Engineering Structures 168 (2018) 308–319

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Response and fragility assessment of bridge columns subjected to barge-bridge collision and scour

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A B S T R A C T

This paper studies barge impact performance of bridge columns. The effect of various design parameters and the free length of pile, which could be either by design or caused by scour, are studied. Additionally, a preliminary analysis is conducted to assess the post-collision safety of bridges to carry traffic loads. In order to aid design and management of bridges with a wide range of design and geometric parameters, metamodels are developed to estimate the force demands and fragility for bridges columns subjected to barge impact. In order to derive these probabilistic models, finite element simulations are performed for 2000 bridges with varying combinations of design characteristics, barge properties, and impact velocities. In each simulation, a non-linear dynamic analysis is performed to evaluate the maximum shear force, moment, shear strain, and curvature in the columns. Following the dynamic analysis, vertical load analysis is conducted to determine the post-collision stability of bridges under vehicular loads. These analyses are repeated for all the bridge samples for various values of free pile lengths (possibly due to pier scour) to understand its effect on the barge impact performance of bridges. The results highlight that depending on the pier properties and impact conditions, the failure may be caused due to shear, flexure, or a combination of both; however, presence of free pile length leads to more flexure dominated failures. Beyond the insights gained from these response analyses, this paper develops parameterized polynomial response surface models, which can be used to predict the shear and flexural response for a wide range of bridge characteristics and collision conditions without the need for any additional finite element simulations. Finite element simulation results are further employed to derive fragility models using logistic regression. These fragilities can be applied to a wide range of bridges and collision conditions to evaluate the probabilities of exceeding the ultimate shear strain and column curvature capacity limits when a bridge pier is subjected to barge impact. The metamodels developed in this study are applied to a case study bridge to show the variation in demands and fragility as the bridge parameters, free pile length (scour depth), and collision conditions are varied.

1. Introduction

Analysis of past bridge failures reveal that barge-bridge collision has caused a large number of bridge failures [1,2]. Some of these barge-bridge collision events have caused catastrophic bridge failures causing loss of life; for example, in 2002 barge-bridge collision led to the collapse of the highway bridge on I-40 over the Arkansas River in Oklahoma. Consequently, several studies have assessed the performance of bridges subjected to barge collision. One of the early studies performed static and dynamic crushing experiments on scaled ship bows using an impact hammer [3]; the results from this study have been used by AASHTO to develop guidelines to estimate forces due to barge impact. Other studies have focused on experimentally evaluating the stiffness properties of the barge bow [4,5] and evaluating dynamic impact loads on the bridge sub-structure [6]. However, most of the papers addressing barge-bridge collision have used analytical methods to study bridge response under barge impact.

Yuan et al. [7] performed finite element analysis with high resolution finite element models wherein they studied the collision of an individual barge and a flotilla of several barges with a rigid pier. Furthermore, effect of pier stiffness was also assessed using a simplified barge pier collision model, where the column was replaced with a spring. McVay et al. [8] have used experimental results to study the dynamic soil structure interaction due to barge impact. McVay et al. suggest that the effect of soil structure interaction can be reasonably captured via finite element modeling using non-linear P-y and T-z springs. Cowan et al. [9] performed finite element simulations with a detailed finite element model of the barge and a rigid pier model and

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https://doi.org/10.1016/j.engstruct.2018.04.082
Received 30 May 2017; Received in revised form 27 February 2018; Accepted 23 April 2018

validated their model using experimental results. The validated model was used to develop barge bow force deformation relationships for various pier geometries and shapes of the impact surface. Using finite element simulations, Getter and Consolazio [10] further extended the barge bow force deformation relationship for oblique angles of impact. Kantrales et al. [11] further studied the barge bow force deformation behavior using experimental tests and finite element simulations for large bow deformations. The results from Kantrales et al. reinforce findings from previous studies by Cowan et al. [9] and Getter and Consolazio [10] which show that rounded impact surfaces cause lower impact forces compared to flat impact surfaces. Sha and Hao [12] performed high resolution finite element simulations of barge collision with a single pier modeled using non-linear material models. Their results show that plastic deformations in the pier increase the impact duration but lead to a decrease in the maximum forces. Sha and Hao [13] included the effects of pile and soil structure interaction during barge collision in their high resolution finite element model and validated it using experimental results. Furthermore, empirical formulae were also developed by Sha and Hao to predict peak impact forces and impact duration. Similar finite element analyses were performed by Fan and Yuan [14] for ship impact with pile supported structures.

