Review

Numerical Models for Sediment Transport by Tsunamis

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Sediment transport by tsunamis causes serious human injury and damage to buildings, coastal topography, and marine ecosystems. To understand processes of sediment transport by tsunamis, experimental and numerical studies as well as field investigations are important. In this study, we summarize experimental and numerical models for transport of sandy sediments or a large block, and then discuss their limitations and possible improvements. Although some problems and difficulties remain, these models generally are able to reproduce experimental results, and they can be adapted to the modeling of sediment transport by real-scale tsunami events. When these models have been improved to handle mixed grain sizes and multiple blocks, it will be possible to estimate hydraulic properties (hydraulic force, current velocity, and inundation area) of historical and prehistoric tsunamis more precisely by constraining the models with information on existing tsunami deposits and boulders. Moreover, sediment transport models are useful for estimating the spatial distribution of sediments eroded and redeposited by tsunamis; thus, such models will be helpful in the selection of drilling sites for core samples in investigations of historical and prehistoric tsunami deposits.

Keywords : tsunami deposit, tsunami boulder, sediment transport model, hydraulic experiment

I. Introduction

On 26 December 2004, one of the largest tsunamis (the 2004 Indian Ocean tsunami) in human history struck coastal areas of countries surrounding the Indian Ocean, causing severe property damage and loss of life and forcing us to think anew about the fearful consequences of a tsunami disaster (Imamura *et al.*, 2006). Tsunamis often strike at-risk countries, where there is an urgent need to improve countermeasures against tsunami disasters (*e.g.* Stone and Kerr, 2005). Once a large tsunami is generated, it has many severe consequences, including human injury and death and damage to buildings, coastal topography, and marine and coastal ecosystems. Moreover, large tsunamis remove sediments from the sea bottom and beaches and transport them landward or seaward.

As a result, port function may be hampered by the deposition of large amounts of sediments (Takahashi *et al.*, 1993), and fisheries and agricultural areas may be severely damaged by inundation of seawater or by burial under salty sediments (*e.g.* Nakaya *et al.*, 2005). On the other hand, sandy sediments transported by a tsunami and deposited on land or on the sea bottom become part of the geologic record that can be used to identify historical or prehistoric tsunami events (*e.g.* Atwater, 1987; Minoura *et al.*, 1987; Dawson *et al.*, 1988; Nanayama *et al.*, 2003; Cisternas *et al.*, 2005).

Tsunami damage is related mainly to the hydraulic force and current velocity of a tsunami rather than to the inundation depth or wave height (*e.g.* Noji *et al.*, 1993). Hydraulic force and current velocity can sometimes be estimated on the basis of information in aerial photographs

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using Cameron effect, if available (Takahashi *et al.*, 1993), as well as from differences in inundation depth between the front and rear of structures (Matsutomi *et al.*, 2005a, 2006). Moreover, in the case of the 2004 Indian Ocean tsunami, current velocity was estimated from video recordings (Borrero, 2005 ; Matsutomi *et al.*, 2005a). However, in general, hydraulic force and current velocity are difficult to estimate from field observation data. Even when a field survey is conducted immediately after a tsunami event, many data on inundation depth and area and wave height are usually collected, but very few data on hydraulic force or current velocity are obtained.

Alternatively, might it be possible to estimate the hydraulic properties of a tsunami, in particular, hydraulic force and current velocity, from information recorded in tsunami deposits, such as deposit thickness, grain size, and spatial distribution? If so, then we might be able to estimate the nature and behavior of historical and prehistoric tsunamis in greater detail, which would be useful for evaluating

the risk of future tsunami disasters in the same region as the deposits. Two approaches have been used to estimate hydraulic properties of tsunamis from tsunami deposits. A sedimentological approach has empirically estimated wave period and current velocity from the lithology, sedimentary structures, and grain size of tsunami deposits (*e.g.* Fujiwara *et al.*, 2003 ; Fujiwara, 2004). On the other hand, experimental and numerical approaches reproduce the sediment transport processes of tsunamis (Fig. 1, *e.g.* Takahashi *et al.*, 2000). For example, tsunami inundation processes have been estimated by using the spatial distribution of tsunami deposits to constrain a numerical model (Titov *et al.*, 2001 ; Jaffe and Gelfenbaum, 2002 ; Koshimura *et al.*, 2002).

