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PENETRATION OF SPILLED FUEL OIL C AND ITS INFLUENCE ON THE SEAWATER INFILTRATION INTO SANDY BEACH SEDIMENTS

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Abstract : The purpose of this study is to clarify the effects of wave and tidal actions on the penetration of spilled oil into sandy beach and to evaluate the influence of the penetrated oil on seawater infiltration by wave action in sandy beach and its ecological implications. Infiltration process of seawater and fuel oil C into sediments and the effect of the penetrated oil on seawater were evaluated by use of a sandy beach simulator.

Seawater was infiltrated by both wave action and tidal fluctuation into the sandy beach sediments. However, spilled fuel oil C penetrated into the sediments only by tidal fluctuation and not by wave action. The first tide is the most important for the penetration of stranded oil. Penetration depth is significantly affected by stranded oil volume. The infiltration of seawater was reduced by the increase in the penetrated oil volume and blocked about 91% when oil volume was 4 L/m^2. The reduction of seawater infiltration in flooded condition will result in the decrease in the supplies of oxygen, nutrients and organic matters necessary for the survival of benthic organisms in sandy beach.

Key Words : fuel oil C, model sandy beach, seawater infiltration, wave and tidal action

INTRODUCTION

On March 1989, the tanker Exxon Valdez grounded in Prince William Sound, Alaska, subsequently spilling 37,000 tones of Alaska North Slope crude oil.[1] In the incident of the tanker Nakhodka, its body was broken into two parts and more than 6,000 tones fuel oil C was spilled out into the Japan sea, on January 1997.[2] These huge oil spill incidents caused a significant deterioration of ocean and shoreline environment. About a half of 37,000 tones of spilled oil from the Exxon Valdez incident was stranded on the 2,000 km shorelines of the Prince William Sound.[1] The penetration depth of the stranded oil into thesediments is one of the most significant factors in biodegradation processes and/or physical dispersion.[3] However, the behavior of stranded oil into the sediments has not been fully understood.

Volatile fraction, 30~40% of crude oil that has acute toxicity to benthic communities is generally evaporated, before the spilled oil stranded on the coastal zone. Therefore, it is

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likely that the stranded oil blocks interstitial spaces of sediments, reduces water infiltration, and results in the decrease in oxygen, nutrients and other food supply to benthic communities.

On the other hand, wave action and/or tidal fluctuation in sandy beach ecosystem is known to play an important role in seawater infiltration process during which dissolved and particulate organic matter are transported and then mineralized by the interstitial fauna.[4)]

The purpose of this study is to clarify the effects of wave and tidal actions on the penetration of spilled oil into sandy beach and to evaluate the influence of the penetrated oil on seawater infiltration by wave action in sandy beach and its ecological implications. We made visualization of infiltration process of seawater and fuel oil C into sediments by use of a sandy beach simulator controlled wave and tide and evaluated the effect of the penetrated oil on seawater infiltration into the sediments.

EXPERIMENTAL METHODS

Model Sandy Beach

Sandy beach simulator was composed of a model sandy beach, wave maker, tidal controlling device, temperature controlling system, and computer controlling system (Figure 1). The simulator made of FRP (fiberglass reinforced plastic) has a window to observe infiltration behavior of oil and seawater and has a size of 1 m long, 0.5 m wide and 1 m high, which is filled with 0.14 m^3 transparent glass beads (diameter=1.0 mm, density=2.5 g/cm^3) to visualize the infiltration of fuel oil C and seawater as sandy beach model sediment. The sediments was profiled with a slope of around 10/100 (length and height ratio). Synthetic seawater was made to have a salinity of 32 ± 2 psu using tap water and a commercial salt (MARINE-TEC. Co., Sealife). Water temperature was controlled at 15 ± 1℃.

