Several boulder transport formulations are available, which are based on the transport distance of coastal boulders to provide estimates of the hydraulic processes from past storm wave and tsunami events. However, experiments in a small wave tank generally underestimate the transport distance of boulders due to the limited size of the input waves and scaling issues, thus additional validation based on large-scale laboratory tests is necessary to be conducted. We conducted laboratory experiment of boulder transport in a super-large wave flume of 205 m length. In this study, we used 0.35–0.53 kg of rectangular blocks for our experiments. The observed transport distance of the rectangular blocks that made of cement and limestone for our experiments was 45 m in maximum. We also observed block velocity that its transport mode was changed sliding to rolling or saltation. The scale and flow velocity in our experiment is far higher than in other previous studies. We obtained high quality data of block velocity and transport modes for the validation of the formulations and the development of the new formulations. This contributes to research of coastal boulders formed by tsunami or storm wave.

**Key words**: coastal boulder, wave tank experiment, tsunami, storm wave

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**Introduction**

The location of coastal boulders transported by extreme waves such as tsunamis or storm waves can be used for a simple estimate of wave size by reproducing sedimentation process of boulder using boulder transport formulations. Several boulder transport formulations have been proposed in the past and they have been used for mainly two purposes: a) to estimate the wave size of a historical wave event; and b) to differentiate between boulders transported by tsunamis and storm waves (e.g., Nott, 1997, 2003; Goto et al., 2009; Nandasena et al., 2011; Watanabe et al., 2016, 2019).

Nott (1997, 2003) developed an inverse model for coastal boulders that can estimate the flow velocity and wave height necessary to overturn a boulder from tsunami or storm waves. Nandasena et al. (2011) improved the equation of Nott (2003) and proposed a model, which can estimate the minimum flow velocity to move boulders through sliding, rolling, or saltation motion. These models can provide a simple estimate of tsunami or storm wave processes solely based on the size and density of the boulder. However, in order to better estimate the size of a wave, a forward model of boulder transport should be used that computes the inundation together with the boulder motion (Imamura et al., 2008). Imamura et al. (2008) proposed a formulation, which...
can reproduce the boulder transport distance by introducing an empirical coefficient of friction based on hydraulic experiments with cubic shaped blocks. Nandasena et al. (2013) also developed a boulder transport model, which solves for motion of boulders such as sliding, rolling, and saltation. Zainali and Weiss (2015) conducted a three-dimensional rectangular block transport simulation based on the SPH method and revealed that the transport distance of a block of 1.55 g/cm³ density can be reproduced reasonably well.

These models have been used for estimation of boulder transport processes in nature. Imamura et al. (2008) and Goto et al. (2010a) conducted boulder transport simulations for the 1771 Meiwatsu tsunami at Ishigaki Island, Japan, and validated their proposed model with field data. The model was further applied to boulders in Thailand that were transported by the 2004 Indian Ocean tsunami. Kennedy et al. (2016) improved the boulder transport equation proposed by Imamura et al. (2008) by including a lift force component and used the improved model to reconstruct the movements of coastal boulders from extreme storm waves during the 2013 Typhoon Haiyan.

Validation of numerical models with experimental data is important because data from field surveys are limited (Kotake et al., 2008). In the forward boulder transport equation, some empirical parameters such as drag or friction coefficients were determined by laboratory experiments under limited conditions (e.g., Imamura et al., 2008); in particular, tests were conducted only in small wave tanks of about ~20 m length (e.g., Petroff et al., 2001; Okada et al., 2007; Imamura et al., 2008; Nandasena et al., 2013; Liu et al., 2014; Bressan et al., 2018). However, experiments in a small wave tank have scaling issues such as underestimated size of the input waves which induce the underestimated or overestimated transport distance of boulders, thus additional validation based on large-scale laboratory tests is necessary.

In this study, we presented the experiment data for the validation of boulder transport model. We firstly conducted a boulder transport experiment in a huge wave tank of 205 m length. The scale of experiment in this study is 10 to 20 times larger than in the tanks that were used in the previous studies. Therefore, the validation of the model can be conducted under the wave conditions much closer to real-scale tsunami waves than in any previous experiments.