For disaster prevention purposes, experimental and numerical models of sandy and block sediment transport by tsunamis have been developed by coastal engineers (Noji *et al.*, 1993 ; Takahashi *et al.*, 1993) seeking to maintain port function in the face of topographic changes caused by tsunami sedimentation and to clar-

Fig. 1 A flowchart indicating the relationships among field surveys, hydraulic experiments, and numerical models for the clarification of sediment transport by tsunamis

ify transport processes of large blocks, including tetrapods used in breakwater construction, by tsunamis. These models, which have recently received practical improvements by many researchers (Fujii *et al.*, 1998 ; Takahashi *et al.*, 1999, 2000 ; Imamura *et al.*, 2001, in press ; Sugawara *et al.*, 2003, 2004a ; Nishihata *et al.*, 2005), are also useful for sedimentological and paleontological studies of tsunami deposits designed to clarify depositional processes. On the other hand, sedimentological and paleontological data on tsunami deposits provide important constraints on such models, and their accuracy and reproducibility are evaluated using such data (Fig. 1). Therefore, cooperation among investigators in the two research fields leads to complementary advantages and is critically important for future study of sediment transport by tsunamis. Here, we summarize hydraulic experiments and numerical models of sandy and block sediment transport, which have developed during the past 15 years, and discuss the current status of these models, their problems, and improvements.

II. Hydraulic experiments and numerical calculation of tsunami inundation

Real-time measurement of sediment transport by a tsunami is technically difficult at present ; thus, we observe instead sediment erosion, transport, and deposition by tsunamis. Not only sedimentological studies but also hydraulic experiments (Kato *et al.*, 2000 ; Hasegawa *et al.*, 2001 ; Sugawara *et al.*, 2003, 2004b) and numerical analyses (Takahashi *et al.*, 1993, 1999, 2000 ; Fujii *et al.*, 1998 ; Sugawara *et al.*, 2004a ; Nishihata *et al.*, 2005) can be used to improve our understanding of sediment suspension, transport, and deposition.

At the Disaster Control Research Center, Tohoku University, hydraulic experiments are conducted in a water tank, 10 m long and 30 cm wide, with a flat floor (Fig. 2, *e.g.* Sugawara *et al.*, 2004b ; Imamura *et al.*, in press). A gate located 300 cm from the upstream end of the tank confines water in a storage tank, and a bore is generated by the rapid opening of the gate (Fig. 2). The initial water depth on the flat floor on the downstream side of the gate is 1.2 cm.

Fig. 2 Schematic diagrams showing a water tank for conducting hydraulic sediment transport experiments

(a) Initial condition, (b) generation and run-up of the bore after rapid opening of the gate, and (c) dewatering process during backwash flow. Sand and a block are set in their initial positions for each experiment. Modified from Imamura *et al.* (in press).

The current velocity of the bore can be changed by adjusting the amount of water in the storage tank. A variable-gradient flat slope, used to simulate the shore, is at the downstream end of the tank. The surfaces of the flat floor and slope are smooth and impermeable, but bottom friction can be changed by using different slope materials. The generated bore runs up the slope, reaches a maximum inundation level, and then flows back toward the upstream side as backwash current. The backwash current is dewatered through a drainage gate in the upstream end of the storage tank. Using this system, we can measure the amount of sediments deposited and eroded by a single bore (Fig. 2).

