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Effects of tsunami magnitude and terrestrial topography on sedimentary processes and distribution of tsunami deposits in flume experiments

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ABSTRACT

To identify and interpret tsunami deposits correctly, a better understanding of the effects of both tsunami magnitude and topographic setting are required. In the present study, laboratory experiments were performed to model these effects on sedimentary processes and the distribution of tsunami deposits on coastal lowlands. The experiments directed tsunamis of eight different magnitudes on to three different models of terrestrial topography: one with flat topography, one with a shallow water-filled pool, and one with a deep water-filled pool. The results suggested a relationship between the distribution of tsunami deposits and the hydraulic condition of the tsunami flow onto the terrestrial topography. In particular, the tsunami deposits in the pools were spatially more variable than those on land because of the variation in flow intensity associated with transformation of the flow from supercritical to subcritical with a hydraulic jump. We observed a gap between the landward extent of deposits and the tsunami inundation distance, particularly in the experiments with a pool. The total amount of sediment in tsunami deposits on the terrestrial area was found to depend on the magnitude of the tsunami, but the thickness of the deposits at any one given spot did not always depend on the tsunami magnitude, even in the same topographic. These results show that terrestrial topography has significant effects on the spatial distribution of tsunami deposits that must be taken into consideration when interpreting the history and magnitude of paleotsunami events from tsunami deposits.

1. Introduction

As an indicator of the history and magnitude of paleotsunami events, tsunami deposits have received considerable attention. In particular, sandy tsunami deposits on coastal lowlands with/without coastal lakes or lagoons have been considered a possible key to reconstruct the behavior of paleotsunamis (e.g., Jaffe and Gelfenbaum, 2007; Smith et al., 2007; Sawai et al., 2012; Goto et al., 2014a; Namegaya and Satake, 2014). In addition, water bodies in coastal lowlands, which are commonly isolated from the effects of high-energy waves or rivers despite their closeness to the sea, have been favored for study because of the greater potential they offer for preservation of recognizable tsunami deposits. Several studies, therefore, have attempted reconstructions of paleotsunami events from the deposits in coastal lakes and lagoons (Minoura and Nakaya, 1991; Bondevik et al., 1997; Hutchinson et al., 1997, 2000; Clague et al., 1999; Sawai, 2002; Nanayama et al., 2003; Kelsey et al., 2005; Sawai et al., 2008; Donato et al., 2009; López, 2012).

A better understanding of the distribution of tsunami deposits on coastal lowlands would improve the identification and interpretation of paleotsunami deposits in the geologic record, which may assist in future risk assessment. For instance, the relationship between the landward extent of recognizable tsunami deposits and water inundation area has been discussed as a means for estimating inundation limits of past events (e.g., Gelfenbaum and Jaffe, 2003; Jaffe et al., 2006; Apotsos et al., 2011; Goto et al., 2011, 2014a, 2014b; Morton et al., 2011; Abe et al., 2012; Cheng and Weiss, 2013; Sugawara et al., 2014). The distribution of tsunami deposit thickness may also aid estimates of hydrodynamic features of tsunamis, including their flow velocity and height (e.g., Jaffe and Gelfenbaum, 2007; Goto et al., 2014a). In addition, an understanding of the possible distribution of tsunami deposits on terrestrial areas is crucial for determining appropriate sampling sites.

Because the features of tsunami deposits may be affected by the magnitude of the tsunami, the characteristics of the bottom sediment, and the coastal and terrestrial topography, must all be understood for confident identification and interpretation of tsunami deposits. Many post-tsunami surveys have helped improve this understanding, especially those made after the 2011 Tohoku-oki tsunami (e.g., Goto et al., 2011, 2014a; Abe et al., 2012; Naruse et al., 2012; Shishikura et al., 2012; Takashimizu et al., 2012). However, progress remains hampered by the limited range of tsunami magnitudes and topographic settings available for field studies.

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Flume experiments, in which sedimentary conditions can be easily controlled, can provide insights into the sedimentary processes of tsunamis and the distribution of tsunami deposits that can aid future field surveys. Previous laboratory studies of tsunami erosion and deposition (e.g., Hasegawa et al., 2001; Kobayashi and Lawrence, 2004; Sugawara et al., 2004, 2008; Tsujimoto et al., 2008; Young et al., 2010; Chen et al., 2012; Furusato and Tanaka, 2014) have dealt mainly with tsunami magnitude, and no laboratory study has focused on terrestrial topography such as a water body on a coastal lowland. With this in mind, we designed an experimental program to simulate the cross-shore setting in which a single run-up tsunami flow without a strong backwash flow transports sediments from a nearshore zone onto a coastal lowland. Our experimental setup examined the effects of tsunami magnitude and the presence of a pre-existing pool in coastal lowlands on the distribution of resulting tsunami deposits.

2. Experimental methods

The flume used was 12 m long, 0.2 m wide, and 0.4 m deep, with a glass side wall (Fig. 1a). It was divided into the following areas from seaward to landward: a water storage tank with a gate (4.0 m long), an offshore horizontal seabed (1.8 m) with an initial water depth (h_0) of 50 mm, a slope of 1/20 (3.0 m long and 0.15 m high), a terrestrial area (2.0 m long and 0.15 m high), and a drainage tank (1.2 m long) to hinder tsunami backwash. A flat bed of sand (0.7 m long and 10 mm high) consisting of well-sorted quartz sand (median diameter 0.20 mm, specific gravity 2.63) was placed on the upper part of the slope.

