NUMERICAL SIMULATION OF CURRENT-INDUCED DEFORMATION AND MOVEMENT OF THE OIL SLICK UNDER THE ICE COVER

Yoshitaka Matsuzaki¹, Toshinori Ogasawara¹, Shigeki Sakai¹
Koh Izumiyama² and Shigeo Kanada²

¹Iwate University, Morioka, Japan
²National Maritime Research Institute, Tokyo, Japan

ABSTRACT
The full operation of crude oil and natural gas offshore the island of Sakhalin has just started. If oil spills accidentally, a coastal area along the Sea of Okhotsk in Hokkaido, Japan might suffer serious environmental damage from the spilled oil since there is a strong southward ocean current in the Sea of Okhotsk. The sea surface in this area is covered by ice in winter, therefore it would not be possible to find the spilled oil. In this study, a numerical simulation model is developed to predict the deformation and movement of an oil slick induced by a current under the ice cover. The validity of the model is examined by the comparisons with experimental results. And also, the effects of the current velocity, the amount of the spilled oil and the properties of the oil on the speed of the oil slick movement are discussed based on the numerical results.

KEY WORDS: Oil; Ice; Current; Deformation and Movement; Numerical Simulation

INTRODUCTION
The full operation of crude oil and natural gas offshore the island of Sakhalin has just started. If oil spills accidentally, the coast area along the Sea of Okhotsk in Hokkaido, Japan might suffer serious environmental damage from the spilled oil since there is a strong southward ocean current in the Sea of Okhotsk as shown in Figure 1 (Wakatsuchi, 2001). The sea surface in this area is covered by ice in winter. If oil spills, the spilled oil spreads under the ice and drifts by currents to the coast area along the Sea of Okhotsk in Hokkaido. Therefore, it is necessary to examine the influences of currents on the oil slick under the ice.
It is very hard to find the spilled oil under the ice, so a numerical simulation will be a useful procedure to predict the position and the extent of the spilled oil. In this study, a numerical simulation model is developed to predict the deformation and movement of an oil slick induced by a current under the ice cover. The validity of the model is examined by the comparisons with experimental results. And also, the effects of the current velocity, the amount of the spilled oil and the properties of the oil on the speed of the oil slick movement are discussed based on the numerical results.

![Figure 1](image1.png) The ocean current in the Sea of Okhotsk (Wakatsuchi, 2001) and the operation site

**PREVIOUS STUDIES ON AN OIL SLICK DEFORMATION AND MOVEMENT BY CURRENT UNDER ICE COVER**

Sakai et al. (1999) performed a series of experiments to study effects of current on the oil slick under an ice sheet. In their experiments, a doped model ice was used and the current under the ice was generated by toeing the ice sheet floating on the water at constant speed (Figure 2). The results of their experiments can be summarized as bellows: If the current velocity is small, the oil slick does not deform and not move. When the current velocity is large, there are three patterns of deformation and movement of oil slick; (a) move with a stable shape (left in Figure 3), (b) deform and move simultaneously (center in Figure 3), (c) move and be split (right in Figure 3). In the cases of (a) and (b), the speed of oil slick movement is stable. The deformation and movement patterns are classified by an initial area of oil slick (corresponds to total volume of oil) and the current velocity as shown in Figure 4. When the current velocity is less than 10cm/s, the oil slick does not deform and not move, and when the current velocity exceeds 20cm/s, the both side of oil slick is split, while this tendency slightly differs depending on an initial area of oil slick.

