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On the splash-up of tsunami bore impact

Harrison T.-S. Ko *, Harry Yeh

Oregon State University, Department of Civil and Construction Engineering, USA

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ABSTRACT

Impulsive forces on a box-shaped structure due to bore impact are investigated experimentally. Experiments are conducted in the laboratory by generating a Gaussian-shaped wave onto a step before impacting structures of three different cross-shore to long-shore length ratios. The relationship between measurements of the splash-up flow on the structure wall and the force measurements is investigated. The pressures are predicted based on the Euler model. Maximum impact forces are found to occur during the run-down phase after the maximum splash-up value is reached. The uniform vertical velocity profile assumption used in the Euler model yields a better estimate for the impact force than the linear and hydrostatic assumptions. In order to verify the pressure distribution during the splash-up flow, we utilize the pressure data collected from a separate experiment in a large-scale laboratory flume. The combined evidence suggests that the flow near the splash-up tip behaves like a solid body projectile.

1. Introduction

When tsunamis approach shore, they often create breaking waves, transform into turbulent bores, and inundate coastal communities (Yeh, 1991). A bore is a broken wave with a long wavelength having a steep and turbulent wave front that propagates over still water (Hibberd and Peregrine, 1979).

FEMA P646 (FEMA, 2012) (and recently ASCE 7-16 (ASCE, 2017)) provides guidelines to estimate tsunami loads based on several sub-categorized loading components: Hydrostatic net forces (lateral forces on walls due to the pressure of standing water), buoyant forces (vertical hydrostatic forces on the structure), hydrodynamic forces (lateral force on the structure or individual elements due to water flow), impulsive forces (lateral force caused by the leading edge of a surge of water impacting a structure), debris impact forces (lateral forces from water-borne debris), and debris damming forces (additional lateral force due to the accumulation of debris across the object). Impulsive forces are transient, difficult to estimate, and hence are evaluated empirically. Here, we focus on the impulsive forces due to bore impact. The impact of translatory waves, such as bores, on vertical structures often results in a "splash-up" phenomenon during the impulsive phase (see Fig. 1). The objective of this study is to explore the relationship between the wave runup and the net force exerted on the structure during bore impact. Note that the term "splash-up" will be used hereinafter to describe the deflected water-body running up on the wall during the bore impact.

The relationship between the splash-up motion on a structure wall and impulsive loads has received some attention in the literature. Cumberbatch (1960) presented an analytical model for the impact of a two-dimensional fluid wedge onto a flat surface. This model assumes a constant wedge angle of an inviscid fluid. Cumberbatch found that the surge force is greater than the total momentum past the wall location by factors of 1.6 and 2.4 for the wedge angles of 22.5 and 45°, respectively. Cross (1967) studied surge impact on a vertical wall through his laboratory experiments. Based on the experimental observations, he inferred that the maximum force occurs when the splash-up tongue collapses onto the incoming surge forming the reflected bore.

Fukui et al. (1963) measured pressures exerted by bores on a levee using a two-dimensional flume. They observed two characteristic pressure patterns: 1) an impulsive/dynamic pressure observed just after the bore impacted the levee, and 2) a continuous pressure observed after the reflection of the bore. The vertical distribution of the second pressure pattern was found to be approximately hydrostatic.

Ramsden (1996) experimentally investigated the forces and overturning moments produced by tsunamis on vertical walls. The splash-up

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* Corresponding author.
E-mail addresses: koh@oregonstate.edu (H.T.-S. Ko), harry@engr.orst.edu (H. Yeh).

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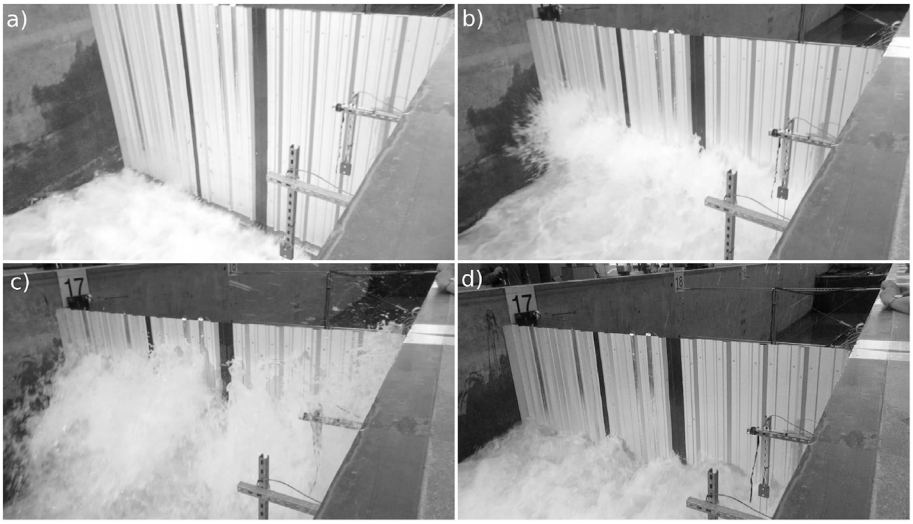

