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EXPERIMENTS ON THE ENTRAINMENT OF SEDIMENT BY TURBIDITY CURRENTS WITH THE USE OF SUBMARINE SEDIMENT

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ABSTRACT

Laboratory experiments on the entrainment of sediment due to turbidity currents were performed with the use of submarine sediment sampled in a deep ocean floor. In order to obtain the relationship between the entrainment rate of sediment and the shear velocity, we measured the velocity and the suspended sediment concentration by the use of a closed conduit in which water and sediment are circulated by a pump. We found from the experimental results that the entrainment rate of sediment is proportional to the shear velocity divided by the settling velocity of sediment.

Keywords: turbidity current, entrainment rate, submarine sediment, deep ocean floor

1. INTRODUCTION

Due to the recent development of surveying technology, a variety of characteristic topographies such as submarine canyons and fans have been found on the ocean floor. The main agent that causes the formation of submarine canyons and fans is considered to be a turbidity current (Imran, Parker and Harff, 2002; Izumi, 2004; Kostic and Parker, 2006). The turbidity current is density flow with high concentration of suspended sediment entrained from the ocean floor. When a water body including a large amount of sediment has higher density than the surrounding water, flow is driven by the gravity force in the downstream direction. Turbidity currents can be self-accelerated by entraining sediment from the ocean floor. Because of this self-accelerating nature, turbidity currents occasionally travel unexpectedly long distance, and are potentially highly destructive. It has been reported that turbidity currents caused damage to submarine cables, and triggered tsunamis. Thus, to understand detailed behaviour of turbidity currents is of great importance from an engineering point of view as well as a scientific point of view. In order to shed further light on the generation and the development processes of turbidity currents, information as to how much sediment is entrained by flow is essential. Though a number of experiments on the entrainment of sediment into flowing water have been performed so far (Garcia and Parker, 1993, for example), no experiments have been done with the use of submarine sediment to the authors' knowledge.

In this study, we performed laboratory experiments with the use of submarine sediment sampled in a deep ocean floor in order to elucidate the entrainment of sediment by turbidity currents. In the experiments, the velocity and the suspended sediment concentration were measured to obtain the entrainment rate as a function of the bed shear velocity.

2. SUBMARINE SEDIMENT

Sediment Sampling

The sediment used in this study was sampled with the use of a remote controlled submersible vessel "Hyper Dolphin" and its mother vessel "Natsushima" on an 800 m deep ocean floor off the coast of Tokachi in Hokkaido on June 7, 2006. The sampling point is shown as D in Figure 1, located inside a submarine canyon. If the submarine canyon was formed by turbidity currents, the bed in the submarine canyon is expected to be composed of sediment transported by turbidity currents.

The submarine sediment was sampled with the use of manipulators of Hyper Dolphin as shown in Figure 2. The sediment on the ocean floor was scooped into a container, which was pull up to the mother vessel Natsushima. The color of the sampled sediment was blackish brown as shown in Figure 3, and was found rather cohesive when touched.

