Marine Geology 405 (2018) 77–91

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

Sediment transport modeling of multiple grain sizes for the 2011 Tohoku tsunami on a steep coastal valley of Numanohama, northeast Japan

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ARTICLE INFO

Keywords:
Tsunami sediment transport
The 2011 Tohoku tsunami
V-shaped coastal valley
Sediment thickness
Grain size distribution
Numerical model

ABSTRACT

The grain size distribution of a tsunami deposit may have a correlation with the tsunami inundation process, and further with the tsunami source characteristics. We test this hypothesis using thickness and grain size distribution data of the 2011 Tohoku tsunami deposit in Numanohama coast, Iwate Prefecture, Japan. Here, we build and validate a tsunami sediment transport model that can simulate deposit thickness and grain size distribution. Our numerical model has three layers: parent (bed), deposit (bed), and suspended load layers. The two bed-layers contain information about the grain size distribution. This numerical model can handle a wide range of grain sizes from 0.063 (4ϕ) to 5.657 mm (−2.5ϕ). The grain size distributions at 12 sample points along a 900 m transect from the beach, through a marsh, and up to the inundation limit, are used to validate the tsunami sediment transport model. We adopt a reference tsunami source model that can well reproduce the observed tsunami run-up heights ranging from 16 to 35 m along the steep valley during the 2011 tsunami. The simulated sand thickness distribution along the transect is consistent with the observed thickness ranging from 3 to 23 cm. The computed net erosion and deposition suggest that most of the sand deposit was originated from the near shore. The shapes of the simulated grain size distributions represented by their sorting, skewness, kurtosis, and mean at most of the sample sites are similar to the observations. The differences between the observed and simulated peak of grain size distributions are less than 1ϕ. To evaluate the sensitivity to the tsunami source model, we test five tsunami scenarios which are modified from the reference source model. While the tsunami scenario with 120% of the reference amplitude can also reproduce the thickness and grain size distribution, the scenarios with amplitudes smaller than 80% of the reference or with wave periods shorter than 50% of the reference source model underestimate the thickness and cannot reproduce the grain size distributions. Our simulation results suggest that it is possible to estimate tsunami wave amplitude and wave period from sediment deposit thickness and grain size distribution data.

1. Introduction

To study tsunami hazard, good knowledge about past tsunamis, including events before the start of written history, is required. The study of prehistoric tsunami events i.e., paleotsunami study, can be done by analyzing paleotsunami deposits (Atwater, 1987; Bourgeois et al., 1988; Dawson and Stewart, 2007). In Japan, paleotsunami deposit studies in the Sendai Plain revealed details of a major tsunami which is consistent with the historical record of the 869 CE Jogan earthquake (Minoura et al., 2001; Namegaya and Satake, 2014). The predecessor of the 2004 Indian Ocean tsunami was revealed from tsunami deposits collected around the Indian Ocean such as the west coast of Thailand and the northern part of Sumatra, Indonesia (Jankaew et al., 2008; Monecke et al., 2008; Rubin et al., 2017).

Inverse models have been developed in previous studies to estimate tsunami characteristics such as flow speed and depth from tsunami deposits. An inverse modeling method which assumes local equilibrium between turbulent suspension and settling has been applied for several tsunami cases (Jaffe and Gelfenbuam, 2007; Jaffe et al., 2011; Jaffe et al., 2012). This method works best with deposits with suspension grading but may give inaccurate estimations if the deposit was significantly formed by another process such as bedload deposition. An inverse model of Moore et al. (2007) assumes a short-duration unidirectional flow and most grains are transported in suspension. In

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https://doi.org/10.1016/j.margeo.2018.08.003
Received 23 May 2018; Received in revised form 3 August 2018; Accepted 19 August 2018
Available online 21 August 2018
0025-3227/

addition to sediment deposit data, the distance between the beach ridge (the sediment source) and the location of the last grains is also needed to estimate the average flow depth and flow velocity of the tsunami. The models of Moore et al. (2007) and Jaffe and Gelfenbuam (2007) are based on different basic assumptions. A joint inversion frame work (TSUFLIND) developed by Tang and Weiss (2015), combines models by Moore et al. (2007), Jaffe and Gelfenbuam (2007) and Soulsby et al. (2007). TSUFLID uses the calculated flow depth and water volume from Soulsby's model to estimate a representative offshore tsunami wave amplitude (Tang and Weiss, 2015). However, these inverse models cannot be applied in Numanohama because the tsunami flow in Numanohama was not unidirectional and the bedload transport was might be significant.

Tsunami sediment transport models have been used for modern tsunami events to increase our understanding on the relationship between the tsunami flow and deposit (e.g., Apotsos et al., 2011; Gusman et al., 2012a, b; Li et al., 2012; Sugawara et al., 2014). A numerical model of tsunami sediment transport was developed to investigate the erosion and deposition of sand deposits on the bottom of Kesennuma Bay in Japan during the 1960 Chile tsunami (Takahashi et al., 2001). The tsunami sediment transport model with a capability of simulating inland sediment transportation was used to study coastal erosion and deposition processes during the 2004 Indian Ocean tsunami (Gusman et al., 2012a, b). This paper presents a tsunami sediment transport model that can simulate the grain size distribution, a capability which was not available in the previous numerical model.

