

Autonomous Spilled Oil and Gas Tracking Buoy System and Application to Marine Disaster Prevention System

N. Kato¹, H. Senga¹, H. Suzuki¹, Y. Okano², T. Ban², Y. Takagi², M. Yoshie³, T. Tanaka³, N. Sakagami⁴

1: Osaka University, Graduate School of Engineering

2: Osaka University, Graduate School of Engineering Science

3: Port and Airport Research Institute

4: Tokai University, Faculty of Marine Science & Technology

1. Introduction

There have been many major sea oil spills in recent years. These spills damage not only the ocean environment but also regional economies. Once spilled oil washes ashore, it is difficult to effectively recover it. This results in a high residual amount of spilled oil and long-term damage to the environment as well as to marine and human life.

Explosion of offshore oil rig at Gulf of Mexico in 2010 has roused our attention to danger of a large amount of oil spill from subsea oil production systems. On the other hand, once gas blows out from seabed by an accident of subsea oil production system or by a seismic activity and subsea landslide in the area of ample reserves of methane hydrate in the sea, it seriously damages not only ships and airplanes, but also natural environment.

To know when, where and how much the spilled oil and gas float up on the sea surface, and where the floating oil on the sea surface drift ashore, we need information of advection, diffusion and dispersion of underwater oil and gas, and its prediction.

To prevent oil spills from spreading and causing further damage over wider areas and over time, the spilled oil must be recovered while it is still drifting on the sea surface. An oil drifting simulation must be carried out to determine where the spilled oil will wash ashore and to adequately deploy oil recovery machines before this occurs. We need the information on the exact location of the drifting oil and the meteorological and oceanographic data around it transmitted in real time so that oil recovery operations can be smoothly coordinated and adequate measures can be taken at coastal areas using information obtained from the oil drifting simulation enhanced by data assimilation.

The objectives of this study are as follows:

(1)Autonomous tracking and monitoring of spilled plumes of oil and gas from subsea production facilities by an underwater buoy robot,

(2)Autonomous tracking of spilled oil on the sea surface and transmission of useful data to a land station through satellites in real time by multiple floating buoy robots,

(3)Improvement of the accuracy of simulations for predicting diffusion and drifting of spilled oil and gas by incorporating the real-time data from these robots.

The several authors have developed spilled oil tracking autonomous buoys (SOTAB) [1][2] and numerical simulation program of drifting of spilled oil. This research project adopts the following methods to realize these objectives:

(1)An underwater buoy robot equipped with a buoyancy control device and two pairs of rotational fins for guidance and control, and sensors to detect dissolved gas and oil will be developed. It will be tested in areas in the Gulf of Mexico and off Niigata where methane gas is released.

(2)Multiple floating buoy robots equipped with sails—the orien-

tation and size of which are adjustable—and sensors to detect oil slicks on the sea surface will be developed. They will be tested in Japan using artificial targets on the sea surface, and in Norway using real oil on the sea surface.

(3)A data fusion method incorporating real-time measured data from buoy robots in simulation models for not only gas and oil blowouts, but also spilled oil drifting on the sea surface will be developed.

The system described above can be applied to regular environmental monitoring around subsea production facilities, the collection of spilled oil drifting on the sea surface, and the deployment of oil-recovery devices(see Fig.1).

2. Autonomous tracking and monitoring of spilled plumes of oil and gas from seabed by an underwater buoy robot

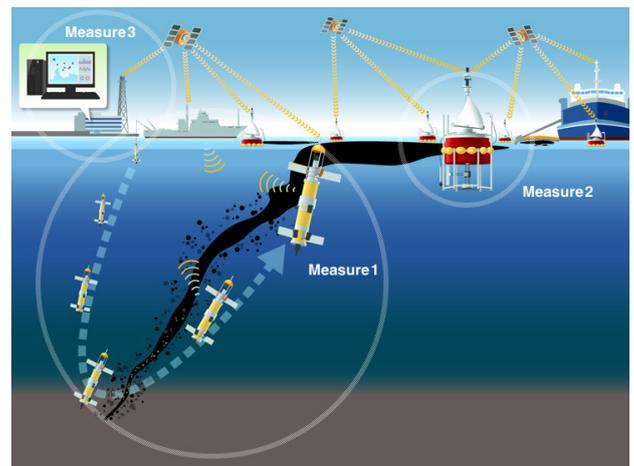


Fig.1 Autonomous tracking and monitoring system of spilled plumes of oil and gas from seabed

