SPREADING OF OIL UNDER ICE COVERS: EFFECTS OF BOTTOM ROUGHNESS OF ICE

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ABSTRACT
Results of experimental and numerical studies on oil spreading under ice covers are presented. A focus is made on the effects of ice bottom roughness. Numerical computation was made for field data measured at the Sea of Okhotsk. Both experimental and computed results showed that oil area under ice decreases with the increase of the roughness height of ice bottom.

INTRODUCTION
Developments of petroleum resources are underway in several ice-covered waters in the world. One such region is offshore Sakhalin in the Sea of Okhotsk. Commercial production of oil had already commenced in one of oil fields there in 1999. Annual production reached 1.4 million metric tons in 2000 (Sabirova, 2000) and a part of produced oil was carried to Japan in 2001 (Nemoto, 2001). More productions from other oil fields are planned in the near future. Sakhalin is located just to the north of Japan. This geographical condition makes the region a favorable source of energy supply to Japan, which lacks domestic energy resources and is striving to widen its potential sources. The condition, however, also makes Japan vulnerable to risks of environmental pollution that always accompany development and transportation of oil. Special attention is paid to oil spills under existence of ice on which knowledge remains quite limited, especially in Japan.

A research project was initiated in 2000 to study the behaviour and recovery of oil in icy waters. Five organizations, including Hokkaido University, Iwate University, Civil Engineering Research Institute of Hokkaido (CERI), North Japan Port Consultants Co., Ltd. and National Maritime Research Institute (NMRI), are involved in the project. One objective of the project is to elucidate the behaviour of oil spilled in ice-covered waters. NMRI and Iwate University are working on this problem by way of experimental and numerical methods, respectively. This paper presents results of their work on oil

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spreading under continuous ice covers. A focus is placed on the effects of ice bottom roughness on the oil spreading.

**METHODS OF STUDY**

Brief descriptions are given below on the methods of experimental and numerical studies on oil spreading under ice covers. For more details readers can refer Izumiyama et al. (2002) and Sakai et al. (2002), respectively.

Oil spill tests were performed at an ice model basin of NMRI. Figure 1 is a schematic drawing of the test set-up. Oil was released from a nozzle placed beneath the ice cover. Oil spread along the ice-water interface forming a thin layer. Tow VTR cameras recorded the spreading motion of the oil from above and beneath it. Oil was spilled at a given constant discharge rate for a given duration and then stopped.

A numerical calculation code was developed at Iwate University for oil spreading under a continuous ice cover. In the code motions of oil are described by the long wave theory. Computation is made in a staggered difference scheme for space and a leap-frog difference scheme for time. The ice bottom profile is given as the boundary conditions to the oil motion. The code can make computation for any arbitrary ice bottom profiles.

**EXPERIMENTAL RESULTS**

In total six tests were made under ice sheets with bottom roughness. Ice bottom profiling was made for four ice sheets. Figure 2 shows a picture of the oil under the ice. Analysis was made on pictures like Figure 2 to calculate oil area. Figure 3 is an example of plots of measured oil area as a function of elapsed time. In this case oil was spilled for a period of 0 to 1800 sec. Oil area increases in proportion to time for the period. There is a slight increase of oil area even after the stopping of the oil discharge.

Figure 1: Experimental Set-up.

Figure 2: A picture of oil spreading under an ice cover with bottom roughness.
A comparison was made between oil area under an ice sheet with bottom roughness and that under a level ice sheet. A theory derived by Izumiyama et al. (1998) was used to calculate oil area under a level ice sheet. The theory agrees very well with the results of the laboratory experiments reported in Izumiyama, et al. (2002). Figure 4 shows a comparison of the measured oil area, $A_R$, and the oil area calculated by the theory, $A_L$, at the time of oil stoppage (at 1800 seconds in Figure 2 for instance). The figure clearly shows that bottom roughness makes oil area significantly smaller than that under a level ice sheet.

A concept of a significant wave height is commonly used to evaluate the height of random water waves. The significant wave height, $H_s$, is calculated from a power spectral density (PSD) function, $P(k)$, of the wave profile as

$$H_s = 4\sqrt{m_0},$$  \hspace{1cm} (1)

where

$$m_0 = \int P(k)dk$$  \hspace{1cm} (2)

and $k$ is wave number. In this study a “significant roughness” was calculated from measured profile data using equations (1) and (2) to quantify the ice bottom roughness.