The simulator was based on the design of surf zone to simulate the infiltration of seawater and spilled oil by breaking wave in surf zone. Breaking wave height (Hb) and wave periods used in this study were 30 mm and 0.8 sec, respectively, considering low energy sandy beach. Breaking wave generated by the wave maker is classified as collapsing type.[5)] Tidal fluctuation was made by gravimetrical flow of water by the difference in hydraulic head resulting from rising and falling of the tidal controlling tank. Tidal velocity was determined as 0.009 cm/s based on the mean tidal range of 2 m for 6 hours in Hiroshima Bay, Japan. The water level in the simulator was fluctuated in the tidal range of 20 cm as shown in Figure 2.

Seawater Tracer and Oil

0.02 mol/L of potassium permanganate

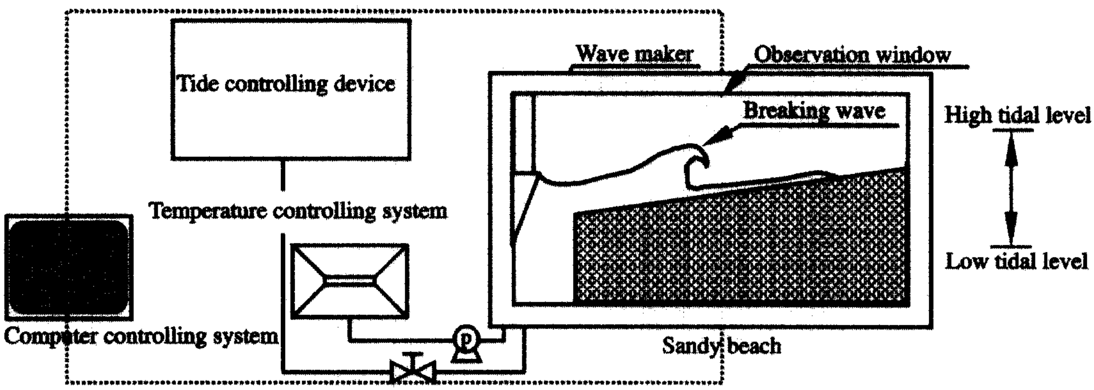

Figure 1. Schematic diagram of experimental set-up.

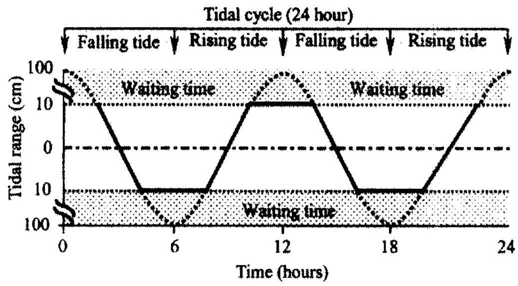

Figure 2. Tidal fluctuation. The dash line shows tidal range in present study.

($KMnO_4$) was used as a tracer of seawater. 25 mL of the tracer of was injected on the upper layer of the glass beads by pipette. The viscosity, density and pour point of fuel oil C used in this study were 162 (mm^2/s at 50℃), 0.95 (g/cm^3 at 15℃) and -10℃, respectively. The amount of fuel oil C applied over the surface of the sediment was 1 L/m^2. To evaluate the effect of oil volume on seawater infiltration, 4 L/m^2 of fuel oil C was also applied based on previous studies on oil spills.[6~10)]

Effects of Wave and Tidal Actions on Penetrations of Seawater and Oil

Three experimental conditions, wave only (for 5 minutes), tide only (for 6 hours) and wave and tide condition (for 6 hours), were adopted to study the effects of physical factor on oil penetration into the sediments. In this study, infiltration behavior of seawater was also tested to compare with that of fuel oil C. In the case of the wave only, waves were applied for 5 minutes without any tidal movement. In the case of the tide only, the water level was changed by tidal fluctuation with the range of 20 cm without any wave. Both wave and tidal fluctuation with the range of 20 cm were applied for a tidal cycle of the wave and tide in combination.

