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Reprint of "Boulder transport by the 2011 Great East Japan tsunami: Comprehensive field observations and whither model predictions?"

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ABSTRACT

Predicting the local size of a historic high-energy event from its boulders using numerical models is a challenging research topic. Modern high-energy events and their deposits are useful to validate these models; however, validating the accuracy of the results is difficult due to the scarcity of good datasets or the ambiguity of existing field data. Data on boulders transported by the 2011 Great East Japan tsunami at coastal sites (Settai, Taro, and Karakuwa) on the northeast coast of Japan were compiled. Pre-tsunami locations and settings and transport distances were found from evidence such as photographs, aerial images, and the testimony of survivors. The estimated weight of the boulders analyzed ranged from 11 to as much as 167 t, while the transport distance varied from a few to up to 600 m. Modeling results predicted that the minimum limit of maximum flow velocity of the tsunami at the pre-tsunami locations of the boulders varied from 4.2 to 6.8 m/s. The measured maximum flow depths at Settai (17–18 m) and Taro (14 m) were within the predicted range of flow depth when the Froude number = 1.0–1.5. Numerical model estimates for an older boulder (285 t) in Settai indicate that it was probably transported by a historical tsunami (1611 Keicho Sanriku event?) which may have been similar to or bigger than that of the 2011 event in the area. The maximum flow velocity could not have been less than 6.1 m/s, and if the boulder was transported to the present location by rolling, the flow velocity must have been within 7.5–23.7 m/s. Following systematic validation, the numerical modeling of boulder transport is proving promising for reconstructing the local magnitude of historical, high-energy events. Further improvements can be made with additional high quality field data from modern high-energy events.

1. Introduction

High-energy deposits are an important feature of events such as tsunamis or large storms (Scheffers, 2008; Goto et al., 2010a), and are useful in helping to estimate the magnitude (local size) of past events in the absence of precise information (Nott, 2003; Jaffe and Gelfenbaum, 2007; Imamura et al., 2008). Deposits vary greatly in grain size from finer (sand or mud) to coarser sediments (big boulders or clasts). The characteristics of the deposit, such as thickness, distribution, and extent of the finer sediments, and transport distance of the coarser material change depending upon the source availability and magnitude of the hydraulic force, which is determined primarily by flow depth, flow velocity, and density of the fluid (Goto et al., 2007; Nandasena and Tanaka, 2013). However, the characteristics of the topography, such as changing slope and roughness of the ground, including vegetation and man-made structures, can locally modify the characteristics of the deposit (Nandasena et al., 2011a). This information has been identified, documented, and used to infer the nature of historical, high-energy events throughout the world from deposits, such as fine sediments in Japan (e.g., Fujiwara and Kamataki, 2007), Newfoundland (e.g., Moore et al., 2007), North America (e.g., Peters et al., 2007), and Thailand (e.g., Srisutam and Wagner, 2010a); and boulder deposits in Australia (e.g., Nott, 1997), Scotland and Ireland (e.g., Hall et al., 2006), Greece (e.g., Scheffers and Scheffers, 2007), Italy (e.g., Mastronuzzi et al., 2007), New Zealand (e.g., Kennedy et al., 2007), Hawaii (e.g., Goff et al., 2006), Algeria (e.g., Maouche et al., 2009), Iceland (e.g., Etienne and Paris, 2010), Japan (e.g., Goto et al., 2010a), Sicily (e.g., Barbano et al., 2010), Iran (e.g., Shah-hosseini et al., 2011), South Africa (e.g., Salzmann and Green, 2012), and the southern Caribbean (e.g., Engel and May, 2012).

Numerical models are used to estimate the local magnitude of high-energy events in terms of flow depth, flow velocity, and run-up from their deposits, such as inverse/forward type models for sand deposits (Jaffe and Gelfenbaum, 2007; Soulsby et al., 2007) and boulder deposits (Nott, 2003; Imamura et al., 2008; Nandasena et al., 2011a; Nandasena and Tanaka, 2013). These models have been used widely (Goto et al., 2010b; Srisutam and Wagner, 2010b; Jaffe et al., 2011, 2012; Nandasena et al., 2011b and references therein). Debates concerning model use and predictions (Costa et al., 2011; Paris et al., 2012) and

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theoretical modifications (Benner et al., 2010; Nandasena et al., 2011b) are common and often discussed in the literature. It is not surprising though that simplified models do not simulate well the complex non-linear processes involved. Nonetheless, numerical models are extremely useful for reconstructing the past and predicting future events. These numerical models receive considerable attention, and modeling results are widely accepted without experimental validation to estimate the magnitude of historical high-energy events. Imamura et al. (2008) and Nandasena and Tanaka (2013) conducted small scale laboratory tests to validate their numerical models and compared their modeling results with experimental results of block transport. Fortunately, modern examples (i.e., known high-energy events with precise data concerning their deposits) are available for use in validating models thus ensuring and improving their usefulness. In the case of forward modeling of boulder transport, details of the high-energy event (flow depth, flow velocity, and density of fluid), the topography, and boulder characteristics (morphometry, density, pre-transport location), are the primary input parameters necessary to simulate the transport mode and distance of the boulder. For inverse modeling, the characteristics of a boulder (morphometry and density, pre-transport location), and its transport mode and distance are the primary input parameters needed to estimate the magnitude of a high-energy event (flow depth or flow velocity). Both data collection (Goto et al., 2007, 2012; Paris et al., 2009; Etienne et al., 2011) and modeling of boulder transport (forward modeling: Goto et al., 2010b; Nandasena et al., 2011a; inverse modeling: Paris et al., 2010; Spiske and Bahlburg, 2011) have been performed following four recent tsunamis (2004 Indian, 2009 South Pacific, 2010 Chile, and 2011 Great East Japan).