**Method**

The wave tank experiment was conducted at the Central Research Institute of Electric Power Industry, CRIEPI, Japan (Fig. 1). The wave tank is 205 m long (onshore slope; 50 m, bathymetry section; 155 m), 3.4 m wide, and 6 m deep with a maximum operational water depth of 4.5 m. A solitary wave was generated by a wave maker located at left boundary of the wave tank. The water depth at the wave maker was 4.5 m. The section from the wave maker at −115 m to 0 m is a transitional regime for amplification of the

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**Fig. 1** Schematic diagrams of the wave tank. The profile of the wave tank, the point (meter) at which the flow velocity and water level was measured, initial position of a block is also shown. The location of high-speed camera and video camera are also shown.
input wave. From −96 m to −60 m, −60 m to −40 m, and −40 m to 0 m, the gradient of the slope was 1:10, 1:215, and 1:50 respectively (Fig. 1). The shoreline of the wave tank is at 0 m (Fig. 1). From −40 m to 50 m, the channel of the tank forms a constriction. The experimental conditions were determined according to the Froude similarity law with a scale of 1/25. Setting the wave height to 10 cm and 25 cm, we altered the flow velocity of the bore respectively.

The wave tank was separated into two channels from the −40 m point toward inland (Fig. 1). One side was a movable bed for sediment transport experiments, and the other side was a fixed bed for the experiment of bore propagation. Yoshii et al. (2017, 2018) used both sides of the flume for his experiment. In this study, we used only the side with the fixed bed. From the shoreline toward inland, there is a slope of 1:100 that a Manning’s friction is 0.015 m⁻¹/³/s. Due to this gentle slope, hardly any backwash was generated. When, the bore reached the 50 m mark, water discharged to the outside of the tank. We measured water level and flow velocity of the bore at 106 m, −96 m, −60 m, −39.5 m, 0 m, and 10 m with a sampling rate of 100 Hz without blocks (see Appendix 1). The water levels and flow are respectively measured using HAT2-60, 80 and SFT-200, 500 that are products of TOKYO KEISOKU CO., LTD.

We reviewed density and shape of coastal boulders as summarized in Table 2. In this study, the typical boulder density and dimensions are used. We used blocks that made of cement (bricks) and limestone, with densities of 2.1 g/cm³ and 2.5 g/cm³, respectively. We determined the dimensions and density of blocks for our experiment according to actual density and dimensions of boulders obtained by field survey (Table 2). We used the blocks of 5×6×7 cm and 4×6×7 cm in our experiment considering 1/25 Froude scaling.

Before our experiment, the block was set on the shoreline (Fig. 1). Imamura et al. (2008) suggested that the direction of the long axis of the rectangular blocks against the current before the experiment affected to the transport distance of the block. The transport distance becomes large when the direction of the long axis of the block is perpendicular to the current. In this study, we set the direction of the long axis of the block perpendicular to the flow direction at the shoreline before the experiment in order to observe the transport process of the block when the bore transports the block over a long distance.

The total numbers of the experiment are 8 cases (Table 1). In cases 1−4, the blocks made of cement were used. The initial wave height of the solitary wave at the site of wave maker is 10 cm in cases 1 and 2 and 25 cm in cases 3 and 4, respectively. While, in cases 5−8, the blocks made of limestone were used. The initial wave height was 10 cm in cases 5 and 6 and 25 cm in cases 7 and 8, respectively.

All experiments were repeated 3 times for each case to rule out experimental errors. All cases were recorded using video cameras (29 fps) in order to observe the block movements from all sites of the wave tank (Fig. 1). Before the experiment, we filmed the position of the block locations in the wave tank for calibration purposes of the blocks in the movie.

Then, we estimated the block position, block velocity, and the time series of the block velocity from the elapsed time and calibrated position of the blocks estimated by video analysis. In order to derive velocity of the block transported by the bore, we measured the time that the block was passed with an interval of 1 m from the shoreline. Based on the time that the block moves over 1 m distance, the block velocity was derived. When whitecap covered over the block, the time that the block was passed cannot be measured. Thus, we derived the block velocity at the location that the block can be seen in the filmed video.