Penetration of Stranded Fuel Oil C

Long-term experiment for 15 tidal cycles was carried out to study vertical movement of the stranded oil into the sediments. To investigate the effects of stranded oil volume on oil penetration, the penetration depth was recorded under different conditions (1 L/m^2 and 4 L/m^2). The penetration depth of stranded fuel oil C over the tidal cycle was monitored under the condition of wave and tide in combination.

Effects of Penetrated Fuel Oil C on Seawater Infiltration

To evaluate the effects of the penetrated oil on seawater infiltration, infiltration velocity was estimated under different conditions of stranded oil volume (1 L/m^2 and 4 L/m^2) and number of tidal cycles (first tidal cycle and 4th tidal cycles).

Under the oiled and unoiled conditions, time-course of change in seawater infiltration was recorded by a video camera (SONY Co. Digital Handy Camera DCR-VX1000). Then, the infiltration area of seawater into the oiled sandy beach was obtained by analyzing image taken by the video camera using software (Image-Pro Plus, Version 4.5). Infiltration volume of seawater into the sediments by wave action was calculated by using the results of visual experiments. Total infiltrated volume V_w ($m^3/m^2/d$) of seawater by wave action was calculated by Eq. (1).

$$V_w = \frac{A_i \cdot W \cdot P \cdot t \cdot N}{W \cdot L} \quad (1)$$

where A_i=infiltration area of seawater by time-course of change (m^2/s), W=width of flat bed (m), P=porosity, t=elapsed time to move the water level to the length of 1 m (s), N=number of tidal excursion per day (4 times d^{-1}), L=length of flat bed (m), and infiltration area of seawater was given by time-course of change in infiltration area.

RESULTS AND DISCUSSION

Effects of Wave and Tidal Actions on Penetrations of Seawater and Oil

Figure 3 shows the infiltration of seawater and fuel oil C by wave action. Periodic wave

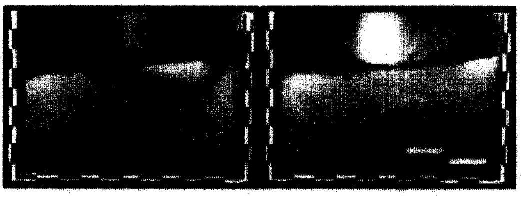

Figure 3. Infiltration behaviors of seawater (left) and fuel oil C (right) by wave action after 90 sec.

caused infiltration of seawater from the wave breaking run-up point with radial direction, that is, in a semi-circular form into the sediments. Waves were a driving force to transport seawater into the sediments. However, different from seawater, fuel oil C did not penetrate into the sediments in spite of the wave action. The infiltration depth of seawater was 18 cm after 300 sec of wave action, but fuel oil C did not penetrate after 300 sec. The difference in the infiltration behaviors between seawater and fuel oil C was probably caused by difference in specific gravity and viscosity.

Figure 4 shows infiltration of seawater and fuel oil C by the tidal fluctuation. Over the falling tide, seawater infiltrated into the sediments and subsequently flowed down to the low seawater level. The fuel oil C, however, penetrated into the sediments with much slower velocity than seawater. The infiltration depths of seawater and fuel oil C after a tide were approximately 10 cm and 2.5 cm, respectively. It is clear that fuel oil C penetrates into the sediments by tidal fluctuation and not by wave action.

Figure 5 shows infiltration of seawater and fuel oil C by wave and tidal action. Seawater infiltrated into the sediments by wave action and more deeply moved by tidal fluctuation. On the other hand, fuel oil C showed almost the same penetration as the tidal fluctuation without wave. The infiltration depths of seawater and fuel oil C after 1,500 sec were about 18 cm and 2.5 cm, respectively. It is clear that infiltration into the sediments showed significant difference between seawater and fuel oil C. The seawater infiltrated by both

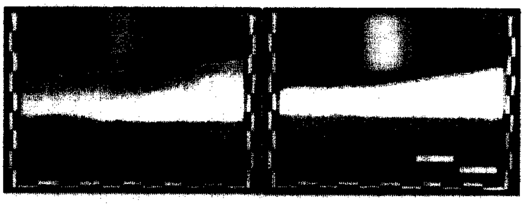

Figure 4. Infiltration behaviors of seawater (left) and fuel oil C (right) by tidal fluctuation after 1,500 sec.

