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Tsunami deposits in a super-large wave flume

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ABSTRACT

Understanding the process of sediment transport under tsunami inundation is essential to providing credible information about potential tsunamis from tsunami deposits. In this study, a super-large wave flume 205 m long and 3.4 m wide was used to investigate the hydraulic process of tsunami inundation and sedimentary features of the resulting tsunami deposit. A uniformly sloping topography (1/50) with a sand dune 0.2 m high was built in the flume and the topography change induced by a solitary wave was measured. The maximum wave height at the shoreline was 0.6 m and the horizontal velocity reached up to 3.5 m/s, resulting in a sediment concentration of up to 5% by volume. The inundation and return flow completely eroded the dune and caused deposition, which showed landward and seaward thinning and fining. The vertical distribution of grain size and density in the inundation flow indicated upward fining and an upward decrease in density, and the deposits showed inverse grading at the base in addition to normal grading. Therefore, the inverse grading was attributed to the depositional process instead of the vertical distribution of grain size in the flow, such as via a traction carpet. The inundation flow was classified into two phases. The first phase flow, which appeared at the front of the inundation flow, was governed by the wave speed at the shoreline. The second phase flow, which occurred near the dune, was controlled by the difference in wave levels in front of and behind the dune. The deposits caused by the first phase flow (near the inundation limit) were constant regardless of the presence of the dune, indicating that the effect of the dune on the deposits was limited in the nearshore region. The deposits near the inundation limit, showing rapid fining and different chemical compositions, were carried by muddy foam floating on the water surface. The sediment supply from offshore to onshore over the dune was small and the erosion of the sand dune accounted for 36% of the onshore deposits. The offshore deposits were mainly caused by wave motion and the contribution of the onshore sediment brought by the return flow was small (24%). However, the return flow had a large effect on the sedimentary structure of the offshore deposits, such as seaward fining. Our results will help to examine the physical processes resulting in the empirically established common sedimentary characteristics of tsunami deposits and will provide a detailed data set to validate sediment transport models used in numerical simulations.

1. Introduction

Tsunami deposits, ranging from mud to huge boulders, are a fascinating tool for geology and seismology because they allow understanding of the history of ancient tsunamis over the past few thousand years. After several megathrust earthquakes and resulting catastrophic tsunamis in recent decades, information on ancient tsunamis has been growing in importance for engineering applications, including urban policy, evacuation planning, and nuclear hazard assessment (e.g. González et al., 2007; Japan Nuclear Energy Safety Organization, 2014).

The accumulation of geological information about tsunami deposits in the field, mainly since the 1990s, empirically revealed the characteristics of present (e.g. Peters and Jaffe, 2010) and ancient (e.g. Goff et al., 2010) tsunami deposits. The commonly observed characteristics are objective, reliable identification criteria for tsunami deposits (e.g. Chagué-Goff et al., 2011; Chagué-Goff et al., 2012b). Recent studies reconstructed the hydraulic parameters of tsunamis from tsunami deposits by using inverse analyses (e.g. Jaffe and Gelfenbuam, 2007; Soulsby et al., 2007; Furusato and Tanaka, 2014; Tang and Weiss, 2015).

Despite the progress in geological studies, hydrodynamic studies on

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the processes of tsunami inundation, sediment transport, and deposition are still limited. Geological studies are usually conducted in places likely to preserve deposits, such as shallow lakes, marshes, and gently sloping topography. In particular, sand dunes near the shoreline are expected to be suitable places, mainly because of the undisturbed environments behind the dune and the ease of identification (e.g. Nanayama et al., 2003; Monecke et al., 2008; Prendergast et al., 2012). In these topographies, topography change, sediment transport, and deposition contribute greatly to the complexity of hydrodynamics behind dunes.

Experimental investigation is a promising method for unearthing sediment transport during tsunamis (Jaffe et al., 2016). However, laboratory experiments for tsunami sediment transport face problems with scaling. The settling velocity of particles can violate the theoretical scale ratio. The scaling rule based on the Froude number, which is commonly used for similarity criteria to scale down the hydraulic parameters, requires the settling velocity to follow the square root of the physical scale ratio. However, the settling velocity of particles < 62.5 μm is proportional to the square of grain size according Stokes' law, which violates the scaling rule.

Therefore, most experimental approaches to sand transport during tsunamis have increased the horizontal velocity instead of scaling down particle size (e.g. Takahashi et al., 2000; Yoshii et al., 2009; Yamaguchi and Sekiguchi, 2015; Johnson et al., 2016). These approaches have contributed to understanding the local sediment transport under high horizontal velocity. Because the topography from offshore to the inundation limit has not been reproduced in small-scale experiments, the source of tsunami deposits, erosion and deposition processes, and topography change remains unclear.

