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LABORATORY EXPERIMENTS ON THE EFFECTS OF BACKWASH CURRENTS OF TSUNAMIS ON SAND TRANSPORT

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For estimating the effects of tsunami current on sand movements, a laboratory experiment was conducted. The distribution of sand on the slop after run-up and backwash currents was measured. Tsunami over land flow was modeled as a turbulent bore generated by quickly opening of a gate. Nine cases with different tsunami heights and sad diameters were conducted. On the land slope (1/20), the maximum length of sand deposit after the backwash is limited to the range close to the shoreline compared to that after the run-up. In particular, this tendency is remarkable for the case of high water depth in the tank (case H30D22-simulating a big tsunami): the length of sand deposit decreased by half by the backwash compared to the case after the run-up. Based on results, it concluded that the effect of back wash currents on the maximum sand deposit length varied with sand mobility index. Therefore the backwash effect should be considered for risk assessments from historical tsunami deposits.

Key Words **:** *Flume experiments, tank water level, sand diameter, sand mobility index, historical tsunami*

1. INTRODUCTION

Tsunamis can bring a large amount of sea sand into land and ports, and hindered the socioeconomic functions. On the other hand, paleo tsunami-sand deposits are useful to analyze the magnitude of historical tsunamis (cf. Sawai et al. 2009, Uchida et al. 2010, Goto et al. 2011). After the 2011 Tohoku-oki tsunami, the importance of the information of historical sand deposition increased (Goto et al. 2011) in Japan. There has been some research related to sand transport by tsunamis, such as field observations (Minoura et al. 1987,), numerical simulations (Goto and Imamura 2007), and laboratory experiments (Hasegawa et al. 2001, Sugawara et al. 2003, Harada et al. 2011, Takahashi et al. 2011). However there is insufficient knowledge of the process in details and the characteristics of sand transport. Because of difficulty of observation of sand transport due to a real tsunami, laboratory experiments can provide important information. Harada et al. (2011) reported that the distribution of tsunami deposit is influenced by the grain size. Hasegawa et al. (2001) pointed out that the effects of backwash current on sand distribution. However, the effects of sand diameter and tsunami heights on sand transport were not addressed in the previous research. From the qualitative point of view, flow velocity and flow depth of a tsunami, grain size and land slope have combined effects on the characteristics of sand transport.

The estimation of maximum inundation length of paleo tsunamis using the characteristics of sand deposits is important for disaster management in future. For understanding the sand deposition inland after a tsunami, we believe that an estimation of the effects of not only the tsunami run-up but also the backwash is needed. In this study, we conducted laboratory experiments to simulate the sand transport on land due to tsunamis. Particularly, the effects of backwash were investigated using a range of tsunami heights and grain sizes. In this paper, we describe mainly the experimental results for understanding the sand transport phenomenon itself due to tsunamis.