Here we report on a field survey conducted along the coast of northeast Japan from Misawa to Sendai in August, five months after the 2011 Great East Japan tsunami (hereafter “the 2011 tsunami”). Boulders with different types of pre-transport settings (submerged, subaerial, joint bounded, and cliff top) that were transported by the 2011 tsunami were observed and measured. Boulder data and local characteristics of the tsunami at each study site were recorded. This paper first focuses on field observations of boulders transported by the 2011 tsunami and then compares these data with numerical model predictions.

2. Field reconnaissance

The northeast coast of Japan facing the Pacific Ocean is known as the “Sanriku coast” and borders the Aomori, Iwate, and Miyagi Prefectures. This coast exhibits characteristics of a ria coastline, including geomorphic features such as cliffs, steep slopes, narrow bays, small lowlands between topographic highs, pocket beaches, peninsulas, and tombolos. The coast is mainly composed of sediments (sand and gravels) and sedimentary and volcanic rock outcrops. These outcrops possess numerous joints and typically appear as cliffs or steep rocky soil slopes. An outcrop provides a natural source of sharp-cornered blocks/clasts on the coast, which become rounded or semi-rounded boulders with prolonged exposure to weathering under both mechanical (e.g. wave action) and chemical processes (e.g. dissolution). They commonly appear as isolated boulders or groups of clasts near their source or joint bounded blocks with irregular shapes in rock slopes or on cliffs.

During the field survey, several coastal sites (Fig. 1) were identified in Iwate and Miyagi Prefectures where boulders and clasts were

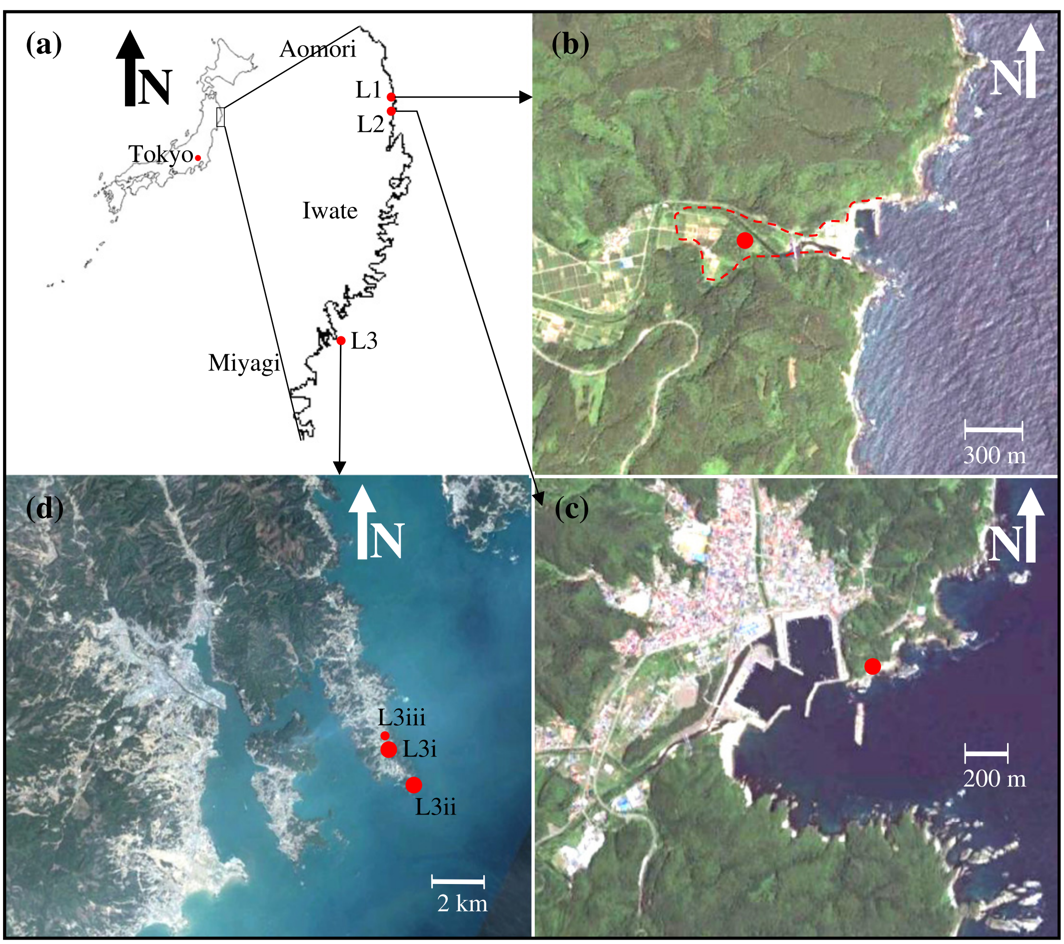

Fig. 1. (a) Boulder sites on the northeast coast of Japan, (b) Settai, Iwate Prefecture (39° 48′ 48″N, 141 58′ 33″E), (c) Taro, Iwate Prefecture (39° 43′ 58″N, 141° 58′ 47″E), and (d) Karakuwa Peninsula, Miyagi Prefecture (38° 52′ 34″N, 141° 39′ 31″E). Note that circles indicate the location of the boulder site. Fig. 1b–d shows sites before the 2011 tsunami. Source of Fig. 1b–d: Google Earth.