Ocean Engineering 127 (2016) 158–169

Contents lists available at ScienceDirect

Ocean Engineering

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

# Experimental investigation of tsunami-borne debris impact force on structures: Factors affecting impulse-momentum formula

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ARTICLE INFO

*Keywords:*
Impact
Debris
Tsunami
Structure
Force

ABSTRACT

This study investigates factors affecting tsunami-borne debris impact force on structures. Debris collision accelerations were measured at the contact point on the structure's seaward wall using disc- and box-shaped smart debris devices; the equation of motion was used to estimate the debris impact forces from the measured accelerations. Also, the impact force was measured at the base of the structure using a multi-axis load cell, and compared with the forces determined using the smart debris devices. The basic impulse-momentum formula was modified by the addition of coefficients, taking into account the added mass and the debris velocity. Debris shape also influenced the impact force. Deformability of the debris and flexibility of the structure both reduced the debris impact force.

## 1. Introduction

Typically, tsunami waves break near the coastline, generating bores that travel inland at high velocity and are capable of transporting heavy objects. Impact forces from tsunami-borne debris such as shipping containers, boats, floating driftwood, automobiles, etc. can cause significant damage to structures during tsunami events (NRC, 2004; Saatçioğlu, 2009; Saatcioglu et al., 2006). Debris impact is associated with either a 'punching force' that is generally very large in magnitude and acts on the structure's cladding over a small area, or a force acting bodily on the structure that has the potential to overturn the structure or push it off its foundations. Both the strength of cladding material and the structure stability are of concern for design of structures subject to tsunami-borne debris impact. The seaward walls of structures are the most vulnerable to cladding damage from the impact of floating debris. Rupture of the cladding allows water to enter the structure at high velocity, potentially causing secondary damage. Estimation of the maximum force from floating debris collision with a structure is complicated by interaction between the debris, the structure, and the tsunami bore. The maximum force is influenced by the debris parameters (i.e., shape, density, deformability, orientation, and velocity), tsunami bore height and velocity, and properties of the structure itself, especially stiffness and inertia for light flexible structures (Haehnel and Daly, 2002, 2004).

Various experimental techniques have been used to investigate debris impact. Physical modelling of the floating debris impact has received some attention, particularly the impact of wooden debris (Haehnel and Daly, 2002, 2004; Matsutomi, 2009; Nouri et al., 2010; Yeh et al., 2005). Recently, a collaborative research project, involving the University of Hawaii, Lehigh University, and Oregon State University, has been carried out to study the impact force of shipping containers and wooden poles during tsunami events (Ko, 2013; Kobayashi et al., 2012; Paczkowski et al., 2012; Piran-Aghl et al., 2013; Riggs et al., 2013).

Impulse-momentum, work-energy and contact-stiffness are three approaches for estimating the debris impact force at the point of contact on a structure. Haehnel and Daly (2002, 2004) studied the three approaches for estimating the impact force of flood driven debris on structures. For each approach, the force is considered to be a function of the debris mass and velocity, plus an additional parameter depending on the approach: the contact duration for the impulse-momentum approach, the stopping distance for the work-energy approach, and the effective contact-stiffness of the collision for the contact-stiffness approach (Haehnel and Daly, 2002). However, Haehnel and Daly (2004) concluded that, if the structure is very rigid, the three approaches are theoretically equivalent for describing the impact of a debris object (in their case a log); based on their conclusion, they developed a single degree of freedom model. They used their model to demonstrate that the additional parameters for the three approaches are not independent, i.e. the contact duration depends on the mass of the debris and the effective contact stiffness of the collision, and the stopping distance depends on mass, contact-stiffness and velocity.

In Guidelines for Structures for Vertical Evacuation from Tsunami,

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http://dx.doi.org/10.1016/j.oceaneng.2016.09.008
Received 8 September 2015; Received in revised form 15 August 2016; Accepted 6 September 2016
Available online 11 October 2016
0029-8018/ 

FEMA (2012) adopted the use of the contact-stiffness approach, to estimate the debris impact force ($F_{di}$), taking into account the effect of the added mass of water:

$$F_{di} = 1.3u_d\sqrt{k_e m_d C_{add}} \tag{1}$$

where $u_d$ is the debris velocity, $m_d$ is the debris mass, $C_{add}$ is the added mass coefficient and $k_e$ is the resultant effective stiffness of the impact. FEMA recommends added mass coefficients of 1 and 2, for a log with longitudinal axis parallel and at right angles to the flow, respectively).

On the other hand, in the design guidelines for flood impact loads, ASCE (2010) and FEMA (2011) recommend the use of the impulse-momentum approach:

$$F_{di} = \frac{\pi m_d u_d}{2\Delta t} \tag{2}$$

in which $\Delta t$ is the contact duration and the term $\pi/2$ is included to give the maximum impact force rather than the average force, assuming a sinusoidal variation of force with time (Haehnel and Daly, 2004). FEMA (2011) recommended values for $\Delta t$ from 0.1 to 1 s, while ASCE (2010) suggested $\Delta t$=0.03 s be used. The wide range of values for $\Delta t$ recommended by FEMA and ASCE can lead to large differences in the estimated force. In addition, Eqs. (1) and (2) estimate significantly different peak forces for the debris impact (Piran-Aghl et al., 2013).