Figure 5 shows the ratio of oil areas under ice bottom roughness and level ice sheet, $A_K/A_L$, as a function of significant roughness. As is seen in the figure, the significant roughness in this study is relatively small. Still there is a clear trend of oil area decreasing with increase of significant roughness.
OIL SPILL CALCULATION FOR FIELD CONDITIONS

As a part of the project, CERI is conducting field measurements of ice bottom profile in the Sea of Okhotsk (Sakikawa, 2002 and Yamamoto, 2002). Numerical computation was made for the field data to estimate oil area under actual field conditions. Before the computation, validation of the present numerical model was checked using experimental results. Figure 6 shows correlation of the calculated and measured oil areas at the oil stoppage. Computations were made for four cases of level ice and two with ice bottom roughness, for which two-dimensional profile data was available for computation. Although there is a slight discrepancy, the computation results agree well with experimental ones.

Conditions and results of the computation for field data are summarized in Table 1. For the computation four segments of data, in which speed and direction of ice movement were practically constant, were selected from the field data. PSD and significant roughness were calculated for each segment data. Virtual ice bottom data were created for computation based on PSD of each segment. In the calculation randomized phases were used. It was assumed that a 40,000 m³ of oil, which is roughly the same amount spilled from the Exxon Valdez, spilled from a point source under an ice cover at a constant discharge rate of 1.0 m³/sec.

Table 1: Conditions and Results of Numerical Calculation.

<table>
<thead>
<tr>
<th>Case</th>
<th>01</th>
<th>02</th>
<th>03</th>
<th>04</th>
</tr>
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<tbody>
<tr>
<td>Total Volume of Oil, m³</td>
<td>40,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discharge Rate of Oil, m³/s</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significant Roughness, m</td>
<td>0.237</td>
<td>0.786</td>
<td>0.596</td>
<td>0.985</td>
</tr>
<tr>
<td>Oil Area, at 11.11 hours, km²</td>
<td>0.336</td>
<td>0.166</td>
<td>0.205</td>
<td>0.146</td>
</tr>
<tr>
<td>Oil Area, at 16.67 hours, km²</td>
<td>0.463</td>
<td>0.195</td>
<td>0.248</td>
<td>0.174</td>
</tr>
</tbody>
</table>

Figure 7 shows calculated images of oil areas for the ice bottom of (a) a relatively small roughness and (b) a large roughness. Figure 8(a) shows oil area for the four calculation cases as a function of elapsed time after the spill started. Oil was spilling for the time period of 0 to 40,000 seconds (11.11 hours), which is indicated by a dashed line in the figure, and the calculation was continued up to 60,000 seconds (16.67 hours). Figure 8(b) shows oil areas at the oil stoppage and at the end of calculation. The figure shows the effects of ice bottom roughness on oil area as is seen in experimental results in Figure 5.
DISCUSSION

Results of this study, both the experimental and numerical ones, clearly show that the oil area under an ice cover decreases with an increase of roughness height on the ice bottom. This is due to pooling of oil in pockets of undulating relief on the bottom of the ice cover. Kovacs made field measurements of ice bottom profile using impulse radar systems (Kovacs, 1977; Kovacs et al., 1981). He calculated volume of oil entrapped under ice cover assuming that the oil is pooled in pockets above the mean depth of bottom profile. If his calculation results are applied to the oil volume assumed in the present computation, it would be an oil area of 1.48 km² for first-year sea ice and 0.137 km² for multi-year ice (see data in Kovacs, 1977) and 4.00 to 0.70 km² (see data in Kovacs, 1981). These values are comparable to the present computation results, but seem somewhat larger. This may be due to dynamic movement of sea ice at the Sea of Okhotsk that creates more deformed ice.

In this study a significant roughness was used to evaluate the ice bottom roughness. Equations (1) and (2) are generally used in coastal engineering, because it is known that they give a good approximation to the average of the highest one-third of the waves. It should be noted, however, this is valid only when the probabilistic distribution of the wave height follows a Rayleigh distribution, which is supported by field measurements for fully developed water waves. For the distribution of the roughness height of ice bottom, there are some field measurements. Wadhams measured ice draft from a
submarine in the Arctic ocean and reported that the tail of its probability density function gave a good fit to a negative exponential distribution (Wadhams, 2000). Data measured by CERI in the Sea of Okhotsk also gave a distribution that looks like a negative exponential distribution (Yamamoto, 2002). However, no theory has been established on this issue. In this paper the significant roughness was used as an index to the magnitude of ice bottom roughness. Physical interpretation of this parameter needs more study and accumulation of field data on ice draft.

SUMMARY
This paper presented results of experimental and numerical studies on oil spreading under ice covers. Special focus is placed on the effects of ice bottom roughness. Significant roughness was used to quantify the size of roughness. Experimental results showed that oil area decreases with increase of significant roughness. Computation was made for field conditions measured at the Sea of Okhotsk. Computation results also showed decrease of oil area with increase of significant roughness. Computed oil area was comparable to that calculated from studies by Kovacs, but seemed somewhat larger.

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REFERENCES