We painted three different colors on the block faces in

| Table 1 | Type, dimension, density and weight of the blocks, initial input wave height, and observed transport process of these blocks. In cases 1, 3, and 4, it is likely that the blocks were transported as saltation. |
|---------|------------------|--------------|----------------|-----------------|----------------|
| Type of block | Size of block (cm) | Density of block (g/cm³) | weight of blocks (kg) | Initial input wave height (m) | Transport process |
| Case 1 | brick | 5×6×7 | 2.1 | 0.44 | 0.10 | sliding, rolling (saltation) |
| Case 2 | brick | 4×6×7 | 2.1 | 0.35 | 0.10 | sliding |
| Case 3 | brick | 5×6×7 | 2.1 | 0.44 | 0.25 | sliding, rolling (saltation) |
| Case 4 | brick | 4×6×7 | 2.1 | 0.35 | 0.25 | sliding, rolling (saltation) |
| Case 5 | limestone | 5×6×7 | 2.5 | 0.53 | 0.10 | sliding |
| Case 6 | limestone | 4×6×7 | 2.5 | 0.42 | 0.10 | sliding |
| Case 7 | limestone | 5×6×7 | 2.5 | 0.53 | 0.25 | sliding |
| Case 8 | limestone | 4×6×7 | 2.5 | 0.42 | 0.25 | sliding |
order to clarify their transport behavior. However, from the video camera alone, rolling or saltation motion of blocks could not be inferred because of the low camera resolution and the fact that the two types of transport processes look very much alike. Thus, in order to observe the transitions between rolling and saltation, we estimated the direction of the long axis of the blocks by observing the painted colors of block surfaces based on video analysis. We also used a high-speed camera (500 fps) to observe the initiation of the block transport at the shoreline (Fig. 1).

**Results**

1. Inundation of the bore

With 10 cm of input wave height, 25 cm of water level was measured at -40 m point (Fig. 2a). Then, the bore runs up the slope, reaches a maximum inundation level, and then flows back towards the upstream side as backwash. In this

| Source of data      | Density (g/cm³) | Long axis (m) | Short axis (m) | Height (m) |
|---------------------|-----------------|---------------|----------------|------------|
| Nott (1997)         | 2.7             | -             | -              | -          |
| Nott (2004)         | 2.1             | -             | -              | -          |
| Whelan and Kellett (2005) | 2.5           | -             | -              | -          |
| Goto et al. (2009)  | 2.01            | 1.0           | 0.71           | 0.62       |
| Paris et al. (2009) | 1.1-1.4         | -             | -              | -          |
| Paris et al. (2009) | 1.8-2.4         | -             | -              | -          |
| Barbuno et al. (2010) | 2.3           | -             | -              | -          |
| Goto et al. (2010b) | 1.5-2.3 (average 1.9) | 1.0 | 0.97 | 0.69 |
| Goto et al. (2010c) | 2.1             | 1.0           | 0.85           | 0.62       |
| Goto et al. (2010c) | 1.7 or 2.1      | 1.0           | 0.85           | 0.62       |
| Switzer and Burston (2010) | 2.4           | -             | -              | -          |
| Goto et al. (2011)  | 2.1             | -             | -              | -          |
| Goto et al. (2011)  | 2.25            | -             | -              | -          |
| Hall (2011)         | 3.04            | -             | -              | -          |
| Medina et al. (2011)| 2.0-2.5         | 1.0           | -              | 0.64       |
| Medina et al. (2011)| 2.0-2.5         | 1.0           | -              | 0.75       |
| Medina et al. (2011)| 2.0-2.5         | 1.0           | -              | 0.45       |
| Medina et al. (2011)| 2.0-2.5         | 1.0           | -              | 0.34       |
| Buckley et al. (2012)| 2.4           | 1.0           | 0.68           | 0.38       |
| Buckley et al. (2012)| 2.4           | 0.70          | 0.53           | 0.24       |
| Cox et al. (2012)   | 2.6             | -             | -              | -          |
| Engel and May (2012)| 1.44-2.59       | -             | -              | -          |
| Salzmann and Green (2012) | 2.1         | 2.6           | 1.7            | 0.32       |
| Salzmann and Green (2012) | 2.1         | 2.2           | 1.6            | 0.32       |
| Salzmann and Green (2012) | 2.1         | 1.9           | 1.3            | 0.38       |
| Vacchi et al. (2012)| 2.6             | -             | -              | -          |
| Nandasena et al. (2013)| 2.37-2.81   | -             | -              | -          |
| May et al. (2015)   | 2.01-2.7        | -             | -              | -          |
| Terry et al. (2016) | 1.8             | 2.0           | 1.6            | 1.2        |
| Terry et al. (2016) | 1.8             | 1.1           | 0.82           | 0.59       |
case, the measured maximum water level and flow velocity at the shoreline was 0.32 m and 2.6 m/s, respectively (Fig. 2c).