The above mentioned studies employ high resolution finite element analysis involving millions of degrees of freedom, which leads to high computational costs. Therefore, to reduce the computational time, several studies have focused on developing simplified methodologies to perform barge pier impact analysis. Consolazio and Davidson [15] developed a simplified finite element model to study barge-bridge collision wherein the barge is modeled using a point mass and a spring with appropriate force deformation relation and the columns are modeled using fiber sections. This simplified methodology was verified by comparing the impact force, pier moments, and pier shear obtained from the simplified method and the high resolution finite element models. This approach has been used by Davidson et al. [16] to study the dynamic amplification of pier shear and moments during barge-bridge collision, where static analysis is performed as per AASTO guidelines. Using the same simplified model, Davidson et al. [17] evaluated the failure probability of eight bridges considering the uncertainty in soil and material properties. Using the failure probabilities of the eight bridges they propose an expression for probability of collapse parameterized solely on capacity to demand ratio, primarily for designing bridges as per AASHTO guidelines. Sha and Hao [18] proposed a single degree of freedom model to predict the bridge pier response due to barge impact, which provides reasonable approximations in comparison with responses from a high resolution finite element model. A similar approach was proposed for collision events between ships and bridges by Fan et al. [19]. In order to further simplify the assessment of peak forces caused due to barge impact, Fan and Yuan [20] developed a shock spectrum to obtain the peak moments and shears in the piers. Similarly, Cowan et al. [21] developed a response spectrum based methodology to estimate maximum pier shear and moments for designing bridge columns susceptible to barge impact.

The discussion presented above shows that although several studies have assessed the performance of bridges subjected to barge impact – but most of the studies are deterministic, i.e. they do not consider potential uncertainties emanating from collision conditions, soil properties, and structural characteristics. Consideration of these sources of uncertainties is important for designing new bridges because estimates of the probability of bridge collapse are necessary for designing bridges for barge impact as per AASHTO [22] guidelines. Furthermore, studies have not assessed the effect of free pile length, i.e. relative pile cap placement with respect to the mudline, on the column forces and fragility due to barge impact. Free lengths of pile could be either by design or caused by scour, which results in exposed piles due to removal of surrounding sediments. Moreover, simple models that can be used to predict the maximum demands on bridge columns with a wide range of design parameters, free pile lengths, and barge-bridge collision conditions are not available in the literature. Finally, the safety of bridges to carry vehicular loads after a collision event has also not been assessed in the past studies. Such information is important for risk mitigation planning. Therefore, in order to address all of these gaps, this study provides new probabilistic models of the response and fragility of bridge columns subjected to barge impact, as well as assesses the potential joint threat of scour and practical post-event operational condition of truck and traffic loading. To accomplish these goals, finite element simulations are performed for 2000 bridges with varying design parameters, geometric parameters, barge bow yield force, and impact speed. Additionally, for the same set of 2000 parameter combinations, finite element simulations are performed considering various levels of free pile lengths (pier scour), i.e. with pile caps above the mudline. The results of these finite element analyses are used to understand the effect of free pile length on the demands and failure modes caused by barge impact. Next, response surface metamodels are developed to predict the maximum shear and moment in the column as a function of key structural parameters and collision conditions. Furthermore, in order to evaluate the barge impact fragility of bridge columns, logistic regression models are trained to predict the probability of exceeding the ultimate shear strain and column curvature. The applicability of the response surface and fragility models is showcased for a case study bridge to assess bridge safety as parameters vary, such as the pier dimensions, pile length, scour depth, or barge impact velocity.

2. Finite element modeling of bridges

Simply supported bridges on navigable waterways are considered in this study. These bridges have large circular, elliptical, or wall type columns supported on pile foundations. Herein, bridge columns are assumed to be either circular or wall type. Bridge columns situated in or adjacent to the main navigable channel are, usually but not always, protected from impact by fenders. However, other columns on bridges crossing navigable waterways are not protected and have been hit in past incidents. In order to study the response of bridge piers subjected to barge impact and scour, this study models the bridge and the barge in OpenSees [23]. The general modeling approach for studying barge-bridge collision follows the coupled barge-bridge collision analysis methodology proposed by Consolazio and Davidson [15]. Herein, the barge is modeled using a single degree of freedom system. The mass of the barge is lumped on a node which is attached to a spring representing the barge bow. The force deformation relation of the spring representing the bow is obtained from the crush deformation curves proposed by Cowan et al. [9]. A schematic diagram of the finite element model for a two column bent bridge is shown in Fig. 1. The bridge model is assumed to be composed of 6 simply supported spans, three spans on either side of the bent that is impacted by the barge; Fig. 1 only shows the spans adjacent to the bridge bent subjected to barge collision. Inclusion of additional spans beyond the three spans on either side did not have any considerable influence on the performance of the bridge. Furthermore, the boundary conditions at the end of the outermost spans were also varied but their effect on the bridge performance was observed to be insignificant; therefore, bridges are modeled with simply supported end conditions.

The bridge deck for each span is modeled using a grillage where the longitudinal and transverse elements represent the girders and the deck slab, respectively; additional details on grillage modeling can be found in Hambly [24]. The simply supported spans rest on reinforced concrete bents, consisting of the bent beam and the columns. The bent beams and the bridge columns are modeled using beam column elements with fiber sections. The fiber sections consist of three separate layers consisting of the confined core concrete, the un-confined cover concrete, and the longitudinal steel reinforcement. Transverse reinforcement is not directly modeled in this study; however, the effect of the transverse reinforcement on the confined core concrete is included following