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Debris impact under extreme hydrodynamic conditions part 2: Impact force responses for non-rigid debris collisions

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ABSTRACT

Historical tsunami events have resulted in extreme damage to coastal regions worldwide. Among the various loads associated with tsunami waves, debris impact has been shown to cause major damage to nearshore infrastructure. As a result, debris impact loads have been included prominently in existing design guidelines and standards, such as the FEMA P-646 [11] and ASCE7 Chapter 6 [6]. In the present study, single debris impacts on structures was experimentally investigated under tsunami-like wave conditions. Eccentric and oblique impacts of a model shipping container (length scale 1:40) on a non-rigid structure were examined. The experimental results of the non-rigid impacts are discussed in the context of the existing force equations which were derived under the assumption of rigid-body impact theory. As expected, the elasticity of the structure was determined to influence and, specifically, reduce the magnitude of the debris impact forces. Existing impact force equations are herein critically discussed through comparison with the experimental results and, finally, modifications to existing force equations to account for non-rigid collisions are proposed.

1. Introduction

Tsunami events have resulted in extreme damage to coastal regions throughout the world. The Tohoku Tsunami on the 11th of March 2011, caused over 15 000 casualties, more than 2500 people still missing and around 300 000 people displaced from their homes (Kazama and Noda, 2012). Additionally, the tsunami caused a nuclear meltdown at the Fukushima Daiichi Nuclear Power Plant resulting in radiation and other environmental effects which are still felt today (Kingston, 2012). In 2004, the massive tsunami in the Indian Ocean originating near Sumatra led to the death (or declared missing) of at least 226 000 people, making it one of the most deadly natural disasters in recorded history (Rabinovich et al., 2006; Titov et al., 2005).

Tsunami waves contain a huge amount of energy and thus cause severe damage to structures and objects in their propagation path, including coastal protection structures (Mori et al., 2013). Various researchers (Chock et al., 2013; Ghobarah et al., 2006; Saatcioglu et al., 2005; Yeh et al., 2013) have shown that several buildings and infrastructure onshore failed unexpectedly during such events. The failure of critical infrastructure, such as tsunami evacuation structures, bridges or hospitals, is particularly dangerous due to the importance of these structures in emergency and evacuation planning. An overestimation of the tsunami forces, on the other hand, may result in the design of unnecessarily expensive and uneconomical structures. Research efforts have been made over the past decades to enhance the general understanding of tsunami-induced loading in order to create and improve the current and future building codes, practices, and guidelines. The primary focus of past research was aimed towards understanding the general effects of a tsunami waves hitting a coast, wave-structure interactions, and structural failure (Arikawa, 2011; Arnason et al., 2009; Nouri et al., 2010; St-Germain et al., 2013; Synolakis et al., 1988; Yeh et al., 2014), with limited emphasis on debris loading.

Since virtually anything in the flow path can be entrained by the tsunami-induced inundation and become debris, the debris impact is an ubiquitous problem during such events. Building codes and guidelines have already been developed discussing debris impact but there is still considerable uncertainty regarding influencing factors for debris impact loads. Thus, guidelines, such as FEMA (FEMA, 2012) and ASCE7-6 (ASCE, 2016), offer simplified, conservative, but not yet well validated, approaches (Riggs et al., 2014) which will be outlined in the following section.

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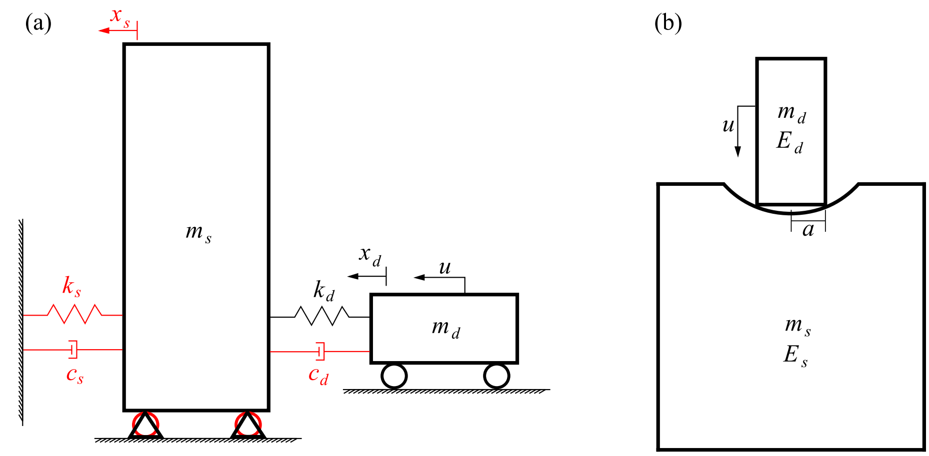

Fig. 1. Schematic of the debris impact model. (a) Single DOF model. The red elements represent the portions of the solution neglected due to simplifying assumptions. (b) Hertzian contact model.

