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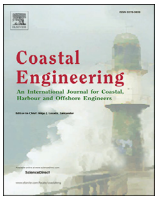

Experimental investigation of debris damming loads under transient supercritical flow conditions

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ABSTRACT

Debris loading during extreme flooding events has been documented by many post-tsunami field surveys of disaster-stricken communities and, as such, it is now considered and accounted for as a critical design consideration in the design of resilient infrastructure. Debris damming is one of the debris loads of concern, occurring when solid objects entrained within the inundating flow accumulate at the face of a structure or structural element. The presence of the debris dam results in increased drag loads on the structure and can have other associated effects, such as flow runup and flow accelerations, that can influence design conditions. The focus of debris damming studies has been within river engineering: therefore, previous studies have been performed in steady-state conditions. The study presented here is the first to examine debris damming in transient, supercritical flow conditions. The study uses a modified dam-break wave as the hydrodynamic forcing condition and the debris are scaled down debris types common in coastal areas (shipping containers, hydro poles, and boards). The analysis includes a qualitative examination of the difference in the debris damming mechanisms as a result of distinct flow conditions associated with a dam-break wave interacting with a surface-piercing obstacle. Additionally, the study determined the influence of the debris dam resulted in a maximum loading condition that occurred earlier and was of greater magnitude than the clear water case.

1. Introduction

The devastation generated by recent major flooding events, such as the 2011 Tohoku Tsunami, captured the attention of regulatory agencies and research bodies worldwide. In many affected areas, coastal structures and critical infrastructure that had been designed to withstand these events failed unexpectedly (Yeh et al., 2013). As a result of these structural failures, several forensic engineering surveys were performed throughout the Tohoku coastal region to identify the causes of such failures (Mori et al., 2011). One of the primary explanations was that building standards and design codes did not properly address the variety of extreme loads associated with a tsunami event (Esteban et al., 2015; Yeh et al., 2014). To address this concern in North America, particularly along the West Coast where the region is at-risk of earthquakes along the Cascadia subduction zone (CREW, 2013), the American Society of Civil Engineering (ASCE) has developed a set of standards (ASCE7 Chapter 6) around the design of critical infrastructure exposed to tsunami events (Chock, 2016).

The ASCE considered the loads broadly in three categories: hydrostatic, hydrodynamic, and waterborne debris impact. Within these categories, three hydraulic load cases (discussed in detail in Section 3.1) were identified as critical in the design of structures for tsunami resilience (Chock, 2016). However, throughout these broad cases in the standard, the influence of debris damming needs to be considered in greater depth (Chock, 2015). Debris damming occurs when waterborne debris accumulates at the face of a structure or in between adjacent structures. The

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accumulation can block openings in buildings where water previously could flow freely, resulting in changing hydrostatic and hydrodynamic loads. Based on observations made during the 2011 Tohoku Tsunami, the prevalence of debris entrained in the flow resulted in the ASCE7 considering the use of breakaway walls to be a relatively ineffective mitigation technique. This is due to transported debris blocking the openings created by the breakaway walls, with the intent to relieve hydrodynamic loading.

Within building standards, debris damming loads are accounted for as hydrodynamic loads acting on a structure (AASHTO, 2012; CSA, 2006; FEMA, 2012), using the drag equation (Bremm et al., 2015):

$$F_D = \frac{1}{2} C_D \rho b h u^2 \tag{1}$$

where C_D is the drag coefficient, ρ is the fluid density, b is the breadth of the debris dam transverse to the flow direction, h is the flow depth, and u is the flow velocity. For bridge piers, C_D is generally taken as 1.4, the same value as a square-ended pier. In the FEMA P646 Guidelines for the Design for Vertical Evacuation from Tsunamis (FEMA, 2012), to conservatively estimate the hydrodynamic loads, a C_D value of 2.0 was recommended.

The recommended breadth of the debris dam also has a variety of definitions. The Canadian Bridge Design Guidelines (CSA, 2006) suggests a breadth equal to that of the bridge pier. FEMA P646 recommends a minimum breadth equal to the largest length of the available debris at the site. ASCE7 Chapter 6 (Chock, 2016) considers any structure, regardless of mitigating breakaway walls, should consider a minimum blockage of 50% for an at-risk exposed section. Field surveys have noted the site-specific nature of debris dam formation (Parola, 2000) and therefore, where possible, site evaluations are recommended across the various standards.

