Coastal Engineering 141 (2018) 24–35

Contents lists available at ScienceDirect

Coastal Engineering

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

Debris impact under extreme hydrodynamic conditions part 1: Hydrodynamics and impact geometry

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ARTICLE INFO

Keywords:
Debris impact
Impact geometry
Tsunami
Influencing factors on debris impact
Coastal engineering

ABSTRACT

In field investigations of major flooding events, debris impact has been identified as a critical load and has thus been included in various building codes, such as FEMA P-646 and ASCE7. However, the evaluation of debris loading solely based on field data is challenging. Therefore, to address the uncertainties related to debris loading, an experimental program investigating debris impacts on structures was performed using a dam-break wave. The debris were down-scaled 6.1 m (20 ft) shipping containers (1:40 geometric scale) which were entrained and displaced by the transient wave conditions. The study presented here examines the influence of the transient flow conditions and the flow features around the structure due to the impinging wave on the debris impact conditions. The influence of the impact geometry (obliqueness, eccentricity) on the impact force is also discussed and possible parameters to describe the impact geometry are introduced.

1. Introduction

Field surveys after the 2004 Indian Ocean and 2011 Tohoku Tsunami detailed the challenges associated with the design of structures capable of withstanding the massive loads associated with these major flooding events (Esteban et al., 2015; Yeh et al., 2013). In the aftermath of these events, emphasis has been placed on identifying and quantifying the various loads that structures can be subjected to. One of the loads that was identified in many field surveys (Robertson et al., 2007; Saatcioglu et al., 2005; Yeh et al., 2013) was debris loading, caused by the impact of solid objects, ranging from smaller construction materials to shipping vessels, entrained within the inundating flow.

Building standards currently tend towards conservative estimations of debris impact forces by assuming the maximum potential load occurs over the course of the tsunami inundation flow. Considering the impact to be a one degree-of-freedom rigid body impact model, the maximum force exerted by an object impacting a structure can be calculated as:

$$F = u\sqrt{km_d} \tag{1}$$

where u is the impact velocity of the debris, k is the stiffness of the debris, and m_d is the mass of the debris. Current standards provide limited guidance with respect to the influence of debris impact geometry, which can result in a reduction in the kinetic energy, and therefore the force, transferred to the structure. FEMA P646 (FEMA, 2012) does not include any considerations for impact geometry into their force equation and ASCE7 (ASCE, 2016) includes a fixed orientation coefficient (0.65 – Tsunami Loads and Effects, 0.80 – Flood Loads). As such, practicing engineers cannot account for variations in the impact force equations due to eccentric or oblique impacts. However, several studies have indicated a significant influence of the debris impact geometry on the impact force (Haehnel and Daly, 2004; Ikeno et al., 2016; Riggs et al., 2014).

Haehnel and Daly (Chanson, 2005) examined the effect of various impact geometries for wood poles hitting a structure. The authors concluded that in their experiments the impact force was greater when the structure was hit by a perfect longitudinal (long axis of debris (DA) parallel to the flow direction) impact ($\theta = 0°$) compared to a transverse one (DA perpendicular to the flow direction) ($\theta = 90°$). However, for $\theta > 0°$, the impact force increased as the angle increased towards $\theta = 90°$. Additionally, central impact forces, where the impact axis (IA) passes through the center-of-gravity (CG), exceeded those of eccentric impacts. This comparison led to a modification of the maximum impact force equation for debris impacts (Eq. (1)). A sketch of the definitions of impact geometry are shown in Fig. 1.

$$F_{max} = eBu\sqrt{k(m + Cm_f)} \tag{2}$$

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https://doi.org/10.1016/j.coastaleng.2018.08.016
Received 8 February 2018; Received in revised form 15 May 2018; Accepted 31 August 2018

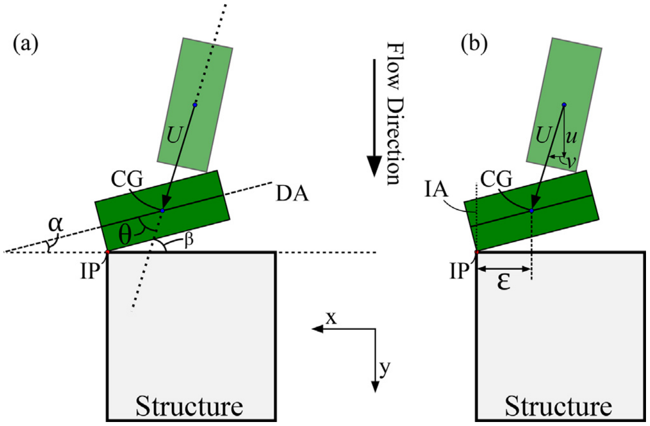

Fig. 1. Geometrical parameters used for oblique (a) and eccentric (b) impacts. CG – center-of-gravity, IA – impact axis, IP – impact point, DA – long axis of debris.

$$e = \frac{1}{\sqrt{1 + \left(\frac{\varepsilon_0}{r_i}\right)\left(1 + \mu\frac{r_0}{\varepsilon_0}\right)}} \tag{3}$$

$$B = \sin\theta \tag{4}$$

$$\frac{1}{k} = \frac{1}{k_t} + \frac{1}{k_l} \tag{5}$$

where e represents the influence of the impact eccentricity, B accounts for the influence of the impact obliqueness, u is the debris impact velocity, k is the stiffness of the debris, m is the mass of the debris, C is the added hydrodynamic mass coefficient, m_f is the mass of the displaced fluid, ε_0 is the distance from the center of gravity of the debris to the point of impact, r_i is the radius of gyration of the debris, μ is the coefficient of friction between the structure and the debris, r_0 is the radius of the log, θ is the angle between the impact velocity vector and the long axis of the debris, k_t is the local stiffness of the structure at the impact zone and k_l is the elastic deformation of the log at impact.