Tsunami sediment transport models could move forward paleotsunami studies from the simple identification of (1) occurrence of past tsunamis, and (2) frequency of tsunamis and into a more useful characterization of past tsunamis by estimating characteristics such as size of tsunami, flow velocity, and tsunami source (location and earthquake magnitude). Such an effort has been done in previous studies using tsunami hydrodynamics models without sediment transport (e.g., Satake et al., 2008; Namegaya and Satake, 2014; Ioki and Tanioka, 2016). This study will show that our coupled tsunami hydrodynamics and sediment transport model has the potential to be developed into a powerful tool for determining paleotsunami characteristics from paleotsunami deposits.

The grain size distribution of a tsunami deposit has been considered to contain information about the characteristics of the tsunami inundation process (Moore et al., 2007, 2011; Jaffe et al., 2012). We analyze the deposits of the 2011 Tohoku tsunami collected along a 900 m transect line in Numanohama (Figs. 1 and 2) to obtain the grain size distribution and use them to validate our tsunami sediment transport model. We also test the idea of using the numerical model in estimating the tsunami source from tsunami deposits by conducting a sensitivity test to the source model.

2. Study area and tsunami deposit data

2.1. Numanohama valley

Numanohama is located approximately 15 km north of Miyako City, Iwate Prefecture, on the Pacific coast of northern Honshu (Fig. 1). The Numanohama coast has a 200 m long sandy beach that is limited by cliffs to the north and south, and the width of both beach and sand dune is about 50 m. At the back of the sand dune is a marsh that is approximately 200 m long and 40 m wide with elevations ranging from 2 to 4 m. The portion of the valley with an elevation lower than 25 m is about 200 m wide at the shore but narrowing to about 60 m wide near the farthest limit of the 2011 tsunami inundation. There are also two sub-valleys to the north of the marsh which climb up in the northwest direction (Fig. 2).

We selected Numanohama for our study because sand layers from the 2011 Tohoku tsunami and older tsunamis have been preserved at the marsh (Goto et al., 2015, 2017). Our long-term goal is to estimate the paleotsunami heights from the distribution of those tsunami deposits. For this end, it is important to calibrate our numerical model for the location using data from a modern era tsunami such as the 2011 Tohoku event. The calibration work in this study is possible because all essential data such as the pre-event topography, tsunami inundation height, source of deposit, the tsunami deposit thickness and grain size distribution, and the earthquake source are well known.

2.2. Observation of tsunami inundation

The 2011 Tohoku tsunami inundated the coastal valley up to 1 km inland, the tsunami inundation map is available from http://www.jsgi-map.org/tsunami/. It appears that the limit of tsunami inundation is strongly controlled by the geomorphology of the coast. The measured tsunami inundation heights around the Numanohama coast range from 16 to 35 m (Tsuji et al., 2011, 2014; Mori et al., 2012) as shown in Fig. 3. The V-shaped valley causes funneling effects which concentrate the tsunami energy and creating the tremendous tsunami run-up heights on the cliffs.

2.3. Tsunami deposit data collection and analysis

A transect was set up in Numanohama along the valley from the coastline to near the limit of tsunami inundation approximately 900 m inland by Goto et al. (2015). Tsunami deposit samples were collected at 15 points by using geo-slicers with a 3-m long sample tray and a shutter plate. The geo-slice samples were 10 cm wide, 3 cm thick and the length ranged from 1.2 to 2.9 m. Four column samples from machine coring drills and one pit sample were also collected. The diameters of the columns samples ranged from 90 to 116 mm and lengths from 1.4 to 5.7 m. The width and depth of the pit were 40 cm and 50 cm, respectively.

The geo-slice samples contain deposits from previous storms and tsunami events including the 2011 Tohoku tsunami. These samples were used to reconstruct the history of tsunamis and storms during the last five centuries in the region in a previous study (Goto et al., 2015). Goto et al. (2017) analyzed gravel composition contained in the tsunami deposits and classified them into three sources: beach, riverbed and slope. Here, we analyze the grain size distribution and measure the thickness of the tsunami deposit at 12 sample points. For the other 8 samples, only the thickness of the tsunami deposits was measured. The thickness of the 2011 tsunami deposit (Fig. 4) ranges from 3 to 23 cm but was very variable, probably because of the complex terrain and microtopography around the marsh.

We conducted grain size analysis for sand samples of the Numanohama beach and the 2011 Tohoku tsunami deposit obtained at 12 locations (L1, L2, L4, L10, L11, L12, L13, L14, C1, C2, C3, and C4). Silt and clay grains ($> 4\phi$) were extracted by wet sieving, and their weights were measured by comparing their dry weights before and after wet sieving. The remaining sand and gravels were sorted into 11 categories using sieves with mesh sizes ranging from -6ϕ to 4ϕ with an interval of 0.5ϕ. The weight percent for each grain size was calculated, and a cumulative grain size distribution curve was obtained for each sample.

The grain size distributions of the samples taken along transect are finer than -4.5ϕ and have peaks between 0ϕ and 1ϕ (Fig. 5). The mean grain sizes of the sample are also between 0ϕ and 1ϕ. Tsunami deposits with unimodal distributions (e.g., L13 and L14) with peaks located between 0ϕ and 1ϕ are similar to the beach sand (Fig. 6). No systematic changes in the peak grain size were observed along the transect. Samples taken from L1, L2, C3, and C4 contained another peak at a coarser grain size of less than -2ϕ (corresponding to a diameter of greater than 4 mm) (Fig. 5). We also calculated sorting, skewness, kurtosis and mean grain size for comparison with the simulation (see Section 5.3).

In this study, the grain size distribution is taken from sand sampled at both on the top and on the seaward side of the beach ridge. The sand