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Modeling tsunami induced debris impacts on bridge structures using the material point method

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Abstract

Bridges represent a key part of infrastructure, playing a critical role in emergency response and post-event reconstruction. In this context, it is important for bridges to be able to survive both ground shaking and the effects of tsunamis. This paper focuses on numerically modeling bridge loading due to tsunamis. Although several studies have addressed the effect tsunami loads on bridges, few have examined the influence of debris carried by the tsunami. These problems involve complex contact interactions between solids and fluids that are not easily accommodated using typical fluid-oriented or solids-oriented numerical frameworks. In this paper the material point method (MPM) is used to address fluid and solid (moving and stationary) interactions with emphasis in evaluating demands on bridge superstructures by tsunami-driven debris.

Two parametric studies have been conducted in this study. The first is aimed at understanding the influence of the contact area and the eccentricity of impact on the impact forces. The results show that the effect of these two factors are reduced with an increase in longitudinal length of the solid object. The second part of the study tries to evaluate the difference between tsunami driven debris impact loads and in-air debris impact loads. The results indicate that tsunami driven debris impacts tend to be larger by upto 35% compared to only in-air impact forces calculated using empirical equations.

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Keywords: Material point method; debris; fluid; impact; tsunami; bridge; fluid-solid interaction.

1. Introduction

Throughout history, strong earthquakes have struck countries all over the world and caused major damage. Most of this damage has been due to ground shaking, but in coastal areas tsunamis induced by earthquakes have resulted in greater loss of lives and infrastructure. As coastal populations continue to increase around the world, understanding and managing tsunami effects on infrastructure becomes increasingly important.

The objective of this study is to give preliminary results for researchers and engineers trying to understand the demands on bridge superstructures by tsunami-driven debris. It is imperative that bridges are able to survive both

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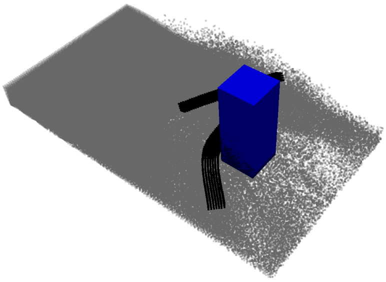
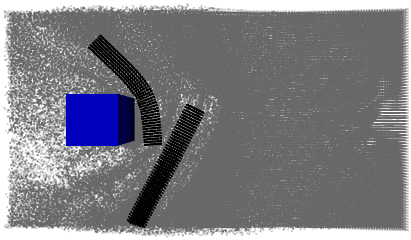


(a)



(b)

Fig. 1: 3-D simulation of two pieces to debris impacting a column causing partial damming.

ground shaking and the effects of tsunamis caused by earthquakes. Many prior numerical and experimental studies considering tsunami induced loads on bridges have been done, especially after the Great East Japan Earthquake. However, few of these earlier studies have examined the influence of debris carried by the tsunami. The studies that have been completed have demonstrated that debris can cause strong impact forces on columns and walls [1–3]. Lessons from these studies should be straightforward to apply to bridge vertical structures (i.e. bridge piers), but need some adjustment when applied to bridge superstructures, since in this case flows carrying debris have different characteristics compared with flows considered in the previous studies. In addition, debris can also affect the fluid motion around the bridge and introduce additional forces with longer duration compared to the impact. This class of problems is not well studied yet in the literature and involve complex contact interactions between solids and fluids. These effects are not easily accommodated with typical fluid-oriented or solid-oriented numerical frameworks. In this research the material point method (MPM) is used to model these complex fluid/solid (moving and stationary) interactions.

The ultimate goal of the work is to model tsunami induced debris impacts in three dimensions like shown in Figure 1 and to understand damming and more complex flows around the superstructure during a tsunami. The results presented in this study are obtained using a single-threaded MPM code. This limits the mesh and particle refinements used in the validation examples and the debris-induced load study is relatively coarse compared to general applications found in the literature. A program allowing for parallel computing and /or one that employs implicit algorithms is necessary for further study in the future.

2. Background

With large peak values, impact forces due to debris (solid objects) can cause severe local damage on bridge components, even though they happen in a very short time. In the literature, impact forces are evaluated using simple equations based on fundamental physics. In ASCE/SEI 7-10 [4], for instance, maximum impact forces F_{Ip} are calculated using impulse-momentum based equations of the form

$$F_{Ip} = \frac{\pi m_d v_d}{2\Delta t_I} \tag{1}$$

where m_d and v_d represent the mass and impact velocity of the debris, and Δt_I is the time interval over which the debris stopped from its original velocity v_d. Recommended and measured values of Δt_I range from 10^{-3} seconds to 1.0 seconds. This diversity of Δt_I results in very different impact forces and hence demands on structural systems. To improve Equation (1) and avoid the need to select a Δt_I, the flexibility of the solid object representing the debris is considered. By simplifying the collision of a debris into a bridge deck by a 1D spring model with equivalent stiffness k_{eq}, Equation (1) can be rewritten as,

$$F_{Ik} = c_I v_d \sqrt{k_{eq} m_d} \tag{2}$$