2.1 Underwater Buoy Robots for Autonomous Tracking and Monitoring of Spilled Plumes of Oil and Gas from Seabed (SOTAB-I)

There have been two types of underwater robots autonomously monitoring marine environments in 3-D space from sea surface to seabed over the long term. One is Argo Float and the other is underwater glider. Argo Float floats vertically and repeats descending and ascending in the vertical direction. However, it does not have a function of active movement in the horizontal direction. Underwater glider has a streamlined body with fixed wings. It can descend and ascend by using a buoyancy control device, while it moves in the horizontal plane like a glider for long distance. However, the ratio of vertical movement distance to horizontal movement distance is small.

An underwater buoy robot movable not only in the vertical direction from sea surface to water depth of 2,000m by a buoyancy control device, but also in the horizontal direction by two pairs of rotational fins(SOTAB-I) is being developed and it will be tested finally in the areas of Gulf of Mexico and off Niigata where methane gas is spilled. The underwater robot will be equipped with an underwater mass spectrometer for detecting dissolved gas and oil, other marine environmental sensors, an acoustic velocimeter with altitude sensor, and an acoustic navigation system with an acoustic modem(see Fig. 2). Figure 3 shows the simulated results on the vertical and horizontal movements of old type of SOTAB-I[1] with the size of 0.27 ϕ ×3.0 m and the mass of 116.0 Kg in the cases that the wing angle is set as 30 degrees and the buoyancy is set as 1, 3, 5 Kg. We can find that the SOTAB-I can move in a wide range both in vertical and horizontal directions.

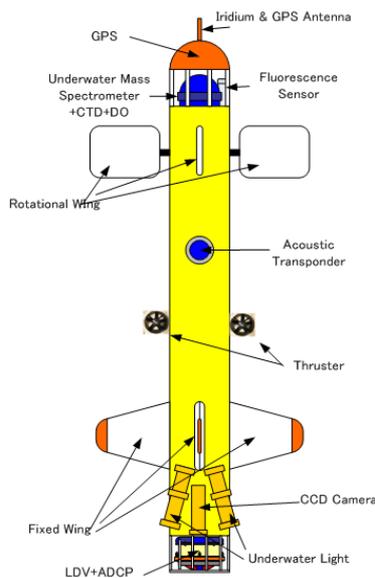


Fig.2 Illustration of SOTAB-I

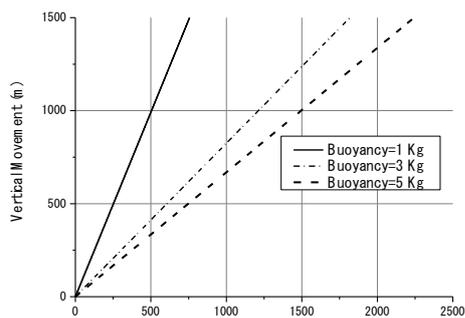


Fig.3 Swimming performance of old type SOTAB-I

2.2 Floating Buoy Robot Autonomously Tracking Spilled Oil Slick Drifting on Sea Surface(SOTAB-II)

Multiple floating buoy robots equipped with sails of which direction and size are both adjustable and detecting sensor of oil slick on sea surface will be developed. They will be tested in Japan using artificial targets on sea surface, and in Norway using real oil on sea surface.

The mission of the tracking and predicting system is that the buoy follows the drifting oil slick automatically and sends the po-

sitioning data and hydrographic phenomena of the position to the operation base continuously. We can watch the oil slick drifting in real-time and predict the precise destination of it using the monitoring data from the buoy. It is an advantage point that the buoy can track the oil slick during night when the air plane can't look for the sea surface and the oil. So it will avoid possibility of the losing oil slicks (Fig.4).

The following existing equipments cannot provide such useful data in real-time and in the long term. Plane flies over the sea and watches the oil slicks by visual recognition. In the night, however, the oil slicks are not visible on the seawater. Fluorescence lidar is a compact imaging lidar system detecting the fluorescence of substances excited using CCD camera. This equipment is mounted on a helicopter and can provide images of spreading spilled oil and its classification even in the night. However, the plane cannot track the spilled oil continuously because of limit of its endurance. Drifting buoys are used to track spilled oil. However, they have no device to track it again, when they get apart once from the spilled oil. The method of the X-band radar detection is used under condition that the vessels can track the oil slicks. It is rare case that the vessels can track the spilled oil continuously because weather of the sea is not always fine. The satellite remote sensing is not carried out more frequently than the plane method.