2. MATERIALS AND METHODS

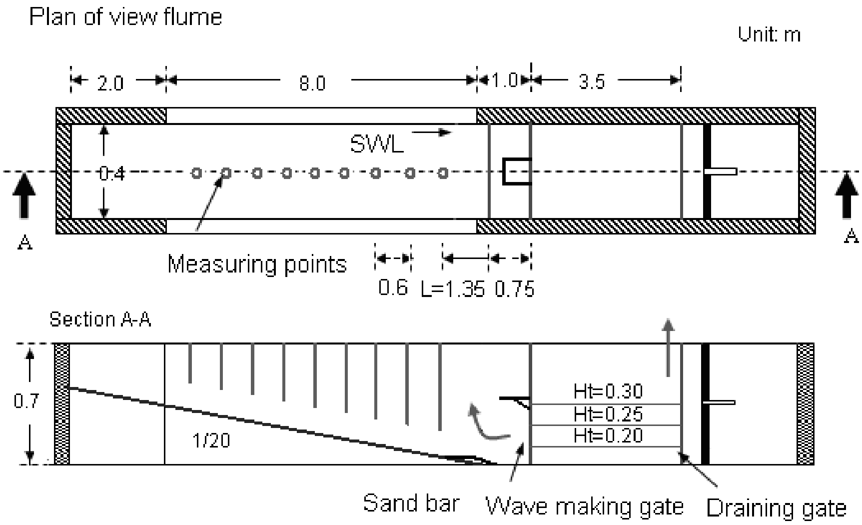

Fig.1 Experimental flume and measuring points

(1) Flume

Laboratory experiments were done in a flume (**Fig. 1** （15.5m long, 0.4m width, and 0.7m height） with a sand glued impermeable slope (1/20). Tsunami over land flow was modeled as a turbulent bore that was generated by rapid opening of a gate. The storage tank is 3.5m long including the wave-making and draining gates. To generate a wave, the wave-making gate was opened, and the draining gate was opened when the wave front stops on the slope (after arrive at the maximum distance) to have an undisturbed backwash. (**Fig. 1**). The source of sand was a sand bar at the shoreline. The sand bar is modeled by a layer of sand with the thickness of 0.05 m, and 1.0 m length (**Fig. 2**). For the preliminary experiments, two sand bar heights (H_b =0.03, 0.015m) were used.

(2) Measurements

The transported sand weight, flow velocity, and flow depth were measured. Ultrasonic displacement meters (KEYENCE Co.,) and propeller type flow meters (KENEK Co.,) were used to measure the flow depth and flow velocity respectively on the slope (**Fig. 1**). The distance between the measuring points is 0.6m. To measure the sand transport of bed and suspended, a wooden trap with cells each 1.4 x 0.2 x 0.2 m was made (**Fig. 2**). Similar equipments have been used in the previous studies (Hasegawa et al. 2001, Harada et al. 2011). The transported sand was measured for both the after run up and after backwash. The timing of trapping were decided based on velocity measurements of each cases. The positions of sand trapping covered inundation length. Each test was conducted three times for the accuracy. Data obtained above methods were represented as notations (**Table 1**). Maximum horizontal sand transported distance is defined by N.D. value (0.025g/cm^2)

Table 1 List of notations

Symbols	Definitions
S_{rt}	Total sand weight on slope after run-up
S_{bt}	total sand weight after backwash (remained after tsunami)
S_r	Sand weight of each point after run-up
S_b	Sand weight of each point after backwash
H_b	Initial sand bar height
H_t	Water level of tank
L	Horizontal distance from SWL to measuring point
LW	Maximum horizontal run-up distance from SWL
LS_r	Maximum horizontal sand transported distance from SWL after run-up
LS_b	Maximum horizontal sand deposit distance from SWL after backwash
$\angle LS$	Difference between L_{sr} and L_{sb}
V_{rm}	Maximum velocity of run-up of each measured point
V_{bm}	Maximum velocity of backwash of each measured point

Fig.2 Sand trap equipments

Table 2 Experimental conditions

Case No.	Ht*1 [cm]	Sand diameter (d50)[mm]
H30D11*2	30	0.11
H30D22	30	0.22
H30D32	30	0.32
H25D11	25	0.11
H25D22	25	0.22
H25D32	25	0.32
H20D11	20	0.11
H20D22	20	0.22
H20D32*2	20	0.32

*1 Tank water level
*2 Used for preliminary experiments

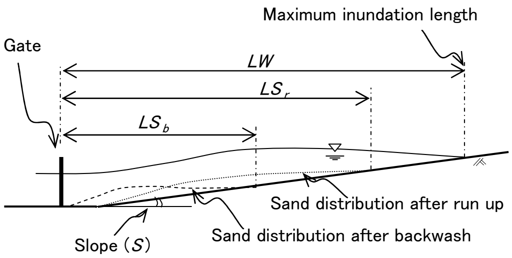

Fig. 3 Schematic figure of notations of experimental results

(3) Experimental conditions

Table 1 shows the experimental cases with the initial water depth of the tank (H_t) and sand diameter. Qualitatively, sand transport is controlled by three factors, tsunami height as the external force, sand size, and land slope. We focused on the two parameters, tsunami height and sand diameter.