While debris damming has been observed in many extreme flooding events, such as the 2005 Hurricane Katrina, 2006 Switzerland Flood, and the 2010 Chilean Tsunami (Robertson et al., 2007; Schmocker and Hager, 2011; Takahashi et al., 2010), the study of debris damming has primarily been performed within the context of river engineering. Bocchiola et al. (2006) examined the spatial distribution of debris damming through randomly placed obstacles. The study found that the amount of debris captured increased with the length of the debris and decreased with the flow velocity. Increased length of the debris resulted in the debris being more often captured by a "bridging" mechanism, where the debris would be caught on multiple obstacles. The "bridging" was more stable than the alternative "leaning" mechanism, where the debris would be captured on a single obstacle. Therefore "bridging" was considered more likely to form a debris dam. Similarly, the higher flow velocities resulted in less stable capture of the debris resulting in the accumulation being washed away prior to a stable dam being formed. In this work, a "debris dam" will refer to a stable formation of debris accumulation and "debris accumulation" will refer to the transient features of debris advected within a flow.

Parola (2000) reported on debris damming at bridge piers for the application in the AASHTO LRFD Bridge Design Specifications (AASHTO, 2012). The study identified the critical piers as those located near the thalweg of the channel due to the tendency of secondary flows to force the debris into the deeper, faster flow conditions. A similar phenomenon was observed in the study of debris transport in unsteady conditions (Goseberg et al., 2016). An analysis of several experimental investigations into debris damming at bridge piers found that the drag coefficient (C_D) was dependent on the blockage ratio, the ratio of the debris dam cross-section and the free-flowing cross-section. It also depended on the contracted Froude number (Fr_c) which is a local Froude number (Fr) in the contracted flow section at the bridge piers.

Schmocker and Hager (2013) examined the formation of debris dams at a debris rack in steady-state flow. The study examined the temporal evolution of the debris dam noting the important stage changes caused by the dam, as well as the corresponding changes in the dam formation characteristics. The stages were described as a first phase where the initial debris accumulation compacted and obstructed the free flow condition. Secondly, the obstruction resulted in rapid backwater rise. Once the obstruction had formed, the decelerated flow reduced the compaction of the dam resulting in the formation of a debris carpet. The study determined that the availability of debris and Froude number influenced the formation of the debris dam and backwater rise.

Pasha and Tanaka (2016) investigated the trapping of debris in inland forests, similar to what was observed in the 2011 Tohoku Tsunami. The study examined the propagation of debris within steady-state subcritical flow. The debris were modelled as rectangular, square, and cylindrical debris. The trapping mechanisms varied between the different debris shapes. The smaller contact area associated with the cylindrical debris resulted in the debris being forced downward and causing multiple debris to pile on top of each other. The capture efficiency (debris captured/total available debris) of the forest was found to increase with the debris length and decrease with decreasing flow velocity.

A thorough review of debris damming literature leads to the conclusion that the examination of debris damming has been predominantly performed in steady-state subcritical flow conditions. However, many flooding events, particularly tsunamis and flash-floods, have transient flow properties (Ghobarah et al., 2006; Ioualalen et al., 2007; Saatcioglu et al., 2005) and can enter into trans-critical/supercritical ($Fr > 1$) flow regimes (Fritz et al., 2006; Matsutomi and Okamoto, 2010; Titov and Synolakis, 1997). Previous research into the hydraulic loads and flow-structure interaction associated with unsteady tsunami-like waves has shown distinctive wave profiles of transient nature that significantly differ from steady-state conditions (Arnason et al., 2009; Goseberg and Schlurmann, 2014; St-Germain et al., 2013). Previous studies into debris loading in transient flow conditions have focused on loading related to debris impact (Ikeno et al., 2016; Shafiei et al., 2016). Therefore, this study examines the formation and loading conditions associated with a debris dam in unsteady supercritical flow conditions with the objectives of:

- Studying the formation of debris dams in unsteady flow conditions and contrasting that to the formation mechanisms described by Schmocker and Hager (2013).
- Examining the influence of debris shape on the formation and stability of the debris dam.
- Determining the runup of the supercritical flow on the obstacle as a result of the debris dam formation.
- Evaluating the loading conditions on the obstacle as a result of the debris dam formation.

This study was coupled with a steady-state examination of debris damming in subcritical flow conditions in the same facility to allow for a direct comparison to steady-state conditions. The steady-steady results will occasionally be referenced throughout this paper, however, the full results can be found in Stolle et al. (2017b). This paper is separated into the following sections: "Experimental Setup" details the facilities and instrumentation used in this study as well as the experimental protocol; "Results" details the key results of the study emphasizing the above stated objectives of the paper; "Discussion" describes key findings in the context of the wider research and discusses potential scale effects; "Conclusions" outlines the results of this study and identifies key conclusions related to the objectives.

2. Experimental setup

2.1. Experimental facilities

The experiments were performed in the High-Discharge Flume at Waseda University, Tokyo (Japan). The flume shown in Fig. 1 was 14.0 m long x 0.40 m wide x 0.80 m high and is typically used in the physical