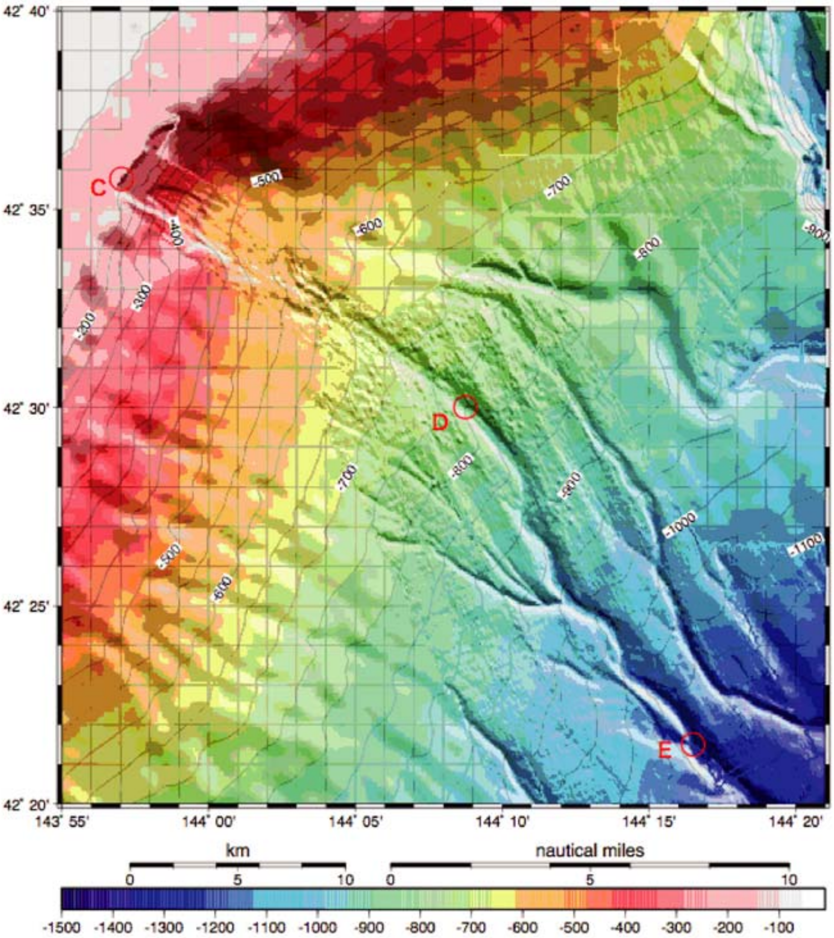

Figure 1 The bathymetry image of the ocean floor off the coast of Tokachi in Hokkaido. The red circle "D" in the middle of the figure is the sampling point of submarine sediment.

Figure 3 The sampling of submarine sediment with the use of manipulators of Hyper Dolphin. The scene is not clearly seen because of suspension of sediment.

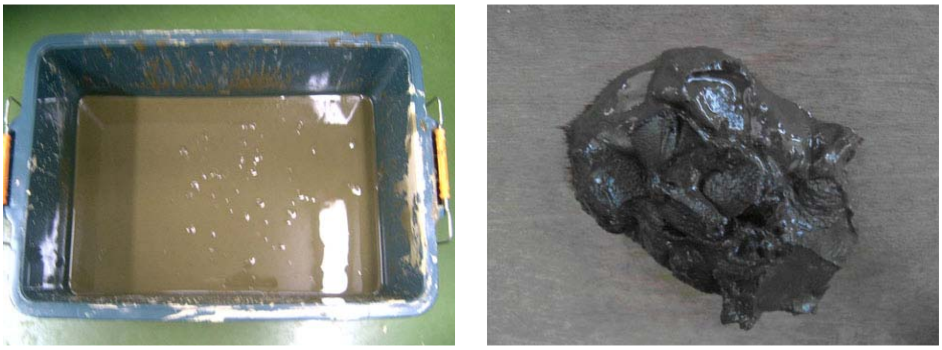

Figure 3 The sediment sampled on the ocean floor.

Sediment Size Analysis

The sediment size of the submarine sediment was analyzed with Microtrac Particle Analyzer (Nikkiso). The particle size distribution obtained in the analysis is shown in Figure 4. The maximum sediment size is 0.30 mm, the median sediment size is 0.024 mm, and D_{84}/D_{16} is 7.3. The sediment is found to be poorly sorted. The settling velocity corresponding to the median sediment size is 0.42 mm/s (Dietrich, 1982).

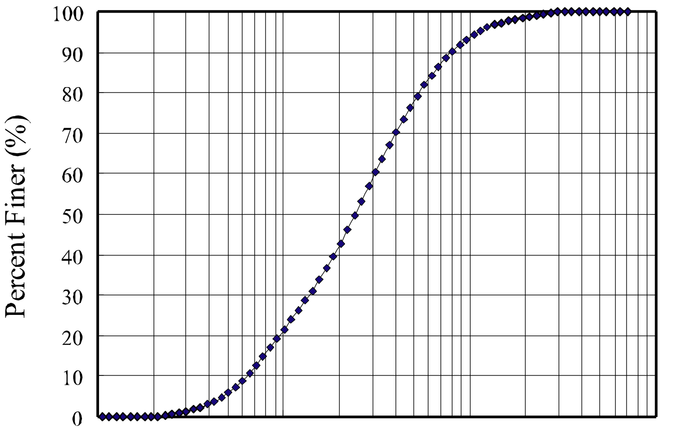

Figure 4 The sediment size distribution of the submarine sediment.

4. EXPERIMENTS

A series of laboratory experiments were performed to measure the velocity and the suspended sediment concentration. The channel used in the experiments is a 15 cm high, 8 cm wide, 200 cm long duct as shown in Figure 5. The amount of the submarine sediment sampled on the ocean floor is limited, so that a closed circulated channel was used in experiments in order for sediment not to be washed away, and to achieve sufficient bed shear stresses. Water is circulated in the channel with a pump, and the flow velocity can be controlled by a valve from 0 to 40 cm/s. There are five small holes on the upper wall of the channel for measurement of velocity and suspended sediment concentration.

