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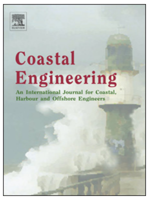

Experimental analysis of debris motion due the obstruction from fixed obstacles in tsunami-like flow conditions

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ABSTRACT

Experimental research was conducted focusing on debris motion over a horizontal apron featuring vertical obstacles in the path of the debris propagation. The apron was designed as a typical representation of a harbor threatened by an inundating tsunami. The experimental setup idealized often complex harbor settings. The debris was a scaled-down 20-foot shipping container modelled at a 1 in 40 Froude length scale. Offand onshore regions were separated by a vertical quay wall which allowed the incoming elongated solitary wave used to represent the first part of a tsunami to steepen, break and propagate over the initially dry surface as a tsunami-like bore. In the path of propagation, a varying number of debris were entrained within the inundating bore over the horizontal apron. The entrained debris interacted with regularly spaced vertical obstacles representing infrastructure and houses within the propagation path. Varying debris and obstacle arrangements were tested to evaluate the effects the obstacles would have on the debris' maximum longitudinal displacement and the spreading angle. The main conclusion is that the spreading angle of the debris is not as significantly altered by the presence of obstacles on the harbor apron whereas the maximum longitudinal displacement of the debris was significantly affected.

1. Introduction

Over the past several decades, major tsunami events, such as the 2004 Indian Ocean tsunami, the 2010 Chilean tsunami, and the 2011 Tohoku tsunami have been responsible for catastrophic damage to local communities and associated infrastructure near the shoreline as well as unprecedented loss of human lives. The damage was often due to the lack of necessary capacity for structures to sustain the extreme forces associated with the inundating tsunami bore (Ghobarah et al., 2006; Palermo et al., 2009, 2013; Yeh et al., 2014; Esteban et al., 2015). Among numerous reasons, the loss of life is often attributed to low levels of preparedness, missing or inadequate evacuation routes or available shelter infrastructure. To date, there is still major uncertainties related to the proper design of evacuation shelters against hydrodynamic loading, random debris impact forces, debris damming, and scouring processes occurring at various instants over the run-up and run-down sequence. However, the American Society of Civil Engineering (ASCE) Standards Subcommittee on *Tsunami Loads and Effects* (of which the third author is a member) is currently developing a new chapter in the 2016 release of the ASCE7 standard which aims to remedy some uncertainty involved in the design process related to buildings located in tsunami-prone regions through condensed stipulations in mandatory language.

According to the Federal Emergency Management Agency (FEMA) P-646 design guideline (2012), many large scale tsunamis break in shallow waters, forming a *tsunami bore* which is characterized by a violently foaming, turbulent and steep wave front propagating on top of the much longer main tsunami wave in finite water depth. The breaking is predominant for leading elevation waves and occurs as a result of wave shoaling and non-linear transformations over the continental shelfs (Yeh, 2009). At the shoreline, the tsunami bore continues propagating on-shore due to its momentum and is thereafter termed a *tsunami bore*. A second or third tsunami wave crest, which in some cases could be larger than the first one, could spread inland as a tsunami bore (now over a wet bed) as the first wave has already inundated initially dry land. Therefore it is paramount to define the design loads based on these two hydrodynamic conditions, namely tsunami bores travelling over a wet bed and tsunami bores propagating over dry ground.

Many structures are not properly designed against such extreme hydrodynamics as many guidelines do not address the issue of tsunami loading explicitly (Palermo et al., 2009; Esteban et al., 2014; Yeh et al., 2014). Guidelines and standards, such as FEMA P55 (FEMA P-55, 2011) and ASCE7 Chapter 5 (Coulbourne, 2011), focus primarily on

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coastal flooding and only briefly mention the extreme loading conditions resulting from tsunami. The *National Building Code of Canada* (*NBCC*) (*2005*) acknowledges in its “Design for seismic effects” that the damage from earthquakes can be a result of a tsunami but lacks to provide guidelines regarding the potential loading conditions (Palermo et al., 2009). Due to the tragic loss of life and major economic losses, research groups and governing bodies world-wide have begun to focus on better understanding the loading conditions on structures due to tsunami bores and bores.

The primary focus of the existing research has been on the hydrodynamic loading as a result of the inundating tsunami bore and a number of load estimations for hydrodynamic loading were proposed (Ramsden, 1996; Arnason et al., 2009; Nouri et al., 2010; St-Germain et al., 2012; Chinnarasri et al., 2013; Wei et al., 2015). However, in forensic engineering site surveys of affect coastal communities, significant secondary damage has been observed from debris entrained within the bore (Ghobarah et al., 2006; Palermo et al., 2009, 2013; Takahashi et al., 2010; Naito et al., 2014). Despite the prevalence of debris impact, significantly less work has gone into the study of these loading conditions and the most significant gap in the understanding of debris impact is the nature of the debris motion within the inundating bore. The study of debris motion has been difficult as a large number of variables, such as flow conditions (Matsutomi, 2009), debris physical characteristics (Imamura et al., 2008; Matsutomi, 2009; Shafiei et al., 2014), surrounding environment (Naito et al., 2014; Rueben et al., 2014) and many more, have significant roles in affecting the debris motion.