(4) Preliminary experiment

Harada et al. (2011) reported that the location of sand source affects the characteristics of sand deposit. In our study, the boundary of the source is at the edge of the slope. For estimating the effect of initial sand amount of the source on experimental results, preliminary experiments were conducted. As for representative conditions, two cases: the large tsunami height with small sand diameter (H30D11), and low tsunami height with large sand diameter (H20D32) were selected (**Table 2**). The initial sand volumes were changed by changing the sand bar height (H_b=0.05, 0.03, 0.015m).

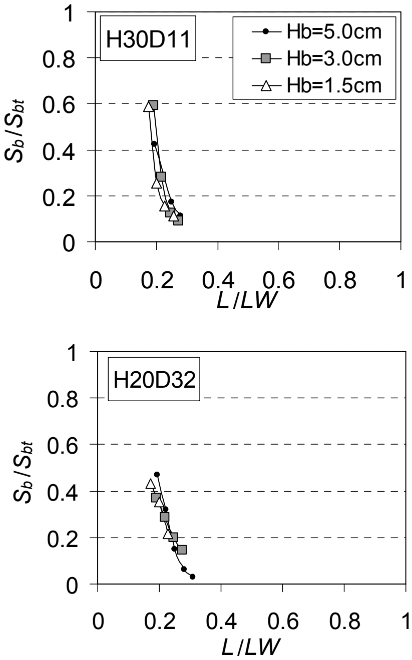

Fig. 4 The effects of initial sand bar height on sand distribution

3. RESULTS AND DISCUSSIONS

(1) Effects of initial sand bar height

Fig. 4 shows the results of the preliminary experiments. With different heights of the sand bar the sand distribution pattern on the slope after backwash did not change greatly. The effects of the initial sand bar height on the sand distribution after the backwash were relatively small. Furthermore, although it is not shown, change in the run-up length by the different sand bar heights was less than 5%. Therefore, the effect of sand bar height can be neglected to discuss the results of this study.

(2) Current

The tsunami currents play an important role in the sand transport and deposit on ground.

Fig. 5 shows the maximum velocity of both run-up (V_{rm}) and backwash (V_{bm}) of each point. Except for the low water level case, the maximum

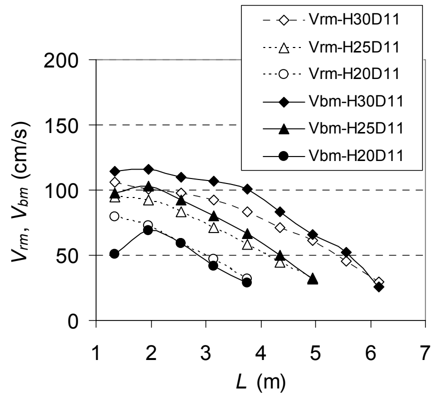

Fig. 5 Maximum velocity of each case

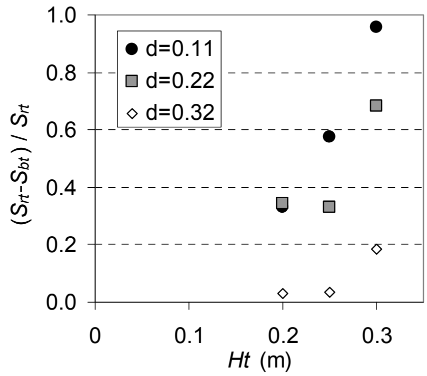

Fig. 6 Relationship between tank water level and ratio of total sand volume removed by backwash to total sand volume on slope after run-up