Because of the restricted scale of the water tank, it is difficult to reproduce a real-scale tsunami wave in this tank. Therefore, the results must be interpreted in light of the principle of similitude. In general, the Froude number F_r and nondimensional bed shear stress (Shields number) τ_* of experimental current are set to be close to the values of a putative tsunami wave current :

$$F_r = \frac{u}{\sqrt{gh}} \quad \dots\dots(2.1)$$

$$\tau_* = \frac{u_*^2}{sgd} : s = \frac{\rho_s - \rho_f}{\rho_f} \quad \dots\dots(2.2)$$

where u is velocity, g is gravitational acceleration, h is still-water depth, u_* is shear velocity, ρ_s and ρ_f are sediment particle and fluid densities, respectively, and d is particle diameter. In the water tank experiment, the Shields number is within a similar range to that of real-scale tsunamis (Sugawara *et al.*, 2003). The slope gradient and current duration should also be adjusted to values similar to those of a putative tsunami wave current (Sugawara *et al.*, 2004b). Further improvements of the water tank will be required for more detailed studies.

Before the calculation of the sediment transport process, accurate reproduction of the wave current is required. Shallow-water theory is used for numerical calculation of a tsunami propagation in the shallow region and run-up.

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} = 0 \quad \dots\dots(2.3)$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x} \left(\frac{M^2}{D} \right) + gD \frac{\partial \eta}{\partial x} + \frac{gn^2}{D^{7/3}} M |M| = 0 \quad \dots\dots(2.4)$$

where η is the vertical displacement of the water surface above the still-water surface, M is the discharge flux in the x direction, D is total water depth ($=h+\eta$), and n is Manning's roughness coefficient. Equations (2.3) and (2.4) represent the equations of continuity and motion, respectively. The staggered leap-frog method, a finite-difference method, is used to solve these equations numerically (Goto *et al.*, 1997 ; Takahashi, 2004). The condition of the wave front is based on Kotani *et al.* (1998).

III. Numerical model of sandy sediment transport

1. Background

Tsunamis transport abundant sediments as bed load or suspended load (Takahashi *et al.*, 1993). Sediment transport resulting in sand deposition damages farm crops (Nakaya *et al.*, 2005), port functions (Takahashi *et al.*, 1993 ; Tomita *et al.*, 2006), thermal and nuclear power plants (Takahashi *et al.*, 2000), and marine ecosystems (*e.g.* Comley *et al.*, 2005) ; sand erosion damages buildings and coastal vegetation (Harada *et al.*, 2002 ; Danielsen *et al.*, 2005 ; Tanaka *et al.*, 2005 ; Yanagisawa *et al.*, 2006), and beach pollution caused by debris deposition accompanying beach sand movement damages tourism (Yasuda and Harada, 2005). Moreover, abundant debris floated in the tsunami wave currents of the 2004 Indian Ocean tsunami at Banda Aceh, Indonesia. It is one of the noticeable phenomena and enhanced the damage in the city center (*e.g.* Matsutomi *et al.*, 2005b). Because coefficient of viscosity of water becomes high due to the mixture of fine sediment particles, viscosity of the tsunami wave current, which inundated on land and suspended large amount of sediments, might have become high, and thus the tsunami wave current might have easily drifted abundant debris.

By taking into account such complexities, numerical models of sediment transport can be useful for improving the reliability of disaster assessment. Moreover, sediment transport models are also useful for investigating the hydraulic properties and behavior of historical and pre-

historic tsunamis both on land and in the sea (Takahashi *et al.*, 1999, 2000). In view of these problems and considerations, numerical models of sandy sediment transport by tsunamis have been developed (Takahashi *et al.*, 1993) and improved (Asai *et al.*, 1998 ; Fujii *et al.*, 1998 ; Takahashi *et al.*, 1999, 2000 ; Nishihata *et al.*, 2005). In this section, we describe a sediment transport model developed by Takahashi *et al.* (1993, 1999, 2000) and applied to experimental water tank results by Sugawara *et al.* (2004a), and summarize an example of its application and some of its problems and limitations.

