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Parametric studies of pile-supported protective structures subjected to barge impact using simplified models

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ABSTRACT

Independent protective structures supported by concrete-filled steel pipes have been widely used to protect bridge piers from vessel impact. In a high-energy impact scenario, such protective structures can absorb a large amount of energy through plastic deformation. Many previous studies are based on empirical static analysis which ignores important dynamic effects involved in an impact event. Finite-element simulation serves as an alternative approach which is commonly used for dynamic analysis of vessel collisions. However, finite-element simulation is expensive regarding both calculation time and computing resources. To conquer these problems, a simplified impact model considering soil-pile interactions and geometric non-linearity is developed in this paper based on the coupled multi-degree-of-freedom model previously proposed by the authors. The computational cost can be remarkably reduced by the simplified models. The influences of pile cross-section diameter, pipe thickness, pile length, free span of pile and soil properties on the energy dissipation capacity of pile-supported protective structures are investigated in this paper using the simplified models.

1. Introduction

Vessel impact is a potential hazard for bridge piers located in navigation waterways. To avoid direct contact between vessels and bridge piers, independent protective structures are widely used in bridge engineering. The pile-supported protective structures are representative of the independent protective structures. They are adopted and installed for long-span bridges such as the Rosario-Victoria Bridge in Argentina [1], the Rhine Bridge in Kehl, Germany [2], the American Sunshine Skyway Bridge [3], etc. The advantage of pile-supported protective structures lies in their high energy dissipation capacity. A vessel with high impact energy can be prevented from direct contact with bridge piers when such protective structures are properly designed and installed.

Extensive studies pertaining to pile-supported structures were conducted previously. Rao et al. [4] and Patsch et al. [5] conducted field tests to study the loading behavior of pile-supported structures. However, the static analyses used in corresponding studies ignore important dynamic effects, i.e. inertia forces and damping forces, involved in a high-energy impact event. Zhu et al. [6] conducted a series of hammer impact tests on single piles. It was observed that the inertia force of a pile shaft is not influential upon the maximum bending moment of the pile shaft but strongly affects the load-displacement curves of a pile during impact. However, the stiffness of a rigid hammer is much larger than that of a real vessel, thus the energy dissipation process during a vessel impact event could be different from that observed from a hammer impact test. In addition, experimental impact tests are often costly and time-consuming. Finite-element (FE) simulations were thus extensively used for dynamic analyses of vessel impact on protective structures [7,8]. Compared with experimental impact tests, FE simulations are less costly and much easier to be conducted. However,

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FE simulations suffer from several fundamental problems. Generally, a substantial investment of time and effort is required for non-linear modeling of the vessel, the piles, the connecting beams, and the soil. In addition, the computational demands involved in conducting high-resolution non-linear contact/impact analysis often demand supercomputing resources and excessive computing time [6,9]. Simplified models are thus often required by engineering designs and scientific studies. Zhu et al. [6] proposed a simplified 2D quasi-static analysis method which can be used to estimate the lateral deflection of a pile-supported structure efficiently. However, neglecting structural inertia forces results in an overestimation of the lateral deflection of pile head and underestimation of energy dissipation capacity of a pile-supported structure [6]. Fan and Yuan [8] proposed a simplified two degree-of-freedom (DOF) analytical model where a non-linear macro-element is utilized to represent the mechanical behavior of a ship bow during an impact event and the equivalent capacity of a pile-supported structure was generated by detailed FE simulations. This analytical model is proved to be of sufficient accuracy and efficiency. However, these existing simplified models often require physical experiments or FE simulations beforehand to generate the load-deflection curve of a pile-supported structure. In addition, dynamic soil-pile interactions during impact cannot be directly obtained from these simplified models. Other simplified models include the Coupled Vessel Impact Analysis (CVIA) technique proposed by University of Florida (UF) [9], the simplified impact model proposed by Yuan [10,11] and the simplified impact model proposed by Sha [12]. However, several problems regarding model simplicity or prediction accuracy often exist in these simplified models [13,14].