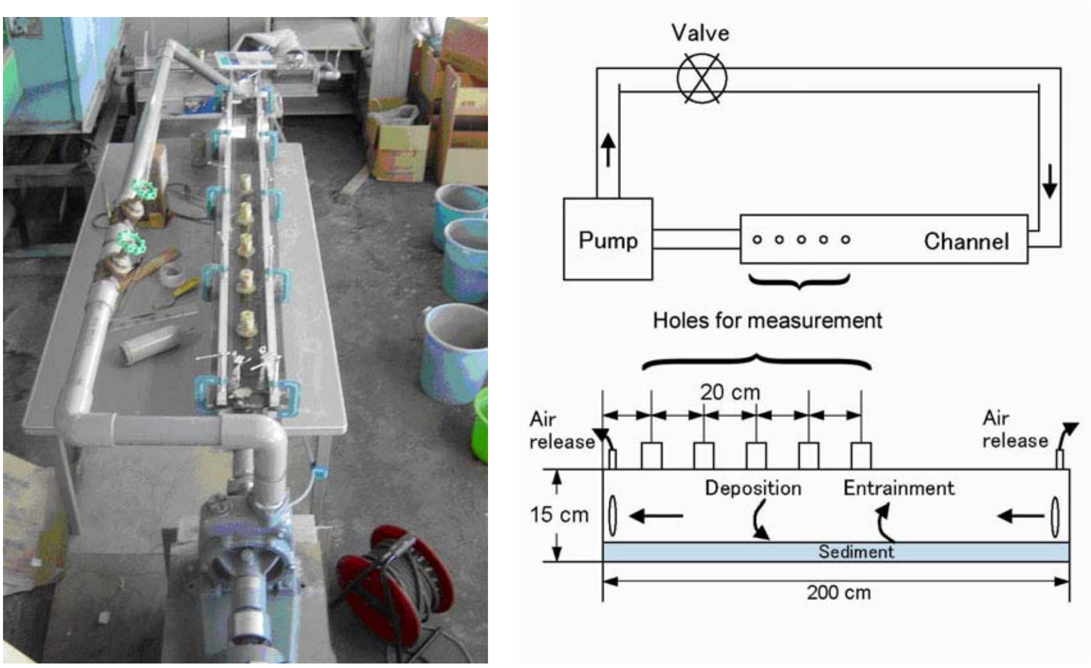

Figure 5 Experimental apparatus.

Velocity Distribution

In order to find if fully-developed turbulent flow is achieved in the channel, the streamwise velocity was measured without sediment. The measurement was performed by installing an electromagnetic velocimeter from the holes made at the upper wall of the channel. The velocity distribution in the vertical direction is shown in Figure 6. The locations A, B, C, D and E correspond to holes located 1, 1.2, 1.4, 1.6, and 1.8 m downstream of the channel inlet, respectively. As seen in the figure, the flow is fully-developed at all the points except for the location A. Therefore, we decided to conduct the measurement at the location from B to E.

Suspended Sediment Concentrations

The suspended sediment concentration was measured by sampling turbid water flowing in the channel. Sampling tubes were inserted into the channel through holes. Approximately 30 to 50 cm^3 of turbid water was taken into graduators through tubes. The whole weight of the graduator with turbid water was measured with a precision scale. After drying the graduator in a dry oven, the weight of the graduator with only sediment was measured with the precision scale. The concentration of suspended sediment was calculated from the weights of the graduator before and after drying.

The suspended sediment concentration in the vertical direction is shown in Figure 7. The concentration distribution is found to be almost uniform in the vertical direction. Thus, we assumed that the concentration in the channel can be represented by the concentration at the center of the channel.