2. Numerical model

Sandy sediments are transported as bed and suspended loads by tsunamis. Although in reality no clear boundary exists between these two layers, Takahashi *et al.* (2000) assumed two distinct layers in their model (Fig. 3). In this model, movement of sediments in the flow direction within the bed- and suspended-load layers, settling of sediments from the suspended layer to the bed-load layer, and the entrainment of sediments from the bed load to the suspended load layer are considered (Takahashi *et al.*, 2000). In this model, fluxes are conserved

in each layer (Fig. 3, lower panel). Takahashi *et al.* (2000) introduced the concept of the exchange load w_{ex} to describe the net load, the balance between suspension and settling of sediments between the two layers. The governing equations of their model are as follows :

$$\frac{\partial Z_B}{\partial t} + \frac{1}{1-\lambda} \left(\frac{\partial q_B}{\partial x} + w_{ex} \right) = 0 \quad \dots\dots(3.1)$$

$$\frac{\partial \bar{C}_s M}{\partial x} - w_{ex} + \frac{\partial \bar{C}_s h}{\partial t} = 0 \quad \dots\dots(3.2)$$

$$w_{ex} = \varepsilon_z \frac{\partial C}{\partial z} - w_0 C \quad \dots\dots(3.3)$$

where Z_B is height of the bed above the reference level, λ is porosity, q_B is bed-load rate, M is flow flux, C_s is the mean particle concentration in the suspended-load layer, h is the water depth, ε_z is the vertical diffusion coefficient, C is the suspended-sediment concentration, and w_0 is the settling velocity. Equations (3.1) and (3.2) represent the equations of continuity in the bed-load and suspended-load layers, respectively.

Takahashi *et al.* (2000) adopted equations of a non-dimensional bed load and a non-dimensional exchange load for tsunami based on the hy-

Fig. 3 Diagram showing the modeling of two separate layers (suspended-load layer and bed-load layer) based on Takahashi *et al.* (2000)

$\bar{C}_B$ is the mean concentration of the bed-load layer, and h_B is the thickness of the bed-load layer. Other parameters are defined in the text.

draulic experiment, because current velocity of the tsunami is faster than the stream flow and these equations for stream flow are inapplicable to the tsunami. According to Takahashi *et al.* (2000), the nondimensional bed-load transport rate Φ_B and the nondimensional exchange rate Ψ_{rise} can be empirically related to the Shields number as follows :

$$\Phi_B = 21\tau_*^{3/2} \quad \dots\dots(3.4)$$

$$\Psi_{rise} = 0.012\tau_*^2 \quad \dots\dots(3.5)$$

Based on equations (3.4) and (3.5), Takahashi *et al.* (2000) proposed the following equations for the bed load and exchange load of a tsunami.

$$q_B = 21\sqrt{sgd^3}\tau_*^{3/2} \quad \dots\dots(3.6)$$

$$w_{ex} = 0.012\sqrt{sgd}\tau_*^2 - w_0\bar{C}_s \quad \dots\dots(3.7)$$

where s is the relative density of the sand particles.

3. Application examples and problems

Sugawara *et al.* (2004a) applied this numerical model to experimental hydraulic results (Figs. 4-a, 5). Because the hydraulic experiment reproduced wave currents well, the experimental results were suitable for evaluating the validity of the sediment transport model. The calculation results generally reproduced the characteristics of the experimental results, including the sedimentation peak at the base of the slope and a wedged-shape sediment deposit on the slope (Fig. 5, Sugawara *et al.*, 2004a). However, calculation results for nondimensional sedimentation sand and remnant sand volumes, which represent the nondimensional sand volume deposited by the run-up current and the sand

Fig. 4 Photographs of (a) experimental results for sandy sediment transport, and (b) a coral fragment transported by the 2004 Indian Ocean tsunami at Pakarang Cape, Thailand

Fig. 5 Comparison of experimental and numerical results for sandy sediment transport
Modified from Sugawara *et al.* (2004a).

volume resting on the slope after the passage of the backwash, respectively, were considerably lower than the values obtained experimentally. In particular, the volume of sand transported by the backwash current was underestimated. These results were probably affected by problems related with the accuracy of the bed load and exchange load equations, and the low reproducibility of the hydraulic experiment results (Sugawara *et al.*, 2004a). In addition, a grain size effect could be an important factor for the inconsistency between the experimental and numerical results.