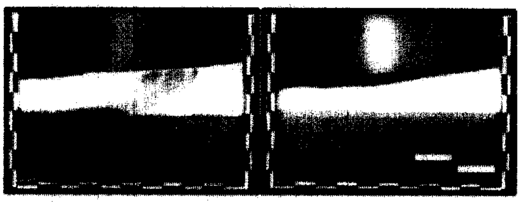

Figure 5. Infiltration behaviors of seawater (left) and fuel oil C (right) by wave and tidal actions after 1,500 sec.

wave action and tidal fluctuation into the sediments in sandy beach. However, fuel oil C penetrated into the sediments in sandy beach only by tidal fluctuation and not by wave action.

Penetration of Stranded Fuel Oil C

Figure 6 shows the changes in the penetration depth of fuel oil C by wave and tidal action. The penetration depth of the stranded fuel oil C after the first tidal cycle was 1.7 cm. It increased with tidal cycles and leveled off after 10 tidal cycles at around 2.4 cm. The penetration depth of stranded oil was slightly increased from the 1st tidal cycle to 7th tidal cycle, however, the depth was not significantly changed after 7th tidal cycle. It must be pointed out that the first tide has the most important effect on the penetration of stranded oil.

Figure 7 shows the effect of the volume of stranded oil on penetration depth of fuel oil C. The penetration depths of fuel oil C for a tide were 2.5 cm and 6 cm for the volume of 1 L/m^2 and 4 L/m^2, respectively. The depth and the rate of penetration depended on the viscosity and volume of the oil and the porosity

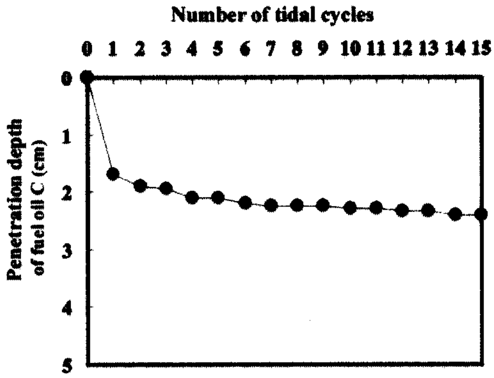

Figure 6. Penetration of stranded fuel oil C by tidal cycles.

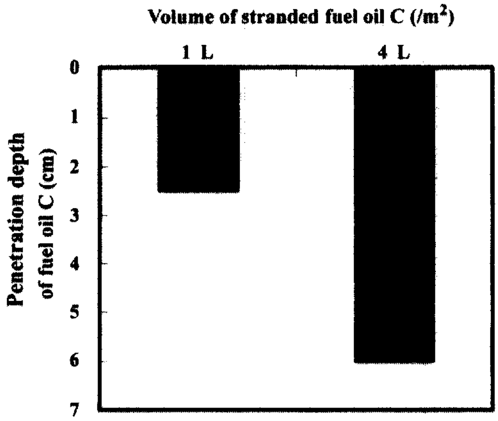

Figure 7. Penetration depth of fuel oil C as affected by the stranded volume.

of the sediment.[3] It is clear that the penetration depth is significantly affected by the volume of stranded oil.

Effect of Penetrated Fuel Oil C on Seawater Infiltration

Figure 8 shows volume of seawater infiltrated (expressed by area) at the 1st and 4th tidal cycle into the sediments penetrated by fuel oil C. The amount of fuel oil C applied was 1 L/m^2. After the first tidal cycle, the volume of seawater infiltration decreased to the half of that under the condition without of oil. The volume of seawater through the penetrated oil layer in the 4th tidal cycle was far smaller than that of the first tidal cycle. The difference in seawater infiltration between the first tidal