To date, scarce research exists that addresses the initiation of debris motion and the entrainment process of multiple debris within reach of a rapid flow. Clearly, sound understanding of the entrainment process, the subsequent transport path and downstream debris concentration are paramount to assess the downstream debris impact hazard. Changes to a dam break wave bore front under dry and wet bet conditions were studied by Khan et al. (2000), who identified the governing parameter for the debris influence on the bore height and celerity to be the ratio of concentration of the mass of the particles to the mass of water upstream of the gate (concentration ratio), and the ratio of the size of the particles relative to the upstream depth (length ratio). High concentration of debris downstream of the gate position resulted in increased bore heights. This observation suggests that besides additional impact loads stemming from the debris entrained in the flow, higher hydrodynamic loads could be expected on structures present in the leeward reach of such flows. Haehnel and Daly (2004) investigated impact forces of single woody debris in flume and basin tests and developed a single-degree-of-freedom model to estimate their impact force, given an upper envelop value of effective contact stiffness between the debris and a rigid structure. It is however unclear how impact forces would develop in the likely case of multiple impact of debris, even under the assumption that not all impacts would occur under a flow-wise directed angle of impact. In this regard, it is again of paramount interest to understand how debris are entrained within a transient flow and how they disperses along its path of transport. On the temporal scale, it is still undetermined how likely it is that hydrodynamic and impact forces occur synchronously and, thus, how load combinations for a practical design should be considered. From experiments involving dam break waves (Arnason et al., 2009; Nouri et al., 2010), it could be conjectured that a time lag exists between the arrival of the bore front and the debris impact. So far, it was however not investigated how this time lag changes over the propagation time elapsed since debris entrainment and for various distances between the original debris site and the impact position. A recent in-situ study on river ice runs suggests that the water wave front of the dam break following a sudden breach of an ice-jam outruns the ice phase by some jam length (Nafziger et al., 2016). A study involving single pieces of wooden logs constrained within a flow-normal motion directly in front of a vertical structure concluded that impact forces may show single peaks which significantly increased overall base shear forces (Nistor et al., 2011); in some experiments however, double peaks resulted from a bounce back effect, the infrequent occurrence of these events point to some degree of randomness involved in the experimental design. This finding stresses the need for better knowledge about the debris motion and entrainment at first in order to assess impact loads accurately.

In addition to floating debris, debris entrained within incoming tsunami waves or bores could also consist of negatively buoyant material originating from dislodged and subsequently dismantled residential or community houses. These high-density, heavier debris could result in design-relevant impact events attacking neighboring infrastructure at lower-lying load carrying points compared with their floating counterpart debris entrained at the free surface of the flow. Transport modes of negatively-buoyant debris in the form of boulders were found to be sliding, rolling and saltation in bore-type flows (Imamura et al., 2008); a more recent study by Zainali and Weiss (2015) however revealed that factors such as the submergence ratio, the boulder geometry and weight as well as their aspect ratios form a complex, non-linear parameter space which defines the dislodgement distance, clearly pointing out the difficulties involved in predicting such processes.

Naito et al. (2014), in a forensic site survey following the 2011 Tohoku Tsunami, developed a simple procedure for determining the spreading angle of debris using satellite images. From this analysis, Naito et al. (2014) noticed that the environment surrounding the debris significantly affected its overall displacement and therefore its potential to impact critical structures and infrastructure. In an experimental attempt to verify estimates of debris spreading, Nistor et al. (2016) experimentally investigated debris spreading over a horizontal apron, neglecting the specific influences of rigid obstacles in the path of the debris. While the spreading angles and total inland displacement were empirically quantified by linear relationships, the effects of the interaction of debris with obstacles located in their path were left for further investigation and make the object of this paper. Debris in built areas would be obstructed by surrounding buildings, assuming the buildings are not destroyed by the tsunami bore or resulting debris impact. These obstructions severely limit the displacement of the debris rendering further research regarding the influence of rigid structures (named obstacles hereafter) on the dispersal of debris in extreme hydrodynamic flows necessary. The effect of obstacles in the pathway of debris on its dispersal has not been investigated before. These effects however deserves particular attention as planners and designers of risk-prone harbor infrastructure require reliable information on how debris spread through the nearshore area and which of the potential buildings lie within debris-impact zones.

Based on the above rationale, the objectives of this paper are to specifically examine:

1) The reciprocal effect of rigid obstacles residing on a horizontal harbor area on the hydraulic conditions of an incoming tsunami bore.
2) The associated effect of the rigid obstacles on the motion of debris of varying count by modelling debris consisting 20-foot shipping containers.
3) The characteristics of the overall motion of the debris influenced by rigid obstacles compared to conditions where no obstacles are present on the harbor area.
4) Whether the presence of obstacles affects and alters trajectories of propagating debris, their overall spreading angles and maximum longitudinal displacements.
5) The method to determine inertial forces exerted on the debris during the initial contact with the incoming wave front and the subsequent impact forces exerted on the obstacles by the moving debris.

This paper is outlined as follows: the “Experimental Setup” introduces the Waseda Tsunami Wave Basin, instrumentation, and the tracking system used in the experiments; the “Results” section presents the analysis performed on the hydrodynamics, debris motion and debris impact; the “Discussion” analyzes the results and places the current work in the context of previous research efforts; “Conclusions” outline