Sugawara *et al.* (2004a) used sand of mixed grain size (150–600 μm) for the hydraulic experiment in an attempt to reproduce the landward-fining feature of tsunami deposits (Mino-ura *et al.*, 1997; Moore, 2000). However, fine grains, because they easily become suspended and slow to settle, are in general more susceptible to current velocity and are thus more movable than coarse grains (*e.g.* Julien, 1995). However, a numerical model of sediment transport taking mixed grain sizes into account has not yet been developed for tsunami sedimentation. Therefore, fully sorted sand (average grain size) is assumed by the model. In other words, differences in the sediment transport process that depend on grain size have not been incorporated into the model. As a result, the model overestimates the amount of coarse sediments larger than the average grain size and underestimates the amount of fine sediments. Considering that actual tsunamis transport sediments with a wide range of grain sizes, the accuracy of the calculation results decline when we apply the existing model to real-scale sediment transport.

Recently, a sediment transport model developed for stream flow is extended in order to incorporate mixed grain sizes into the calculations (*e.g.* Sekine, 2001), although some problems and difficulties remain. In the future, it will be important to apply the method to improve modeling of sediment transport by tsunamis. With the improved model, we will be able to discuss characteristic features of tsunami deposits such as landward fining.

IV. Numerical model for boulder transport

1. Background

It is commonly believed that large tsunami waves can transport huge boulders as well as sandy sediments (*e.g.* Kato and Kimura, 1983). A typical example is the more than 300 boulders of reef scattered along the shore of Ishigaki Island, Japan (*e.g.* Kato and Kimura, 1983; Nakata and Kawana, 1993). These reef boulders, called “tsunami-ishi” in Japanese, are thought to have been transported by the 1771 Meiwa Yaeyama tsunami, which, according to historical documents, had a wave height of ~ 30 m. Moreover, abundant meters-long boulders of coral fragments were transported by the tsunamis associated with the 1883 Krakatau volcanic eruption (Simkin and Fiske, 1983) and the 2004 Indian Ocean tsunami (Fig. 4–b, Goto *et al.*, in press a). Similar large boulders of possible historic or prehistoric tsunami or hurricane origin have been reported from the coastal areas of Japan, Australia, Italy, the United States (Hawaii), Spain, and Portugal (*e.g.* Noji *et al.*, 1993; Mastronuzzi and Sanso, 2000; Nott, 2000, 2004; Noormets *et al.*, 2002, 2004; Whelan and Kelletat, 2005; Scheffers and Kelletat, 2005; Goff *et al.*, 2006).

The ability of a tsunami to transport boulders is closely related to the hydraulic force of the tsunami; thus, estimation of the hydraulic force and current velocity necessary to transport such boulders is easier than those of sandy tsunami deposits. For example, the minimum current velocity necessary to move a boulder can be estimated from the weight and shape of the boulder (*e.g.* Noormets *et al.*, 2004; Nott, 2004). However, numerical calculations are required to understand in detail the transport process and variations in the hydraulic force during boulder transport. In this section, we summarize a numerical model for boulder transport by tsunamis developed by Noji *et al.* (1993) and improved by Imamura *et al.* (2001, in press).

2. Numerical model

External forces, including those produced by the tsunami wave current, acting on the block are represented by hydraulic force F_m , bottom frictional force F_b , and gravitational force F_g along the slope direction (Fig. 6, Noji *et al.*, 1993).

$$\rho_s V \ddot{X} = F_m - F_b - F_g \quad \dots\dots(4.1)$$

where ρ_s is the density of the block, V is the volume of the block, and X is the position of the block in the x -direction. F_m represents the sum of the forces of drag and inertia (Noji *et al.*, 1993).

$$F_m = C_D \frac{1}{2} \rho_f A (U - \dot{X}) |U - \dot{X}| + C_M \rho_f V \ddot{U} - (C_M - 1) \rho_f V \ddot{X} \quad \dots\dots(4.2)$$

where U is the current velocity at the block position, A is the projected area of the block against the current, and C_D and C_M are coefficients of drag and mass, respectively. F_b and F_g are represented as follows.

$$F_b = \mu (\rho_s - \rho_f) V g \cos \theta \frac{\dot{X}}{|\dot{X}|} \quad \dots\dots(4.3)$$

$$F_g = (\rho_s - \rho_f) V g \sin \theta \quad \dots\dots(4.4)$$

where θ is the angle of the slope at the position of the block and μ is the coefficient of friction.