On the other hand, a 25 cm high input wave generates 46 cm of water level was measured at ~40 m point (Fig. 2b). The generated bore reaches up to the 90 m mark of the wave tank. The bore overtopped the discharge level and some water was flowing out of the wave tank. The remaining water returned to the main channel as backwash. The measured maximum water level and velocity at the shoreline in this case was 0.55 m and 3.6 m/s, respectively (Fig. 2d).

2. Block Motion
(1) Transport distance of blocks
When the bore front hits the block, the block starts moving up the slope and finally stops at a particular location in accordance with the decreasing flow velocity. In cases 2 and 4, the blocks were in the opposite direction toward the shoreline by the drawdown. We summarized case number versus final stop position and maximum position of the block in Fig. 3. There is some variation of the observed final stop and maximum position of the blocks. As some studies mentioned, the distance of the block can vary even under repeated flow conditions for the same block (e.g., Petroff et al., 2001; Imamura et al., 2008). The measured maximum velocity over land in previous experiments was 1.3–1.5 m/s, but the maximum velocity in our experiment was 3.6 m/s (Fig. 2d).

(2) Transport mode of blocks
As shown in the images of the high-speed camera, the blocks initially slid due to the impact of the tongue of the

Fig. 2 The measured water level and flow velocity at ~40 m point when initial water level is (a) 10 cm and (b) 25 cm. The measured water level and flow velocity at 0 m point when initial water level is (c) 10 cm and (d) 25 cm are also shown.
Fig. 3  The measured maximum inland position of blocks and (b) the measured final stop position of blocks versus case number.

Fig. 4  The photograph of the block at initial position (0 m) by using high-speed camera in case 3 when (a) the bore didn’t reach the block, (b) the bore reached the block, (c) the bore covered the block, and (d) the bore transported the block. The time that the bore reached to the initial position of the block is 0 s. The location of high-speed camera is shown in Fig. 1.
bore front (Fig. 4). Shortly after and a little later the bore fully reached to the block (Fig. 4). Once the bore covered the block, it was moved toward onshore with the bore. This transport process was the same in all cases. In the cases 3 and 4, the block was transported by rolling motion (Fig. 5) when the velocity of the block was more than 1.1 m/s, while the block was transported by sliding when the velocity of the block was less than 1.1 m/s (Fig. 6a). However, in cases 1 and 2, the block was transported by sliding even if its velocity reached 2.5 m/s. In cases 5 to 8, the block was transported by sliding even though its velocity reached 3.7 m/s (Fig. 6b). This is due to the stronger density of the limestone compared to the cement brick; i.e. a larger flow velocity is required to rotate the limestone blocks.

The blocks finally come to a stop depending on the reduction of flow velocity, which aligns their orientation perpendicular to the direction of the current. In cases 2 and 4, the block was moved by the backwash because its density is low and its dimension is small. Another reason is that the maximum position reached in case 2 is seaward compared to cases 3 and 4 (Fig. 3). In cases 3 and 4, the block was respectively stopped at 41.7 m and 42.7 m. The input bore was released out of the wave tank at 50 m (Fig. 1), so that the strong backwash was not generated at maximum position reached in case 3. The maximum position reached in case 2 is seaward compared to case 3, so that strong backwash was generated, then the block was moved again due to backwash. In case 4, the block was moved by backwash when it was stopped seaward (Fig. 3).

We also derived time series of block velocities based on video analyses (Fig. 7). In all cases, the block velocity reached up to approximate 1.3 s after that block started to move. After that, the maximum block velocity was recorded at 1.3–2.2 s. Then, block velocity had been decreased in accordance with the increasing elapsed time in all cases. However, in case that block density is large (cases 5 to 8), block velocity was quickly decreased compared to cases that block density is low (cases 1 to 4).