In this study, we tackled the scaling problem in laboratory experiments by using one of the largest wave flumes in the world. The Tsunami Sand Transport Laboratory Experiment (TSTLE) project was launched in the Central Research Institute of Electric Power Industry (CRIEPI) to study hydrodynamics of tsunami inundation, sediment transport, and consequent deposits at a high Shields number. This enormous flume enabled us to reproduce the topography from offshore to the inundation limit with a reasonable land slope of 1/50. We focused on the inundation process, sediment transport, and deposition on topography with a sand dune.

2. Methods

We conducted laboratory experiments with a super-large wave flume at CRIEPI (CLWF) (Fig. 1). In the movable-bed channel, a sand bed covered the floor from the start of the channel to 10 m behind the shoreline. A sand dune (0.2 m height, 0.2 m crest width, 0.8 m total width) was located 0.4 m behind the shoreline. The grain size distribution of the sand had a bimodal distribution with peaks at 0.2 and 1–2 mm (Fig. 2). The sand consisted of iron sand (D50 ≈ 0.12 mm) and a small amount of silt and mud (1.3%). Although the sand was silica-dominant, it contained Al_2O_3 (10.9%) and Fe_2O_3 (7.3%).

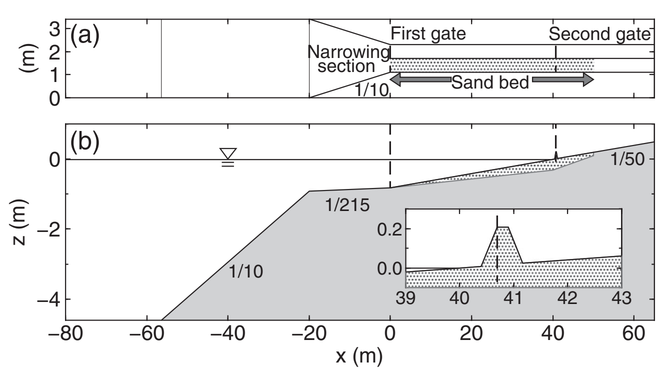

Fig. 1. (a) Plan view and (b) section view of the experimental model. The inset in (b) shows a magnified portion of the section view. The x-axis is defined in the landward direction from the entrance of the channels and the z-axis is defined in the vertical direction from the water surface. The sand bed is set in the dotted area.

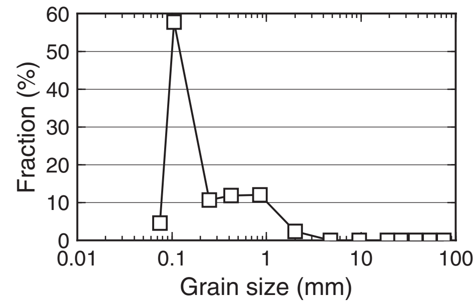

Fig. 2. Grain size distribution of the bed material.

Table 1
Conditions for experimental cases.

Case	Waveform	Dune	Overflow	2nd gate	Trap
C1	Bore	×	×	×	×
C2	Bore	✓	×	×	×
C3	Peaked	✓	✓	×	×
C4	Peaked	✓	✓	✓	×
C5	Peaked	✓	✓	×	✓

We examined five experimental cases with different wave parameters, topography, and gate operation (Table 1). The bore waves (C1 and C2) did not overflow at the end of the channel, whereas the peaked wave (C3–C5) overflowed at the end (Fig. 3). Turbidity (x = 36 and 44 m) and water level (x = 40 and 50 m) were measured in the movable-bed channel, whereas the velocity and water level were measured in the fixed-bed channel. The return flow was blocked by the second gate in C4. The vertical distribution of sediment transport was measured by using the sediment trap in C5.

We obtained sediment samples before and after the experiments and measured the chemical composition and grain size. Hereafter, the weight fraction of grains of ≥1 mm is referred to as D_{vcs} and the median diameter of grains with < 1 mm is referred to as D50.

The model setup, experiments, and analysis are described in full in Supplementary information A.

3. Results

3.1. Hydrodynamics of tsunami inundation

3.1.1. Inundation flow and return flow

The wave collapsed offshore and changed into a bore waveform at the shoreline, and then inundated landward causing a high horizontal velocity at the front of the bore (a detailed description is given in Supplementary information B.1). The wave speed increased as it

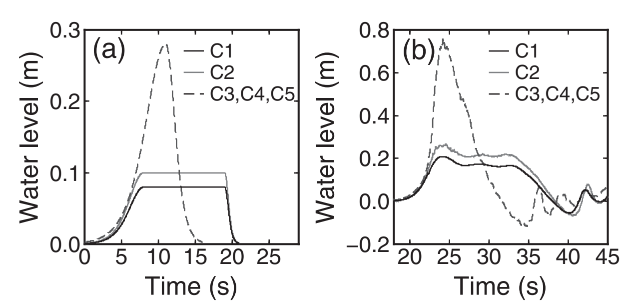

Fig. 3. (a) Input waves for the wave generator and (b) the progressing waves observed at x = 0.5 m.