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Characterization of multi-barge flotilla impact forces on wall structures

Robert A. Walters [a], Michael T. Davidson [b], Gary R. Consolazio [a,*], Robert C. Patev [c]

[a] University of Florida, Department of Civil and Coastal Engineering, P.O. 116580, Gainesville, FL, 32611, USA
[b] University of Florida, Bridge Software Institute, P.O. 116580, Gainesville, FL, 32611, USA
[c] United States Army Corps of Engineers, Risk Management Center, 696 Virginia Road, Concord, MA, 01742, USA

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ABSTRACT

Engineering standards employed in the United States to design concrete waterway control structures for barge impact loading are principally based on data collected from full-scale experimental barge flotilla (barge tow) impact tests. Due to logistical constraints and test costs, the range of parameters that can be varied during physical experiments is typically limited. Consequently, design standards based on such tests have the potential to be undesirably conservative with respect to determination of design impact loads. In the present study, analytical techniques (numerical simulations) are used to quantify barge impact loads over a wider range of conditions than that which would typically be feasible using experimental testing. Nonlinear dynamic finite element models of barge flotillas are developed to accurately represent inelastic barge crushing and inter-barge wire-rope lashing behavior. The models are validated against experimental test data and subsequently used to conduct parametric studies to quantify the influences of impact speed, impact angle, flotilla size, and load measurement technique. A key finding—with implications for design efficiency—is that flotilla impact loads are strongly correlated to the momentum of only barges in the lead row of a flotilla, rather than total momentum of the entire flotilla, as has been assumed in the development of past design standards. Furthermore, it is found that the load measurement technique used in prior experimental impact tests artificially increased the measured loads, relative to impacts from non-instrumented barges, thereby introducing additional conservatism into previously developed design standards.

1. Introduction

Most navigable waterways in the United States (U.S.) have the capacity to support mass transit of materials through the use of barges. During transit, barges often navigate within close proximity to waterway structures, thus posing potential collision risks. Navigational wall structures serve an important role in helping to ensure safe commodity-transport operations near locks and dams. Approach walls, for example, allow barge pilots to execute controlled alignment maneuvers prior to entering

* Corresponding author.
E-mail addresses: rwalters@walterpmoore.com (R.A. Walters), michael@ce.ufl.edu (M.T. Davidson), grc@ce.ufl.edu (G.R. Consolazio), robert.c.patev@usace.army.mil (R.C. Patev).

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locks, but also protect nearby waterway facilities (e.g., hydroelectric dams, gates) from potential damage by either errant or loose barges. Considering that nearly 200 lock sites are distributed along U.S. navigable waterways, wall structures are subjected to nearly daily impacts from vessels, including multi-barge flotillas. As defined here, a barge ‘flotilla’ is a collection of individual barges, typically arranged end-to-end in one or more columns (Fig. 1). Inter-barge lashings, commonly consisting of steel wire rope cables, secure the individual barges together into an integral unit that can be efficiently propelled along navigable waterways using a single (trailing) push boat.

Loads that are associated with accidental barge impacts often control the design of guidance structures and protection systems on navigable waterways. Design procedures [1] currently employed by the U.S. Army Corps of Engineers (USACE) to calculate barge impact loads on navigation wall structures are based primarily on data collected from (physical) experimental tests [2] of barge impacts on rigid concrete wall structures. However, the inventory of navigational structures designed and maintained by the USACE also includes walls of varying levels of structural flexibility.

It is therefore the objective of the present study to determine whether current procedures for calculating design impact loads yield structural designs with suitable conservatism, or excess conservatism, when applied to either rigid wall systems or flexible wall systems. To achieve this objective, finite element (FE) modeling and impact simulation techniques are employed to quantify barge collision loads on wall structures—of varying stiffnesses—over a range of different impact conditions (speed, angle, flotilla size). Integration of such data into the development of future design procedures will lead to navigational wall structures that satisfy more precise definitions of impact resistance while remaining economical.

2. Background

Several prior research efforts aimed at quantifying loads associated with vessel impacts on waterway structures have addressed highway bridge structures. Bridge design codes in the U.S. [3] and Europe [4] prescribe methods for estimating ship impact loads and barge impact loads, and stipulate related structural design requirements. Numerical modeling and analytical techniques have been developed to facilitate design-level loading and response characterizations for ship collisions with bridges ([5,6]). Several studies have also been carried out to refine U.S. code provisions by developing barge impact load prediction procedures with improved accuracy ([7,8]) and improved analysis procedures ([9–11]). However, such advances are specific to bridge structures, where a significant portion of structural mass is typically located well above the waterline—and thus well above the practical range of barge impact elevations. Consequently, dynamic responses exhibited by bridge structures differ fundamentally from those of wall structures when subjected to impact loads. Furthermore, procedures developed as part of the aforementioned studies involved examination of nearly-head-on impact conditions, in which the vessel is brought to an abrupt halt. In contrast, barge flotilla collisions with wall structures generally involve shallow angle ‘glancing’ (i.e., re-directional) impacts, in which the barge slides along the wall rather than being halted. Consequently, because the collision mechanics of barge-bridge impacts differ from those of barge-wall impacts, empirical relationships between energy, momentum, and force developed for barge-bridge interactions do not necessarily apply to barge-wall interactions.

To address this discrepancy, the USACE previously conducted experimental research focusing specifically on barge impact forces on waterway structures such as lock approach walls. Several series of full-scale barge flotilla impact experiments were conducted to quantify impact forces on rigid concrete walls [2,12], as well as semi-flexible prestressed concrete guide walls [13]. Additionally, the USACE has carried out related analytical studies [14] to investigate barge deformation mechanics during wall impacts. These prior research efforts (in particular [2,12]) culminated in the development of the design provisions and load prediction equations contained in USACE ETL 1110-02-563 [1].

Due to the complexities associated with conducting full-scale flotilla impacts in a controlled manner, only barge impact speeds and approach angles were varied during the USACE experiments that formed the basis of ETL 1110-02-563. Consequently, it was not feasible to experimentally explore, or quantify, the important effects that flotilla size (e.g., number of barge rows in the flotilla) has on impact forces. Additionally, experimental instrumentation used by the USACE to measure impact forces during the experiments—a steel load-measurement beam affixed to the bow corner of the impacting barge—was suspected to have increased the effective stiffness of the barge impact zone, and thus, also increased the measured forces. Moreover, for reasons of both safety and economy, the USACE experiments were conducted at relatively low speeds (and low

Fig. 1. One-column, three-row (1 $\times$ 3) flotilla moving along the Intracoastal Waterway in Florida.