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Maximum sand sedimentation distance after backwash current of tsunami — Simple inverse model and laboratory experiments

Eiichi Furusato, Norio Tanaka *

Graduate School of Science and Engineering, Saitama University, 255 Shimo-okubo, Sakura-ku, Saitama 338-8570, Japan
International Institute for Resilient Society, Saitama University, 255 Shimo-okubo, Sakura-ku, Saitama 338-8570, Japan

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ABSTRACT

Estimating the magnitude of a past tsunami is important in tsunami hazard assessment and protection. In particular, sand deposition data provide important information in such processes. The effects of the backwash current of a tsunami on the sand distribution should be considered in estimating the historical tsunami magnitude by field survey data.

A simple inverse model was developed to estimate the maximum distance of a sand deposit from a tsunami considering not only sedimentation but also re-erosion by the backwash current. Laboratory experiments were conducted to understand the characteristics of the effects of backwash current and estimate the parameters needed for the model development. The proposed simple model consists of several macroscopic characteristics of both non-tsunami terms, such as land slope and sand characteristics, and comprehensive tsunami properties, such as the energy gradient of the backwash current and tsunami height. It was assumed that the velocity and water depth of the backwash current are linearly approximated by the law of tsunami current conservation on a land slope. To estimate the decrease in sand layer depth due to re-erosion by the backwash current, the tractive force of the current and the drag force of the sand removed were related with one empirical parameter (ε). Laboratory flume experiments were conducted to calibrate the parameter. Sensitivity analysis confirmed the effect on the changes in the value of ε on the sand deposition distance to be smaller than that of other parameters. In spite of many simple assumptions, the estimate agreed well with the sand deposit distance of the 2011 Great East Japan Earthquake tsunami. Finally, the limitations and effectiveness of the model are discussed. This study developed a useful method for measuring backwash in a relatively extensive land slope where the effect of the backwash current is large and regional topography and land use effects are small.

1. Introduction

After the 2011 Great East Japan Earthquake tsunami (hereafter Tohoku-oki tsunami), Japan, the importance of estimating historical tsunamis for hazard protection increased (Goto et al., 2011; Goto et al., 2012a). In particular, tsunami sediment information plays an important role in tsunami hazard mitigation because tsunami deposits are hard evidence of the area of tsunami inundation (Dawson and Shi, 2000; Goto et al., 2011; Sugawara et al., 2012; Sugawara et al., 2014). To estimate the magnitude of a past large earthquake, the minimum distance of the tsunami inundation calculated by a numerical model has been defined by the extent of the sand deposit (Satake et al., 2008; Sugawara et al., 2011). Goto et al. (2011) asserted the importance of knowing the relationship between the inundation distance and the limit of sand deposit based on the experience of a field survey in the Sendai Plain after the 2011 Tohoku-oki tsunami, because the distance from the coast at which sand was deposited was only 62% of the inundation distance. In the past decade, surveys of sand deposits in recent tsunami events have been conducted for the 1992 Flores, Indonesia, tsunami (Shi et al., 1995), the 1998 Papua New Guinea tsunami (Gelfenbaum and Jaffe, 2003), the 2009 South Pacific tsunami (Apotsos et al., 2011), the 2004 Sumatra tsunami (Bahlburg and Weiss, 2007; Paris et al., 2007; Srinivasalu et al., 2007; Choowong et al., 2008), and the 2011 Tohoku-oki tsunami (Goto et al., 2011, 2012b; Nakamura et al., 2012). There is a wide range of variations in the relationship between maximum inundation limit and sand deposit distance.

Sand transport and deposit by tsunami currents are complicated processes (Dawson and Shi, 2000; Goto et al., 2012b) so that generalization about the relationship is considered difficult. The effects of coastal topography and the extent of erosion on the local sand depositional characteristics are discussed based not only on field surveys of the 2011 Tohoku-oki tsunami (Nakamura et al., 2012), but also on a detailed numerical model that included various site-specific topographic information (Sugawara and Goto, 2012). Although numerical models can

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* Corresponding author at: Graduate School of Science and Engineering, Saitama University, 255 Shimo-okubo, Sakura-ku, Saitama, 338-8570, Japan. Tel./fax: +81 48 858 3564.
E-mail address: tanaka01@mail.saitama-u.ac.jp (N. Tanaka).

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provide precise information with high resolution according to site characteristics, one problem is the large workload of collecting various input data as a forward application (Sugawara et al., 2014). Furthermore, to construct such a detailed, process-based numerical model, an important problem is the difficulty of reconstructing past local topographical data required for such a detailed model procedure.

On the other hand, a simple model that needs little information can provide important information for practical use if enough attention is paid to applying the conditions related to the model assumptions and limitations (Huntington et al., 2007). The inverse model is accepted as an important tool for tsunami hazard risk assessment (Huntington et al., 2007; Sugawara et al., 2014). Recently, several such inverse models have been proposed (Jaffe and Gelfenbaum, 2007; Noda et al., 2007; Soulsby et al., 2007; Pritchard and Dickinson, 2008), although they are still under development (Paris et al., 2012). Nandasena et al. (2011) developed a boulder transport model for estimating paleotsunami magnitudes. Jaffe and Gelfenbaum (2007) proposed a simple inverse model for calculating tsunami flow speed from the thickness and grain size of tsunami deposits and applied it to the 2009 Samoa/Tonga tsunami (Jaffe et al., 2011) and the 2011 Tohoku-oki tsunami (Jaffe et al., 2012).