![Figure 2](image2.png) Experimental equipment
GOVERNING EQUATIONS AND MODELING OF EFFECTS OF CURRENT

Sakai et al. (2003) proposed a numerical simulation model to predict the spreading of oil under the ice cover. In their model, Navier-Stokes equation and the continuity equation were employed as governing equations. Since the thickness of the spreading oil slick under the ice is very thin, the above governing equations are transformed into the following equations (a long wave theory). Here, the viscosity term was given by Izumiyama and Sakai (1998).

\[
\frac{\partial M}{\partial t} + \frac{\partial}{\partial x} \left( \frac{M^2}{h} \right) + \frac{\partial}{\partial y} \left( \frac{MN}{h} \right) + \frac{\rho_o - \rho_w}{\rho_o} g h \frac{\partial \eta}{\partial x} + \frac{4 \mu_o M}{\rho_o h^2} = 0
\]  

(1)

\[
\frac{\partial N}{\partial t} + \frac{\partial}{\partial x} \left( \frac{MN}{h} \right) + \frac{\partial}{\partial y} \left( \frac{N^2}{h} \right) + \frac{\rho_o - \rho_w}{\rho_o} g h \frac{\partial \eta}{\partial y} + \frac{4 \mu_o N}{\rho_o h^2} = 0
\]  

(2)

\[
\frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} + \frac{\partial \eta}{\partial t} = 0
\]  

(3)
Where $M, N$ are the momentum fluxes in $x, y$ direction respectively, $h$ is an oil slick thickness, $\rho_o, \rho_w$ are density of oil and water respectively, $g$ is the gravitational acceleration, $\eta$ is the position of the oil slick bottom, $\mu_o$ is the viscosity of oil. These differential equations are transformed into difference equations in staggered grid, and calculated by leap-frog method. And, an oil-ice-water interfacial tension is considered around the edge of oil slick (Sakai et al., 2003).

In this model, the water just give buoyancy to an oil slick, in other words, the interaction of water and oil is not considered, and then the force of current acting on the oil slick cannot be included in calculations directly. In the following model, effects of current are described by an increment of oil thickness at the oil slick edge that the current acts on (front edge) based on the fact that the oil slick thickness increases when the current acts on it.

To formulate the relations between the current velocity and the increment of the oil slick thickness, a series of experiments were carried out in the ice tank. In this experiment, a doped model ice was used and the current under the ice was generated by toeing the ice sheet floating on the water at constant speed. The experimental conditions are as follows; 1) the oil slick can move freely in the direction of the current (oil volume is 2 liter), 2) the oil slick cannot move in the direction of the current by a stopper (oil volume is 2 and 4 liter). The spreading in the direction normal to the current direction and the split of oil cannot occur because the width of the ice tank is narrow. Photograph 1 is an example of the cross sectional shape when the current acts on the oil slick. Figure 5 shows a relation of increment of oil thickness at the front edge to the current velocity squared. The relation between them is approximated by the line in Figure 5. Sakai et al. (1999) reported that the oil slick does not move in the cases of current velocity less than 10cm/s, and then in a numerical calculation any increment is not added to the thickness at the front edge for such condition of current velocity.

![Photograph 1 An example of the cross-sectional shape when current acts on the oil slick](image)

![Figure 5 Relation between increment of oil thickness at front edge and current velocity squared](image)
Since the regression line in Figure 5 gives an increment when the current direction is normal to the front edge, the increment of oil thickness at each point on the front edge is calculated by the normal component of current. And also, the relative velocity of current to the oil slick is used to calculate an increment when the oil slick is moving.

When the current velocity exceeds 20cm/s, the oil slick is split. In such conditions, the oil slick behavior cannot be treated as continuous fluid motion. Therefore, in the following calculations, the current velocity will be less than 20cm/s. This limitation on calculation conditions is also based on the following observations; The ocean current velocity in the Sea of Okhotsk is 20-30cm/s from September to December (Wakatsuchi, 2001), and that velocity at sea bottom is less than 20cm/s in winter (Sakai et al., 1999).

Calculation procedures are as follows;

1) Initial shape of the oil slick is a circle, and each cell has a certain volume of oil corresponding to the oil thickness when oil slick is static (since the difference of oil and water pressure balances with the interfacial tension, the thickness depends on the oil density and interfacial tension).

2) Increment of oil thickness is assigned at the front edge (upper figure in Figure 7). This value is used only in the calculations of momentum fluxes, not in the oil volume.