Kobayashi et al. (2012) used rigid body dynamics to develop a simple 1D model to estimate the debris impact force on a rigid wall. The analytical solution for the impact of a projectile driven by water can be obtained from the model. Paczkowski et al. (2012) developed a simplified model (see also Riggs et al. (2013)) for estimating debris impact force, considering the longitudinal impact of a pole (Eq. (3)). They modelled the pole as an elastic bar, assuming a uniaxial response, and formulated the impact force as:

$$F_{di} = u_d\sqrt{k_d m_d} \tag{3}$$

Eq. (3) has the same form as that for the contact-stiffness approach (Eq. (1)). Paczkowski et al. concluded that, for the condition of their experiments, the maximum impact force is independent of the total mass of the debris, which is not in agreement with findings of Haehnel and Daly (2002, 2004) and Nouri et al. (2010). The equation developed by Paczkowski et al. is for the small time scale acoustic response of the impact. They recommended further research should consider the longer time-scale gravity waves induced by the impact, including the free surface.

Matsutomi (2009) proposed an empirical equation to estimate the impact force of a wooden log:

$$\frac{F_{di}}{\gamma_d D_d^2 L_d} = 1.6C_{add}\left(\frac{u_d}{\sqrt{g_n D_d}}\right)^{1.2} + \left(\frac{\sigma_d}{\gamma_d L_d}\right)^{0.4} \tag{4}$$

where $\gamma_d$ is the specific weight of the wooden log, $D_d$ is the diameter of the log, $L_d$ is the length of the log, $C_{add}$ is the added mass coefficient which depends on the size and shape of the impacted structure, the types of flow and location of the log in the flow field, $g_n$ is the acceleration of gravity, and $\sigma_d$ is the yield stress of the log. Matsutomi recommended further investigation of impact force variables, using experiments covering wide ranges of values for these variables.

Riggs et al. (2013) reported on full scale in-air axial impact tests using a wood utility pole and shipping container in which the impact target was a reinforced concrete wall. Piran Aghl et al. (2013) reported on the same tests, including the results for a square steel tube. Piran Aghl et al. reported that the impact force increased when non-structural mass was added to a square steel tube (i.e. non-structural mass was firmly attached to the tubes, with the result that the tube's stiffness remained unchanged, but its total mass increased), which is contrary to the conclusion by Paczkowski et al. (2012). Piran Aghl et al. (2013) also found that the impact force was directly related to the impact velocity.

Ko (2013) reported on the investigation of the impact of tsunami-borne debris, in this case a 1:5 scale model, empty standard shipping container in a large tsunami wave flume. The impact target was a rigid column, chosen to reduce obstruction of the flow. Non-structural masses (representing cargo inside a container) were also added to the model containers (non-structural mass could move inside the model). The initial orientation of the object was either longitudinal or transverse, in relation to the flow direction. Ko's results indicated that the longitudinal impact induced the largest impact force. Also, Ko found that increasing the object mass (the addition of non-structural mass) increased impulse and also increased contact duration. Unrestrained non-structural mass inside the model container had no effect on the measured peak impact force. However, non-structural mass was effectively restrained by the downstream end of the container, and increased the mass of the container and subsequently increased the measured impact force.

This review of previous studies shows several approaches to estimating tsunami-borne debris impact force, with proposed equations giving different results. There are various parameters included in the equations within each approach, for which a wide range of values have been proposed. In spite of the importance of the impact force of floating debris, there have been few experiments investigating the influence of various parameters on the impact force. In addition, the approaches and equations presented do not differentiate between the debris impact force at the contact point of collision and the force at the base of the structure. There are various sources of damping causing the force applied at the contact point of collision to be different from the force applied at the structure base. This study investigates factors affecting $F_{di}$ with the aim of identifying where future research should be concentrated. The study also investigates the relationship between the debris impact forces at the contact point of collision and the forces at the structure base.

## 2. Framework for analysis

A generalised form of the basic impulse-momentum formula (proposed by Haehnel and Daly (2004) and ASCE (2010)) is adopted for the horizontal component of the debris impact force at the contact point on the front wall of the structure.

$$(F_{di})_x = C_{add}C_u C_{sh} C_{DD} C_{SS} \times \frac{\pi m_d u_d}{2\Delta t} \tag{5}$$

where the $C'$s are coefficients to describe the effects on the basic variables ($m_d$, $u_d$, and $\Delta t$) of added mass ($C_{add}$), debris impact velocity ($C_u$), debris shape ($C_{Sh}$), deformability of the debris ($C_{DD}$), and stiffness of the structure ($C_{SS}$). The coefficients ($C'$s) affect the value of the force calculated from measured values of the variables. The hypotheses considered in this study, in relation to the coefficients, and brief accounts of the corresponding investigations, are given here.

1) The added mass of the entrained water increases the debris impact force. The added mass depends on the degree of submergence of the debris, which depends on the density of the debris (Hamilton, 2000), which in turn depends on the mass and shape of the debris. In addition, the degree of submergence is influenced by proximity to the structure, because of free-surface effects, such as free-surface tilting and splash (Landweber et al., 1992). The degree of debris submergence was varied by varying debris mass and hence its density. In addition, detailed observations were made of the degree of submergence immediately before impact.
2) The floating debris velocity will reach the bore velocity if the distance between the original position of the debris and the structure is long enough. For a specific (shorter) distance, the floating debris velocity depends on the debris shape, debris mass, and flow depth and velocity. Disc- and box-shaped debris were