μ is constant when the block is transported by sliding, but it is also possible for the block to be transported by rolling or saltation, depending on the block shape and the hydraulic force of the tsunami (Fig. 6). Therefore, Imamura *et al.* (in press) empirically introduced a variable coefficient of friction $\mu(t)$ based on hydraulic experiments by assuming that the coefficient of friction decreases as a result of the reduction in ground contact time when the block is transported by rolling or saltation (Fig. 6).

$$\frac{\mu(t)}{\mu_0} = \frac{2.2}{\beta^2 + 2.2} \quad \dots\dots(4.5)$$

where μ_0 is the coefficient of dynamic friction during sliding and β is a parameter that indicates the degree of contact between the block and the floor (Imamura *et al.*, in press).

3. Application examples and problems

Figure 7 displays the experimental and numerical results of Imamura *et al.* (in press). In this experiment, the block was mainly transported by rolling or saltation (Imamura *et al.*, in press). The numerical results obtained by using a variable coefficient of friction, which assume transport of the block by rolling or saltation, were in good agreement with the experimental results. Numerical results obtained by using the variable coefficient of friction were

Fig. 6 Schematic diagram showing variation in transport mode of a block during hydraulic experiments

The transport mode is (a) sliding or (b) rolling and saltation, depending on the shape and weight of the block as well as on the current velocity. Modified from Imamura *et al.* (in press).

within the error span of the experimental results, although the final stop position of the block in the experimental results showed considerable scatter, especially when the water depth in the storage tank was 30 cm.

This model is applicable only to the movement of a single boulder. However, tsunamis usually transport numerous boulders at the same time (Kato and Kimura, 1983 ; Simkin and Fiske, 1983 ; Goto *et al.*, in press a, b). Therefore, the effect of collisions between boulders and the shielding effect of boulders should be considered in a future model.

V. Limitations of numerical models for sediment transport and needed improvements

Although some problems and difficulties remain and future improvement of models is required, models of sandy sediment and block transport by tsunamis generally reproduce ex-

Fig. 7 Comparison of experimental and numerical results of block transport

Vertical axes indicate (a) the maximum position reached by the block on the slope and (b) its final stop position (see Fig. 2-c). Horizontal axes indicate the initial depth of water in the water storage tank (cm), which determines the current velocity of the bore. Variable μ assumes that the block moves by sliding, rolling, and saltation. Numerical results using variable μ were in good agreement with the experimental results. Modified from Imamura *et al.* (in press).

perimental results. A sediment transport model for sandy sediments was applied to investigate the bathymetric changes at Kesennuma Bay caused by the 1960 Chilean tsunami (Takahashi *et al.*, 2000). It is important to note that the reproducibility of sediment transport is highly dependent on the reproducibility of current velocity of the tsunami in the numerical model, and the distribution pattern of areas of erosion and deposition were well reproduced by this model when the current velocity was well reproduced (Takahashi *et al.*, 2000). Using the model, it is possible to estimate areas of re-deposition and erosion in the bay and offshore. This kind of information could be useful for selecting drilling points for the investigation of historical and prehistoric tsunami deposits. In this way, the model is being scaled up to make it more applicable to real-scale sediment transport by tsunamis. However, because conditions before and after a tsunami are well known in only a few cases, applicability of the model to real-scale tsunami events has not yet been well verified.

Moreover, the sandy sediment transport model was intended to model sediment transport in the sea; though its applicability for modeling transport on land has not yet been verified.