2. Debris impact model

2.1. Impact models

A commonly used approach in design standards (ASCE, 2016; FEMA, 2012) to estimate debris impact forces is derived based on the single degree-of-freedom (DOF) model published by Haehnel and Daly (2004). The single DOF model is based on the two DOF model (Fig. 1(a)) under the assumption that the impact duration is significantly shorter than the natural frequency of the structure and that minimal displacement of the structure occurs. These assumptions suggest that the rigid-body impact theory can be applied (Haehnel and Daly, 2002). The resulting rigid body solution (Fig. 1(a) – black elements) considers only the properties of the debris and its motion in the determination of the maximum impact loading.

Following Newton's Second Law and Hooke's Law, the simplified model can then be described with the following equation:

$$m_d \frac{d^2x}{dt^2} + k_d x = 0 \tag{1}$$

Three major approaches have been used to calculate the maximum impact force from Eq. (1): Contact-Stiffness, Impulse-Momentum, and Work-Energy. These three approaches are dependent on the velocity and mass of the debris (Nistor et al., 2017). However, the proportionality between these parameters varies between the three approaches, as shown in Table 1.

Furthermore, besides the mass and velocity, each approach requires an additional parameter. The Contact-Stiffness approach takes into account the effective contact stiffness (k), described by Eq. (2), which is a combination of structure's stiffness (k_s) and the elastic deformation of the debris on impact (k_d).

Table 1
Proportionality between the impact force (F), the debris mass (m_d) and the debris impact velocity (u).

Approach	Proportionality of F, u and m	Equation	Additional Parameter
Contact-Stiffness (Haehnel and Daly, 2004)	$F \propto u\sqrt{m_d}$	$F = u\sqrt{km_d}$	Effective Contact Stiffness
Impulse-Momentum (Aghl et al., 2014)	$F \propto um_d$	$F = \frac{\pi}{2}\frac{um_d}{\Delta t}$	Impact Duration
Work-Energy (Blok et al., 1983)	$F \propto u^2 m_d$	$F = \frac{u^2 m_d}{\Delta x}$	Stopping Distance

$$\frac{1}{k} = \frac{1}{k_s} + \frac{1}{k_d} \tag{2}$$

The Impulse-Momentum approach includes the impact duration (Δt), while the Work-Energy approach requires the stopping distance of the debris (Δx) (Haehnel and Daly, 2002). The Contact-Stiffness approach is the most commonly used within current building codes which deal with tsunami and flood design, primarily due to the fact that the stiffness is less sensitive than the estimation of the impact duration or stopping distance.

Eq. (3) can be determined by solving for the maximum displacement in Eq. (1) using the Contact-Stiffness approach:

$$F_i = u\sqrt{km_d} \tag{3}$$

The direct solution of Eq. (1) would yield the rigid body solution, where the stiffness of the debris would replace the effective stiffness in Eq. (3). Haehnel and Daly (2004) firstly introduced the effective stiffness model as a method of including the structural properties in the estimation of the maximum debris impact force.

Past research on debris impacts has led to several different equations to calculate debris impact forces outside of the single DOF model. Matsutomi (2009) experimentally examined tsunami wave-induced debris impact loading of small-scale driftwood onto a rigid structure. In order to compensate for potential scale effects, Matsutomi (2009) also conducted full-scale log experiments in-air, employing a pendulum setup. Comparing the in-air and in-water experiments, Matsutomi (2009) determined that the added mass of the driftwood needs to be taken into account. The added mass results from the volume of fluid around driftwood which needs to be decelerated as the impact occurs. Matsutomi's (Matsutomi, 2009) proposed the following equation to estimate the impact force of a single tsunami-driven debris:

$$\frac{F_i}{\gamma_w D^2 L} = 1.6 C_M \left(\frac{u}{\sqrt{gD}}\right)^{1.2} \left(\frac{\sigma}{\gamma_w L}\right)^{0.4} \tag{4}$$

where F_{max} is the maximum impact force, γ_w is the specific weight of the debris, D is the diameter of the debris, L is the length of the debris, C_M is the inertia coefficient with $C_M = 1 + C_O$, C_O is the added mass coefficient, u is the debris impact velocity and σ_f is the yield stress of the debris.

Arikawa et al. (2007) performed 1:5 scale experiments of shipping containers impacting structures under tsunami-like surge fronts. Based on Hertzian contact mechanics (Fig. 1(b)), the following empirical equation was developed:

$$F_i = 0.25\left(\frac{4\sqrt{a}}{3\pi}\frac{1}{K_s + K_d}\right)^{\frac{2}{5}}\left(\frac{5}{4}\frac{m_s m_d}{m_s + m_d}\right)^{\frac{3}{5}} u^{\frac{6}{5}} \tag{5}$$