3) At all edge cells, the term of interfacial tension is added in right-hand side of equation (1), (2).

4) Fluxes and oil volume are calculated alternately by leap-frog method. N1, M2 in lower figure in Figure 7 are calculated commonly, however M1 is always 0, and N2 is 0 when the oil volume in that cell is less than a half of the oil volume in the static condition.

5) When the oil volume in a front edge cell is less than a certain value (cell area \( \times 10^{-8} \) m), the oil volume is considered to be zero and the next cell is a new front edge cell.
NUMERICAL RESULTS AND VALIDITY OF THE PRESENT MODEL

Figure 8 shows comparisons of numerical and experimental results of the deformation and movement of the oil slick in the cases that the density of oil, the interfacial tension, the viscosity of oil are 878kg/m$^3$, 0.05282N/m, 0.254Pa-s, respectively. The oil slick shape at each elapsed time is shifted at regular intervals, since the shapes overlap in a fixed coordinate system. In the numerical results, a shade in the oil slick shape corresponds to the thickness. Numerical results show that effects of oil thickness increment at front edge propagate into the inside of oil slick gradually, and the oil thickness increases at rear edge of the slick, and the oil flows downstream when the oil

Figure 8 Comparison between numerical and experimental results of oil slick deformation

Figure 9 Comparison between numerical and experimental results of oil speed
pressure against the water exceeds the interfacial tension. And also, as the front edge of oil slick becomes flat against the current, the oil thickness at both edges in the direction normal to the current increases, and then the oil slick widens. The calculated shapes of the oil slick agree with the experimental results fairly well for a wide range of the initial area from 400 to 4500 cm$^2$. Figure 9 shows comparisons of numerical and experimental results of the movement speed which was calculated from the position of the center of oil slick. Three figures in Figure 9 correspond to that in Figure 8, respectively. In general, the present model simulates experimental results of the oil speed accurately. However, immediately after the current acts on the oil slick, the movement speed measured in the experiments is much larger than the numerical result. The reasons for this discrepancy is as follows; As shown in the upper figures in Figure 3, the rear edge does not move so much even at the beginning, in other words, the movement of the whole oil slick is not so fast. However, at front edge the oil thickness increases rapidly resulting in the decrease of the area. Therefore, the oil speed which was calculated from the position of the center of oil slick includes the above effects at the beginning.

Figure 10 shows comparisons of numerical and experimental results of the movement speed including other cases. Experimental results indicate that the current velocity is bigger and the initial area of oil slick is smaller, the movement speed is faster. The numerical results agree with experimental results fairly well, and then it can be concluded that the present model simulate the deformation and movement of the oil slick induced by the currents under ice cover accurately.

![Figure 10](image-url) Comparison between numerical and experimental results of oil speed

**EFFECTS OF OIL PROPERTIES ON OIL MOVEMENT SPEEDS**

Characteristics of the deformation and movement of the oil slick by currents under the ice will depend on properties of the oil. In particular, the density and viscosity of the oil and the oil-ice-water interfacial tension are dominant factors to characterize the deformation and movement. Figure 11, 12, 13 show the effects of the density, the interfacial tension and the viscosity on the relations between the oil speed and the current velocity, respectively. In the calculations, the current-induced-increments of the oil thickness at the front edge are assumed not to depend on the oil properties even though the oil thickness varies depending on the oil density and the interfacial tension in the static condition. Figure 11 illustrates the influence of the density on the oil speed. When the density is larger, the movement speed is larger. Figure 12 and Figure 13 show that the oil speed is larger when the interfacial tension is larger and the viscosity is smaller.
CONCLUSIONS

Results of this study can be summarized as follows.

1. The oil thickness at the front edge which the current acts on under the ice is formulated as a function of the current velocity squared.
2. The present simulation method accurately simulates experimental results of the deformation and movement of the oil slick induced by currents under the ice.
3. The calculated results show the effects of the oil properties on the oil movement speed quantitatively.

REFERENCES