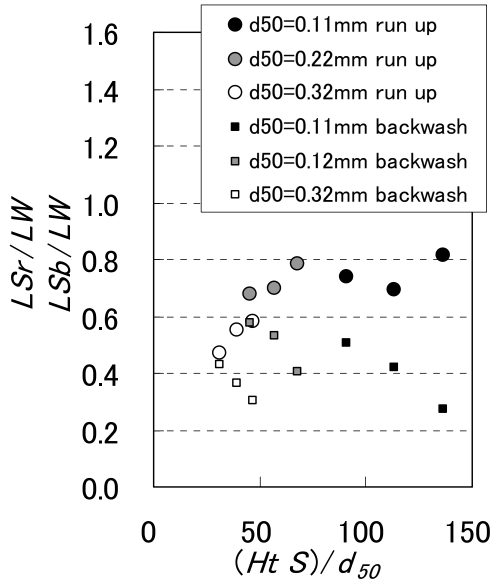

Fig. 7 Relationship between index of sand transport force by tsunami current (*Ht S/d50*) and maximum sand transport distance

velocity of each point of the backwash currents was greater than that of the run-up current.

(3) Total sand weight transport

Fig. 6 shows the ratio of the total sand removed by backwash to the total sand weight on the slope after the run-up.

The Total sand volume removed by backwash current was as high as 90% (H30D11) in the small sand cases (d50=0.11mm). On the other hand, for the large sand and small water level case (H20D11), the effects of backwash currents were very small. Therefore, to estimate total sand deposit weight after tsunami, the effects of backwash current is important depending on tsunami height and sand diameter.

(4) Maximum sand transported distance

Figs. 7 and **8** show the maximum sand transported distance for each case. We named $Ht\ S/d_{50}$ as sand mobility index. We used only one land slope condition (1/20) for the experiment. Thus, $Ht\ S/d_{50}$ varies with only tank water level and sand diameter.

As shown in **Fig. 7**, the ratio of maximum sand distance after run up (LS_r) to maximum run up distance (LW) increased with an increase of Ht S/d50 whereas Ht S/d50 was greater than 70, the relationship was not clear. On the other hand, this distance ratio (LS_r/LW) decreased by one-half after backwash. The range of this ratio varied between 0.3 and 0.6. In the cases of backwash currents, the effect of $Ht\ S/d_{50}$ on the sand transport distance ratio was ambiguous.

Fig. 8 shows the relationship between $Ht\ S/d_{50}$ and the ratio of maximum horizontal sand transport distance after backwash to that of after run up (LS_b/LS_r). With an increase in $Ht\ S/d_{50}$, LS_b/LS_r decreased. The effect of backwash currents on sand transport was significant with an increase in sand mobility index ($Ht\ S/d_{50}$). In particular, when $Ht\ S/d_{50}$ was 140, sand transport distance decreased more than 60% during backwash. In our experimental results, the maximum velocity of backwash currents is same or greater than that of run up currents (**Fig. 6**). According to the characteristics of velocity, the effects of backwash current not only on the total transported sand weight (**Fig. 6**) but also on the maximum deposit distance (**Fig. 7**) were significant. This effect becomes prominent in large $Ht\ S/d_{50}$ cases.

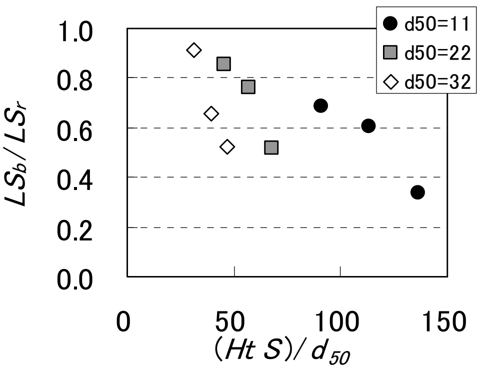

Fig. 8 The relationship between $Ht\ S/d_{50}$ and decrease rate of sand deposit distance by backwash current

4. CONCLUSIONS

We conducted a laboratory experiment for estimating the effects of tsunami currents on sand movement.

The maximum velocity of back wash currents was same or greater than that of run up currents in all cases.

The ratio of total sand weight removed by back wash currents reached over 90 % as maximum. The ratio of sand deposit length to inundation distance was from 0.6 to 0.8 after run up. On the other hand, back wash currents make this length short. This effect was maximum at large Ht S/d50 case.

Research on the effects of backwash currents on sand transport distance with different land slope conditions is needed to analysis historical tsunamis from sand deposits in future.

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