We also derived the angular velocity of the blocks and its direction around the along-axis from the current when the block was transported by rolling in cases 3 and 4 (Fig. 8). The direction of the block’s along-axis greatly fluctuated when the block velocity increased and when the direction pointed close to 0 (towards the shoreline) and the block velocity become small.

Discussion

The scale of our experiment is much close to actual phenomena, thus our experiment data is valid for the validation of numerical modelling. We also could observe the transport mode and velocity of the block on gently slope setting compared to the other studies (e.g., Nandasena et al., 2013; Imamura et al., 2008).

In case 4, the block was transported as sliding when block started to move (Fig. 6a), which is consistent with the description of Liu et al. (2014) who also conducted the laboratory test of block movements due to tsunami. This is because water depth is smaller than block height when the bore reached the initial block position, so that hydraulic force only acts on the lower part of the block and its hydraulic force is small due to small water depth. Thus, the bore cannot rotate the block so that the block was transported as sliding. After that, water depth at the position of the block become higher than block height and current velocity became high, then the bore rotated the block.

In cases 3 and 4, when block velocity was more than 2.8 m/s, angular velocity was not increased but the direction of long axis was greatly fluctuated (Fig. 8). This means that acceleration of rotation was stopped and the block was jumping. Thus, in this time, it is possible that blocks were transported as saltation. On the other hand, in cases 7 and 8,
Fig. 6  Measured boulder velocity and its transport process at each location in (a) case 1–4 and (b) case 5–8. Features are labeled as follows, ○: rolling, ×: sliding.

Fig. 7  Time series of measured block velocity in all cases.

Fig. 8  (a) Measured angular velocity of blocks and (b) the direction of blocks in case 3 and case 4.
the block was transported as sliding even if the block velocity reached to 3.7 m/s (Fig. 6b) because the block density is high in these cases. Thus, block density is important for determining transport mode of blocks as described in Imamura et al. (2008).

We conducted laboratory experiment of boulder transport using wave tank with 205 m long to reduce scaling issues. The obtained experimental data contributes to development or validation of boulder transport formulations for research of coastal boulders formed by tsunami or storm wave.

Conclusions

We conducted laboratory experiments of rectangular block transport processes in a super-large wave flume of 205 m length to get experimental data for the validation of boulder transport formulations. In our experiment, we obtained a detailed dataset of the transport modes, transport distance, and the velocity of the blocks on gentle slopes from bores with a maximum velocity of 3.5 m/s at the shoreline. The scale of our experiment is close to actual phenomena, so that our experiment data can be used for validation or update of boulder transport formulation for sedimentological research of coastal boulders formed by tsunami or storm wave.

Appendix: Experiment data

The measured water level and flow velocity and block velocity at each point was uploaded in the following URL https://data.mendeley.com/datasets/xw45fnmxb/draft?a=9728a7d7-55d8-4311-8601-a253ba1484ee

Acknowledgments

This research was financially supported by a Grant-in-Aid for JSPS fellows (project number 16J01953).

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超大型水槽を活用した巨礫移動実験

渡部真史・吉井匠・Volker Roeber・後藤和久・今村文彦, 2020, 堆積学研究, Vol. 79, No. 1, 15−25

Watanabe, M., Yoshii, T., Volker Roeber, Goto, K. and Imamura, F.: Data of boulder transport experiment in super-large wave flume
Jour. Sed. Soc. Japan, Vol. 79, No. 1, 15−25

巨礫移動モデルを活用すれば、沿岸巨礫を運搬した先史時代の古津波/波浪の規模推定を実施できる可能性がある。巨礫移動モデルの開発や精度検証に活用されてきた従来の巨礫移動実験データは最大でも数十メートル程度の小規模な水槽を用いて、計測されてきた。しかし、巨礫移動モデルの精度検証には、スケーリングによる歪みが小さい大型実験装置を活用した実験データが非常に有効である。

本研究では、全長205mの超大型水路を用いた津波による巨礫移動実験を行って、実環境に近い条件下で巨礫の移動距離、移動速度、運搬過程を計測した。本実験では0.35−0.53kgの直方体ブロックが最長45m運搬され、運搬プロセスが滑動から転動に転移する直方体ブロックの移動速度を計測できた。本実験の縮尺は小さく、巨礫移動計算の精度検証に適した実験データであるため、沿岸巨礫研究に役立つことが期待される。