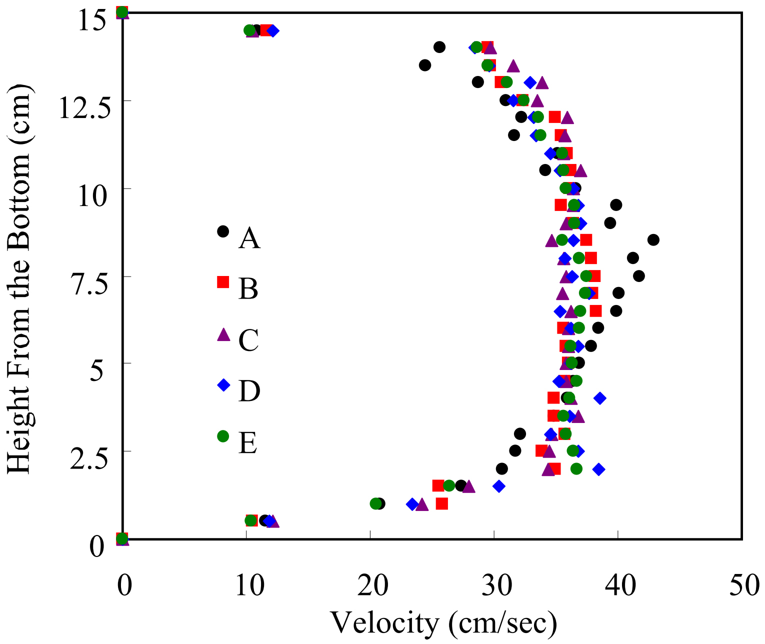

Figure 6 Velocity distributions in the channel without sediment

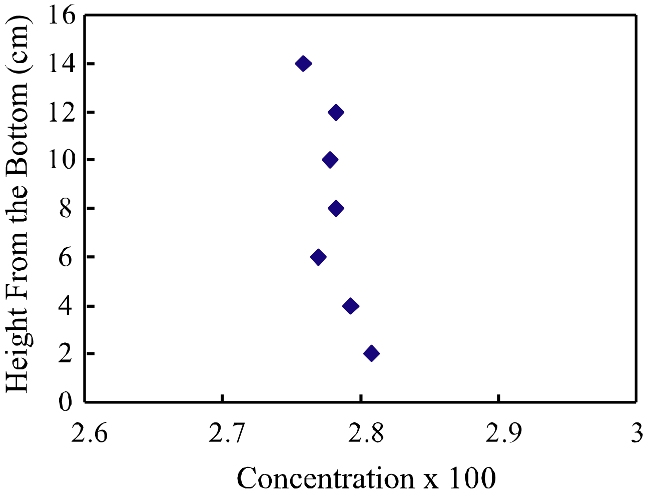

Figure 7 Suspended sediment concentrations.

The Entrainment Rate as a Function of the Shear Velocity

In an equilibrium state, the deposition rate is balanced with the entrainment rate $\widetilde{E}_s$. Because the deposition rate is expressed as the suspended sediment concentration near the bottom c_b multiplied by the settling velocity of sediment w_s, the entrainment rate normalized by the settling velocity E_s is written in the form

$$E_s = \frac{\widetilde{E}_s}{w_s} = c_b \tag{1}$$

In the present experiments, the suspended sediment concentration is almost uniform in the depth direction. Therefore, the uniform suspended sediment concentration is taken as the normalized entrainment rate E_s.

The relationship between the normalize entrainment rate E_s and the shear velocity normalized by the settling velocity u^*/w_s is shown in Figure 8. The symbols denote experimental results, and the solid line corresponds to

$$E_s = 2.1 \times 10^{-3} \left(\frac{u^*}{w_s} \right) \tag{2}$$

The normalized entrainment rate is proportional to the normalized shear velocity. While fresh water is used in Runs 1 and 3, saline water is used in Runs 5 and 6, in which the salinities are 1 % and 3.5 %, respectively. In the case of saline water, it was observed that sediment was flocculated, and tended to be deposited onto the bed. It is found from Figure 8, however, that the entrainment rates are not affected by salinity. This is because flocs formed in water are easily broken into sediment by flow.

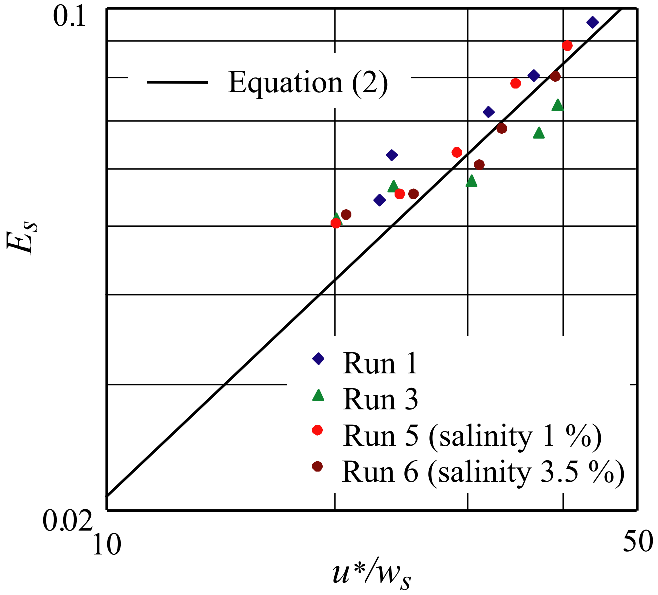

Figure 8 The relationship between E_s and u^*/w_s.

5. CONCLUSION

A series of experiments were performed to obtain the relationship between the entrainment of sediment due to turbidity currents with the use of submarine sediment sampled on an 800 m deep ocean floor off the coast of Tokachi in Hokkaido. The entrainment rate E_s is found to be proportional to the shear velocity divided by the settling velocity u^*/w_s. The effect of the flocculation due to saline water was found to be insignificant for the entrainment rate of sediment.

ACKNOWLEDGMENTS

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