Fig. 1. Photographs of "splash-up" flow on cladding surface due to bore impact.

motions of the bores and the dry-bed surges on the vertical wall were measured. Ramsden (1996) found that the measured pressure for the dry-bed surge rises and appears to stay at a constant level for the entire reflection process. For the bore case, there is an initial sharp peak, which rises faster than that of the dry-bed surge at the onset of the bore impact and then quickly converges to a profile similar to that of the surge. Ramsden (1996) found that the pressure head lies below the splash-up height at the initial onset of impact and then gradually rises to the splash-up head on the wall. From Ramsden's data, it can be observed that the maximum impact force occurs during the downward motion of the flow on the wall, however this observation is not explicitly stated in his paper. Arnason et al. (2009) also demonstrated bore-structure interaction experimentally in the laboratory wave tank using bores generated from a dam-break. For smaller bores, the force during the initial impact is about 50% higher than the hydrodynamic force during the bore passing.

Bullock et al. (2007) performed an experimental investigation on the detailed characteristics of water wave impacts on vertical and sloping walls. Four different types of impact were identified depending the breaking conditions of the wave. One of these types was the broken wave impact, one where the incoming wave breaks before it reaches the structure producing a highly aerated turbulent bore. While generally producing lower impact pressure than the other breaker cases, broken wave impacts have a longer impact duration and occur over much larger distances and thus have engineering significance. Pressure distributions along the vertical wall were measured for the broken wave impact using vertical arrays of pressure transducers. The measurements from the lower section both vertical arrays of pressure transducers showed almost identical pressure time histories which suggested near uniform loading over a significant vertical extent.

Nouri et al. (2010) and Palermo et al. (2013) studied the horizontal pressures and forces exerted by bores on two structures with square and circular cross sections. These studies showed that there are three phases of pressure patterns exerted on the structures: an impulsive phase, a runup phase, and the quasi-steady phase. The pressure pattern during the quasi-steady phase appeared to agree with observations made by Fukui et al. (1963). More recent studies by Takabatake and Kihara (2014) and Kihara et al. (2015) also support the three-phase pressure pattern exerted on structures.

2. Hypothesis

A review of the previous literature relating bore-induced impact on a structure leads to the formulation of two distinct hypotheses that we wish to verify in this study. First, experimental observations from various studies (Cross, 1967; Ramsden, 1996; Takabatake and Kihara, 2014; Kihara et al., 2015; Ramsden and Raichlen, 1990; Robertson, 2017) imply that the peak impulsive force occurs at the instance after the maximum splash-up. We attempt to confirm this by performing independent and precise laboratory experiments.

Second, the vertical pressure distribution is nearly uniform, at least near the leading tip of the splash-up, and thus acts similar to a solid body. This hypothesis resembles the models of the leading-tip motion of the dam-break problem on a dry bed (Whitham, 1955), as well as the runup motion onto a sloping beach (Dressler, 1952; Ho and Meyer, 1962; Shen and Meyer, 1963; Yeh et al., 1989; Pujara et al., 2015). Futhermore, this hypothesis matches pressure measurement observations made by Bullock et al. (2007) (as previously discussed in §1) which suggested almost uniform loading in the vertical direction for broken wave impacts.

Assuming inviscid fluids, the equation of motion can be written as the Euler equation in the vertical direction:

$$\rho \frac{\partial w}{\partial t} + \rho \frac{\partial}{\partial x}(uw) + \rho \frac{\partial}{\partial z}\left(w^2\right) + \frac{\partial p}{\partial z} + \rho g = 0, \tag{1}$$

where ρ is the fluid density, p is the pressure, g is the gravitational constant, (x, z) are the physical coordinates in the horizontal and vertical directions, respectively, and (u, w) are fluid velocities in the horizontal and vertical directions, respectively. Equation (1) can be integrated over the water column from $z' = z$ to $z' = \eta$ with the application of the Leibnitz formula and the kinematic free-surface boundary condition to yield (without approximation):

$$p(x, z, t) = \rho g(\eta - z) - \rho w^2 + \rho \frac{\partial}{\partial t}\int_z^\eta w\, dz' + \rho \frac{\partial}{\partial x}\int_z^\eta uw\, dz'. \tag{2}$$

The right hand side of Eq. (2) has four terms that represent:

- $\rho g(\eta - z)$: static pressure component,
- ρw^2: dynamic pressure component,
- $\rho \frac{\partial}{\partial t}\int_z^\eta w\, dz$: local acceleration component,
- $\rho \frac{\partial}{\partial x}\int_z^\eta uw\, dz$: advective acceleration component.

Since the splash-up flow forms a thin layer and the horizontal velocity at the wall is zero, it is reasonable to assume small horizontal variation and therefore the advective acceleration component is negligible. The formulation of Eq. (2) requires knowledge of the vertical velocity distribution along the wall. Unfortunately, we could not directly measure the fluid velocities of the splash-up motion; we are only able to measure the time variation of the leading-tip of the water surface at the wall (in