Soulsby et al. (2007) developed a simple inverse model for reconstructing tsunami run-up from sedimentary characteristics by using a simple trajectory theory of tsunami hydrodynamics and applied it to the 1929 Grand Banks tsunami and the Holocene Storegga Slide tsunami. Srisutam and Wagner (2010) reported good agreement between observed values of the run-up heights of the 2004 Indian Ocean tsunami and the estimation reconstructed by the modified model of Soulsby et al. (2007). Paris et al. (2012) identified the problems in application of these models for reconstruction due to the large degree of simplification, although they recognized the importance of this kind of simplicity in hazard evaluation. Further improvements are needed for such simple inverse models from various points of view. One important problem of the model is that it neglects the effect of backwash currents, which cause erosion of deposited sand. If the maximum sand deposit distance is decreased by backwash currents, there is a possibility of underestimating the magnitude of a historical tsunami. In hazard risk assessments related to historical tsunamis, more attention should be paid to this problem. Although Jaffe and Gelfenbaum (2007) assumed little erosion of the deposit by the return flow due to slow flow and the effects of local topographic characteristics as the basis of their model, Dawson and Shi (2000) pointed out the effects of backwash flow on sand deposition as well as run-up.

Actually, it is difficult to estimate the difference between distributions of sand deposited after a run-up and by backwash by field observation for a real tsunami. However, laboratory experiments were recently conducted related to sand deposit characteristics (Hasegawa et al., 2001; Sugawara et al., 2003; Harada et al., 2011). Although Harada et al. (2011) discussed the characteristics of sand deposition on a land slope based on only the effects of run-up currents, other experiments (Hasegawa et al., 2001; Sugawara et al., 2003) showed significant effects of backwash currents on sand distribution. Compared to a small land slope area in which the effects of local topography conditions on the sand deposit are relatively large (e.g., The, 2011 Tohoku Earthquake Tsunami Joint Survey (TTJS) Group, 2012), in a steep land slope condition, macroscopic characteristics such as land slope and run-up height will play dominant roles in erosion due to backwash currents. The effectiveness of a simple inverse model based only on macroscopic information for estimating a paleotsunami by using sand deposit records obtained in such areas will be high. Therefore, the objective of this study was to develop a simple inverse model to estimate the tsunami inundation distance by using the maximum sand deposition distance including re-erosion by backwash currents as a first attempt to include the effects of backwash current. Laboratory experiments were conducted to determine the empirical parameters used in the model. Finally, the applicability of the model has been validated for the 2011 Tohoku-oki tsunami, Japan.

2. Model descriptions

The parameters considered for the model are defined in Fig. 1(A). Firstly, tsunami hydrodynamics needed to estimate the effects of backwash currents on erosion of the sand layer deposited by the run-up was linearly approximated from the law of conservation of tsunami currents following Soulsby et al. (2007). In the present study, based on the following assumptions, a simple model was developed to estimate the reduction in both sand deposition depth and distance caused by re-erosion of the backwash current of a tsunami after the initial sand deposit.

2.1. Re-erosion depth of deposited sand by backwash currents

The reduction in the thickness of the sand layer deposited by a run-up tsunami current as re-erosion by backwash current was estimated by the balance of tractive force of the backwash current and drag of sand.

2.1.1. Tractive force of backwash currents (τ)

The tractive force of backwash currents is calculated by assuming a steady uniform flow as:

$$\tau_o(x,t) = \rho_w g h(x,t) i_e(x,t) \tag{1}$$

where x is the horizontal distance from still water line (SWL), t is the duration of tsunami at which the land, higher than the still water line, inundated, ρ_w is the density of water, g is the gravitational acceleration, $h(x,t)$ is the water level for position x and time t, and $i_e(h,t)$ is the energy gradient. Theoretically, a full momentum equation of a tsunami should include inertial and advective terms for estimating tractive force. However, this model intended to solve it simply based on the assumptions adopted in the Soulsby et al. (2007) model. Eq. (1) was used by considering the simple hydrodynamic assumption in the previous model.

The geometric triangle similarity shown in Fig. 1(B), (C), and (D) used to calculate $h(x,t)$ was based on several assumptions. Fig. 1(B) shows identical tsunami hydrodynamics with depth variation over time. As an example, the temporal variation in the water surface at an arbitrary point ($x = x_i$) as well as at the SWL ($x = 0$) is shown. The water level $h(x_i, t_j)$ at an arbitrary point x_i and time t_j can be expressed from the triangle similarity (abc and a′b′c′ in Fig. 1(B)) by

$$h\left(x_i, t_j\right) = \frac{\gamma T + T_b(x_i) - t_j}{T_b(x_i)} h_{max}(x_i) \tag{2}$$

where γ is the ratio of run-up time to total inundation time, T is the total time that the land above still water level is inundated, $T_b(x)$ is the total duration of backwash currents for each point, $h_{max}(x_i)$ is the maximum water level. $h_{max}(x_i)$ is calculated from the distance of the arbitrary point x_i and H (Fig. 1(C)).

$$h_{max}(x_i) = \frac{L_w - x_i}{L_w} H \tag{3}$$

where L_w is the horizontal run-up limit of water, H is the maximum water depth at SWL. Total backwash duration ($T_b(x_i)$) at an arbitrary point x_i can be represented by the backwash time (γT), L_w, and x_i.

$$T_b(x_i) = \frac{L_w - x_i}{L_w} (1-\gamma) T. \tag{4}$$