The coupled multi-degree-of-freedom model (CMM) previously proposed by the authors simplifies the barge vessel into a non-linear mass-spring model (MSM) and the pier column into discrete masses and fiber beam elements. By coupling MSM with the pier column at the impact position, the CMM is developed for dynamic barge-pier impact analyses [13]. Material non-linearity of pier column members are considered by assigning realistic uni-axial stress-strain relationships to discrete section fibers [14]. The prediction quality of CMM was thoroughly assessed for different impact scenarios [13,14]. The verified CMM was then used for devising novel crashworthy devices [15] and reliability analyses of bridge piers subjected to barge impact [16] in previous studies conducted by the authors. This paper aims to develop a simplified impact model considering soil-pile interactions and geometric non-linearity based on CMM for dynamic analyses of pile-supported protective structures subjected to barge impact, and to investigate the influences of several parameters, i.e. pile cross-section diameter, pipe thickness, pile length, free span of pile and soil properties, upon the energy dissipation capacity of pile-supported protective structures using the proposed simplified impact model.

2. Overview of CMM

The CMM previously proposed by the authors simplifies the complex finite-element barge model into a non-linear mass-spring model (MSM) and models the pier column using discrete masses and fiber beam elements [13,14], as shown in Fig. 1 where M_b is the lumped barge mass and V_I is the impact velocity.

As per previous studies [11,13,17,18], the force-deformation curve of a barge during impact (curve 1) generally includes a roughly linear increase of force until a force peak followed by an abrupt decrease of force after the barge yields, as shown in Fig. 2 where u_b is the barge deformation and F is the impact force. Then the force roughly reaches a plateau until the unloading stage. The shape of curve 1 can be regarded as the superposition of two curves - a bi-linear curve (curve 2) and a triangular curve (curve 3), as shown in Fig. 2. Two non-linear springs which act in parallel are thus introduced to represent the barge resistance. The force-deformation curves of two springs are taken to be bi-linear and triangular, respectively, as shown in Fig. 3, where u_1 and u_2 are the yielding deformations of two springs, respectively; F_{sy} is the yielding force of the first spring; F_{sp} is the peak force of the second spring; l_{bs} is the spring length which is taken to be 6.1 m [13,14]; x is the spring deformation. By coupling MSM with a pier column at the impact position, the CMM is developed to predict the dynamic barge impact process efficiently, as shown in Fig. 1 where the transformation of a full barge impact model (FBIM) into the CMM is provided. The values of MSM parameters, i.e. u_1, u_2, F_{sy}, F_{su} and F_{sp}, are determined by an optimization model, the objective of which is to minimize the integration error of impact force time-

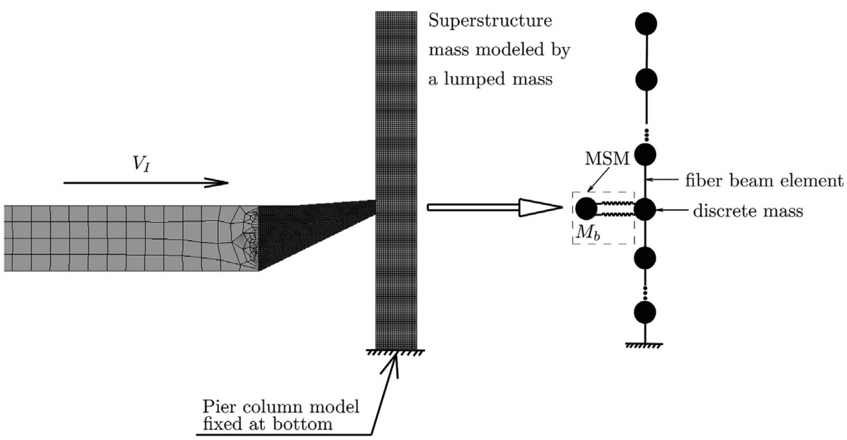

Fig. 1. Transformation of full barge impact model (left) into CMM (right).