Since the late 1980s, studies of tsunami deposits have become popular, and data on tsunami deposits as well as on tsunami wave height, inundation area, and topography have been collected by field surveys conducted just after tsunami events such as the 1992 Flores tsunami (Shi *et al.*, 1995), the 1993 Hokkaido Nansei-Oki tsunami (Nanayama and Shigeno, 2004, 2006), the 1998 Papua New Guinea tsunami (Gelfenbaum *et al.*, 2001), and the 2004 Indian Ocean tsunami (*e.g.* Moore *et al.*, 2006; Fujino *et al.*, in press; Goto *et al.*, in press b). In these cases, reliable field data on tsunamis and tsunami deposits were obtained, allowing us to investigate the sedimentary processes of tsunami deposits and to estimate hydraulic properties of tsunamis with field data, as constraints of the model in the future.

In contrast, estimation of hydraulic properties of tsunamis from past tsunami deposits in the geologic age by the model is usually difficult, because of fragmentary data and the many uncertainties involved. A sedimentological approach based on sedimentary structures and grain size (*e.g.* Fujiwara *et al.*, 2003) is probably more suitable for estimating tsunami hydraulic properties from tsunami deposits in the geologic age.

The block transport model was also applied to a tsunami boulder on Ishigaki Island, Japan, which was transported by the 1771 Meiwa-Yaeyama great tsunami (Imamura *et al.*, 2001, in press). The transport process and the distance that the boulder was transported was modeled numerically and the results were compared with descriptions in historical documents. However, the validity and applicability of the block transport model to real-scale tsunami events needs to be checked. For example, the 2004 Indian Ocean tsunami transported large reef boulders, up to 4 m long, landward at Pakarang Cape, Thailand. The field observations suggest that the first, eastward-directed tsunami wave struck the reef rocks, which were originally located on the shallow sea bottom near the reef edge (300 to 600 m offshore), thereby detached the boulders and transported them shoreward (Goto *et al.*, in press a). No boulders were found on land, indicating that the hydraulic force of the tsunami wave rapidly decreased on reaching the land. In this case, the original and stop positions of boulders are well known, as are the tsunami wave height, inundation area, and topography (Goto *et al.*, in press a). Therefore, the block transport model can be applied in this case to investigate the transport process of boulders.

It was reported that a number of tetrapods were transported inland by the 1983 Nihonkai-Chubu tsunami (Noji *et al.*, 1993). To clarify the transport process and assess future risk, a numerical model of transport of multiple blocks should be developed. As noted above, the present block transport model is applicable only to the movement of a single block. Effects of collisions among blocks and the shielding effect of blocks should be considered in the future model.

VI. Conclusion

In this paper, we described sediment transport models that have been developed for sandy sediments and a boulder. These models generally reproduce experimental results, although improvement is still required. When these models are improved to be able to treat mixed grain sizes and multiple numbers of blocks, we will be able to use them to estimate hydraulic prop-

erties of historical and prehistoric tsunamis more precisely from tsunami deposits and boulders. On the other hand, for further improvement of the models, it will be important to investigate thickness, grain size, sedimentary structures, and spatial distribution of tsunami deposits as well as the wave height and inundation area of tsunamis in the same area during field surveys after future tsunami events.

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津波による土砂・ブロック移動モデルの現状と課題

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〔要 旨〕

津波に伴う土砂移動現象は、海岸の地形変化や海洋・沿岸生態系の破壊などの重大な問題を引き起こす。本論では、海岸工学の分野で開発・改良されてきた津波による土砂、ブロック移動の数値モデルの現状と課題の整理を行い、堆積学的研究との連携について考察した。これらの数値モデルは、まだ課題は多いものの水槽実験結果を比較的良好に再現できており、実スケールの現象に適用できる段階に達しつつある。今後、混合粒径や複数岩

塊移動などに対応できるようモデルを拡張すれば、津波堆積物や津波石を用いて、過去に発生した津波の流体力や流速などの水理量をより定量的に評価できるようになると考えられる。また、土砂移動モデルを利用することで、海底での侵食・堆積量を評価することが可能であり、津波堆積物を発見することを目的とした海底掘削地点の選定にも役立つと考えられる。

キーワード：津波堆積物，津波石，土砂移動モデル，水槽実験

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