therefore, it is evident that the development of optimal management strategies for bridges vulnerable to extreme hydrologic events has failed to capture the complete nature of bridge failures (i.e. the failure of the deck, piers, and/or foundations).

A management strategy includes all of the retrofits that are applied to the bridge during its service life. Retrofits are improvements made to a bridge to reduce its likelihood of failure. Deck retrofits may include the application of restrainers and shear keys with the objective of increasing the capacity to resist deck unseating failures. Piers may be retrofitted with steel jackets in order to increase their strength. Riprap may be added as a retrofit to foundations in order to limit scour. However, bridge retrofit options may have adverse effects on the overall performance of the bridge due to the interdependencies of failure modes. For example, restrainers or shears keys, which may reduce the probability of deck dislodgement, transfer the hydraulic loads to the column and foundation and may increase the probability of failure of those components. Furthermore, by limiting displacement of the deck, submerged flow contraction scour depths may substantially decrease foundation capacity and increase the probability of failure of the foundation. The interdependencies of bridge failure modes and retrofit options have been included in seismic retrofit management. Padgett et al. [33] included the demand increase on the piers due to bridge retrofitting with structural restraints between the deck; by increasing the capacity to resist deck failure, the demand on the pier was affected.

Due to the multiple, dependent failure modes of bridges vulnerable to extreme hydrologic events, and the recognized importance of including all modes when developing optimal management plans to avoid any adverse effects of retrofit, it is essential to develop a systematic method for evaluating risk and assessing the benefit of retrofit actions. Risk accounts for the probability of failure and the social, economic, and environmental consequences of the failure. Risk metrics have been used to prioritize management strategies and aid in the decision making process [24,28,30,34]. Multi-objective formulations have been developed for minimizing life-cycle costs, including initial costs and management costs, and minimizing life-cycle risk [30,35,36]. While these formulations provide insight regarding the tradeoff of life-cycle risk and life-cycle costs, the benefit-cost ratio is an alternative metric which provides a single value to express cost with respect to risk. The benefit-cost ratio *BCR* normalizes the benefit (i.e. the reduction in life-cycle risk) to the life-cycle cost. This ratio not only provides a way to prioritize management strategies but also helps in identifying which ones are profitable (i.e. have a benefit higher than the cost, $BCR > 1$). Benefit-cost ratios have been used to prioritize seismic retrofit options and the repair of aging infrastructure [33,37–39].

This paper examines the importance of including all essential failure modes when assessing the risk and evaluating the cost-effectiveness of management strategies for bridges vulnerable to extreme hydrologic events. Deck, pier, and foundation failure are all included as the failure modes in this study since they best reflect the observed failure modes for bridges exposed to floods, hurricanes, and tsunamis. The proposed methodology for risk assessment systematically accounts for the different failure modes, as well as their respective consequences. An illustrative example is presented for a riverine bridge vulnerable to flooding. However, the methodology can be applied to other hydrologic events. The illustrative example evaluates the effectiveness of management strategies in terms of their benefit-cost ratios. Multiple exposure scenarios are included to highlight the importance of site-specific variations in hazard on the cost-effectiveness of retrofit.

2. Multiple failure modes under hydraulic loads

Bridges may be rendered unpassable by failures in their foundations, piers, and/or deck. Hydraulic pressures on the deck may dislodge the deck from the pier causing deck failure. Hydraulic loads on the bridge piers, in combination with axial, shear, and bending transferred from the deck, may cause pier failure. Scour due to stream flow may undermine the foundation and the demand on the foundation due to hydraulic loads may cause foundation failure. Bridge failure is defined as the event where the bridge deck, pier, and/or foundation fail, since all events result in the bridge being taken out of service. The hydraulic loads and failure modes are summarized in Fig. 1.

2.1. Deck failure

When bridge decks are submerged, or partially submerged, the flowing water imparts hydraulic loads on the deck including drag $F_{D,deck}$, lift $F_{L,deck}$, and overturning moment $M_{CG,deck}$. The drag force is in the transverse direction of the bridge deck, shown in Fig. 2 as the $+y$ direction. The uplift force on the deck is in the opposite direction of gravity, shown as the $+z$ direction in Fig. 2. The methodology for