Both parameters e and B range between 0 and 1, thus leading to a reduction of the maximum impact force, which occurs with $\theta = 90^\circ$ and $\varepsilon_0 = 0$ m. The above equations were validated for large wooden poles and the influence of the eccentricity and obliqueness was tested separately with the debris constrained to a carriage within the flume. Due to challenges in assessing the θ value due to occlusion of the debris around the structure in experimental studies, several other variables have been used in assessing debris impact such as α (the angle between the debris axis and the structure face) and β (angle between the velocity vector and the face of the structure) as indicated in Fig. 1 (Ikeno et al., 2016; Shafiei et al., 2016).

Ikeno et al. (2016) investigated the influence of the impact geometry by conducting large-scale experiments with wooden logs, varying in size and material. The impacts were conducted in-air as well as in-water. The study evaluated the impact of debris on a vertical wall made of steel and the debris were driven by a tsunami-like bore. Ikeno et al. (2016) found a significant reduction in the impact force for oblique collision with angles larger than 20°. In an effort to include the influence of obliqueness, the authors established a function to reduce the calculated impact force. The function was based on the idea that, for longitudinal impact, the kinetic energy of the debris is transmitted to the structure. For cases with oblique impact, a portion of the debris' kinetic energy is transformed into rotational motion around the impact point instead of being transferred into the structure. Ikeno et al. (2016) calculated the reduction of the collision energy by considering the conservation of angular momentum. The reduction function for the impact forces resulted in the factor calculated by Eq. (6) and applied to Eq. (1) as a coefficient.

$$\lambda = \sqrt{\frac{1 + \left(\frac{\varepsilon_0}{r_0}\right)^2 \cos^2\theta}{1 + \left(\frac{\varepsilon_0}{r_0}\right)^2}} \tag{6}$$

However, Ikeno et al. (2016) reported that even these reduced values for the impact force overestimated the observed impact forces for oblique collisions within their experiments. Ikeno et al. (2016) additionally noted that due to splash-up around the structure, the motion immediately preceding the impact could not be captured and therefore an impact velocity away from the structure was used in the estimation of the impact force.

The hydrodynamic conditions around the structure could have a significant influence on the impact. Shafiei et al. (2016) suggested that fluid trapped between the debris and the structure could result in a water cushioning effect. St-Germain et al. (2013), in an investigation of hydrodynamic loading of dam-break waves on surface piercing columns, noted the formation of a stagnation zone characterized by low flow velocities in front of the structure as well as a surface roller that would propagate upstream as the flow transitioned from supercritical to subcritical. These flow regimes may also influence the debris impact velocity as well as the impact geometry.

With the overall objective of examining debris impact loading in transient violent flow conditions, the specific objectives of the presented study are:

- Investigate the relationship between the flow velocity and the impact velocity of a single debris in a dam-break wave representing a tsunami-like flow.
- Determine the influence of flow features around the structure on debris impact velocity and geometry.
- Examine the influence of debris impact geometry and their statistical distributions on maximum impact loading conditions.

This paper is part of a two-series paper. The present first part investigates the hydrodynamic aspects and the impact geometry on debris loading, aspects previously neglected in other studies. As the experimental program represents significant portion of the current work, a detailed report on how the experiments were conducted is provided in the first part of the paper series. The scope of this study is limited to a single type of debris entrained within the leading front of the wave and does not address the quasi-steady stages of a tsunami wave. Part 2 will focus on the debris impact forces and the consequences of flexible structures.

2. Experimental setup

2.1. Dam-break flume

The experimental research reported herein was part of a comprehensive series of tests conducted in the dam-break wave flume at the University of Ottawa, Canada. The flume has a total length of 30.00 m, a width of 1.50 m and a height of 0.72 m. It is divided into two sections: an upstream 21.55 m long reservoir and an 8.45 m long test area. The reservoir and the experimental area were separated by a swing gate designed to generate dam-break wave, simulating tsunami-like flow by suddenly releasing the impounded volume of water. The swing gate has a height of 0.62 m and is made of 0.025 m thick steel frame with marine plywood on its surface and is equipped with a steel counterweight to ease the manual opening process.

Fig. 2 provides a schematic overview of the flume setup: the location of the structure, debris and instrumentation. The spatial origin was chosen to be in the center of the flume, at the upstream edge of the gate with the axis directions as shown in Fig. 2.

The experimental area was fitted with a 0.20 m high false floor on top of the flume floor. The floor in the entire test area was screened