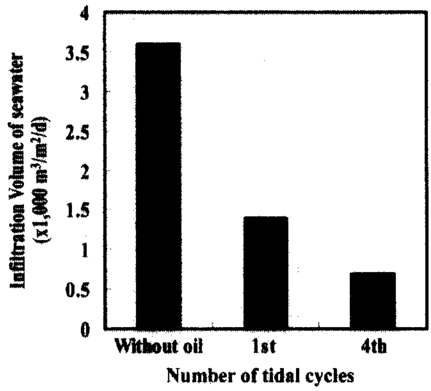

Figure 8. Effect of penetrated fuel oil C on seawater infiltration as affected by the tidal cycle.

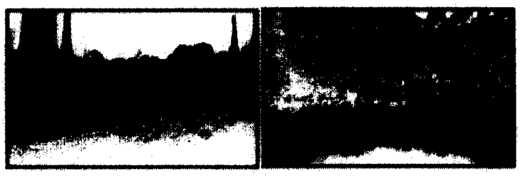

Figure 9. Sediment surface in 1st tidal cycle (left) and 4th tidal cycle (right).

cycle and the 4th tidal cycle was due to re-floatation of penetrated fuel oil C.

We observed that about 20% of the penetrated oil was re-floated from the interstitial spaces like a "balloon" during the rising tide of the first tidal cycle as shown in Figure 9. However, the re-floated oil was penetrated again into the interstitial spaces of sediment during the next falling tide. The amount of re-floatation gradually decreased in tidal cycles, and no re-floatation was observed in the 4th tidal cycle.

Figure 10 shows the effect of the amount of penetrated oil on seawater infiltration. The amount of seawater infiltration was reduced by half when 1 L/m^2 of oil was applied, while the infiltration was almost stopped when 4 L/m^2 of oil was loaded.

We studied the effect of penetrated oil on the seawater infiltration by visualization using the model sandy beach. From these results, it is clear that the amount of seawater infiltration was significantly reduced by the penetrated oil

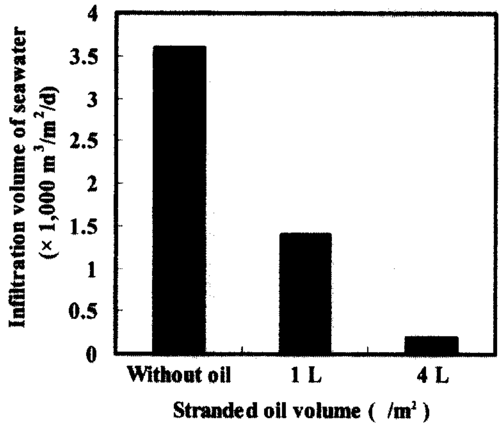

Figure 10. Effect of the amount of penetrated fuel oil C on seawater infiltration.

in sandy beach. Especially, a large amount oil penetration (4 L/m^2) blocked about 91% of seawater infiltration into sandy beach sediments. Therefore, the penetrated oil will have significant influence on benthic organisms by blocking seawater infiltration under flooded condition and decrease supplies of oxygen, nutrients and organic matters into the sandy beach.

CONCLUSIONS

We made visualization of infiltration process of seawater and fuel oil C into sediments by use of a sandy beach simulator controlled wave and tide and evaluated the effect of the penetrated oil on seawater infiltration into the sediments.

The major findings of this study are summarized as follows.

Seawater was infiltrated by both wave action and tidal fluctuation into the sediments in sandy beach. However, spilled fuel oil C penetrated into the sediments only by tidal fluctuation and not by wave action. Infiltration processes into the sediments showed significant difference between seawater and fuel oil C. The first tide was the most important for the penetration of stranded oil. Penetration depth was significantly affected by stranded oil volume. The infiltration of seawater was reduced by the increase in the penetrated oil volume and blocked about 91% when oil volume was 4 L/m^2. The reduction of seawater infiltration in flooded condition will decrease in oxygen supply, nutrients, and organic matters necessary for the survival of benthic organisms in sandy beach.

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