We prepared three topographic models for the terrestrial area: one in which the 1.0-m central section had a shallow (9 mm) pool filled with water (Fig. 1b), one with a deep (45 mm) pool filled with water (Fig. 1c), and a flat model without a pool. The wooden surface of the models was smooth and impermeable. The seaward and landward ends of the pool connected to the adjoining land area through rounded slopes. Positions in the terrestrial area are expressed below as distances from its seaward end (0–2.0 m distance; Fig. 1a). In the rest of the article, the experimental series with shallow pool, deep pool, and without a pool are described as 'SP-series', 'DP-series' and 'F-series', respectively (Table 1).

A tsunami-like bore was generated by opening the gate of the storage tank instantaneously. The magnitude of the tsunami was controlled by the water level of the tank, h_1 (0.18–0.25 m, Table 1). The height of the offshore tsunami wave was recorded by using a capacitance wave gauge (KENEK Co., Ltd.) with a sampling frequency of 100 Hz (Fig. 2). The offshore wave height H_0 is defined as the difference between the elevations of the crest of the first wave and initial water surface. The deposits left on the terrestrial area after the tsunami passed were measured as dry weight within 10-cm distance intervals from the seaward end because the deposits in the present experiments were so thin that its thickness could not be measured. The sediment that was carried past the landward end of the terrestrial area was caught by a mesh cloth in the drainage tank. The dry weight within each interval was considered comparable to the local thickness of tsunami deposits in field studies. Preliminary experiments demonstrated the repeatability of the tsunami waveforms and the distribution of the deposits. The passage of the tsunami and sedimentary processes were recorded by two video cameras alongside the flume. Under the assumption that the tsunami flow was quasi-steady, we used video image analysis to determine the maximum flow velocity U_m from the run-up of the tsunami head.

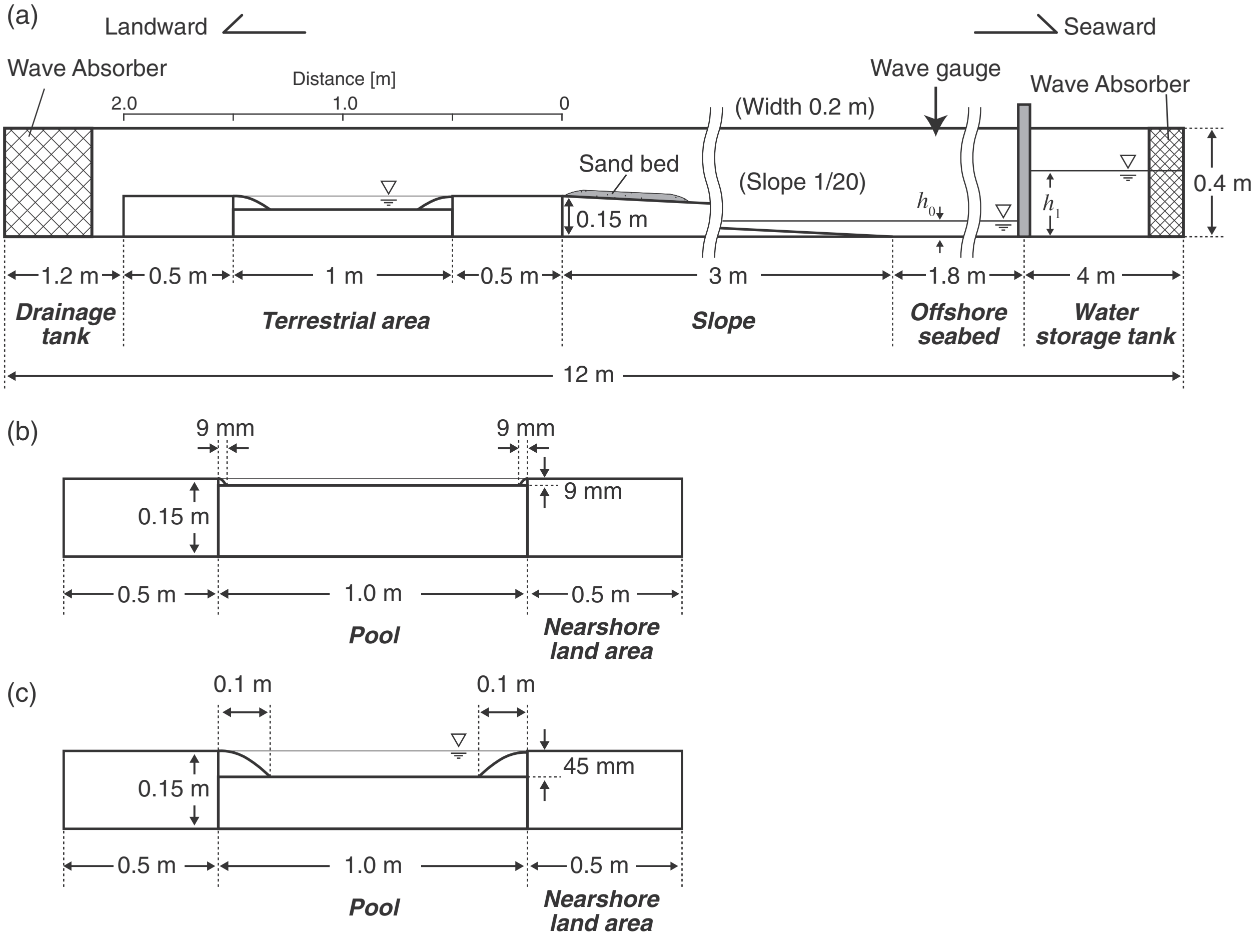

Fig. 1. Schematic design of (a) the flume used in this study, (b) the terrestrial portion of the flume with a shallow pool, and (c) the terrestrial portion with a deep pool.