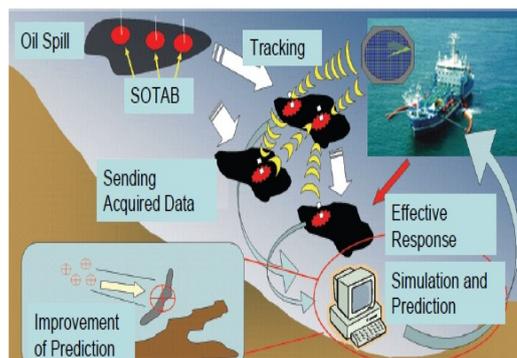


Fig.4 Concept of operation of SOTAB-II system

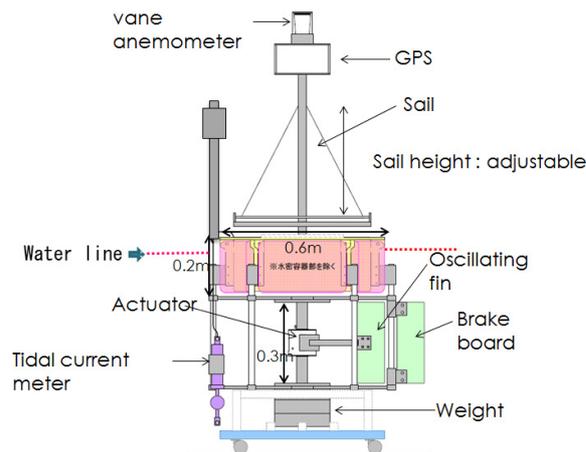


Fig.5 Illustration of SOTAB-II

Our previous experiment using a basic type of SOTAB-II consisting of cylindrical body and a sail [2] (Fig. 5) (height of 1.9 m, mass of 60.0 Kg) showed that the resultant drifting velocity vector of drifting oil slick is composed of water current vector and about 3 % of estimated wind vector at the height of 10 m above the sea surface. The direction of the sail was successfully controlled so as

to become perpendicular to the direction of wind, and the height of the sail was also successfully controlled at the same time so that the velocity of the buoy becomes equal to the drifting speed of the oil slick. A new type of SOTAB-II will be equipped with a fluorescence sensor, GPS, an anemometer, a GPS, an iridium satellite communication device on the top of the mast.

Figure 6 shows a photograph of sea trial of SOTAB-II at Awaji Island sea. Figure 7 shows an example of the trajectories for 18 minutes of SOTAB-II with control of sail, 3 % of wind vector at the height of 10 m above the sea surface, tidal current vector, resultant vector of the 3 % of wind vector and tidal current vector, and a rubber sheet equipped with GPS receiver to imitate the oil drifting, at a sea trial at Awaji Island sea where tidal current speed of 0.4-0.6 m/s and wind speed of 8.0-10.0 m/s were observed. We can see that SOTAB-II drifts with almost the same velocity vector as the resultant vector of the 3 % of wind vector and tidal current vector, and as the rubber sheet.



Fig. 6 Photograph of sea trial of SOTAB-II at Awaji Island sea

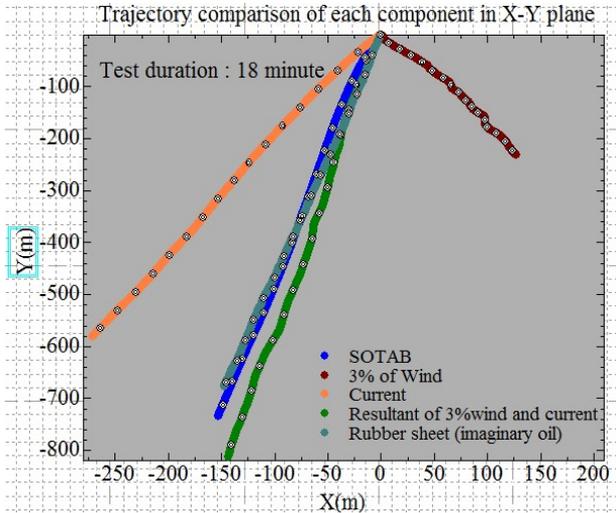


Fig. 7 Trajectories of SOTAB-II and other components with control of sail at a sea trial

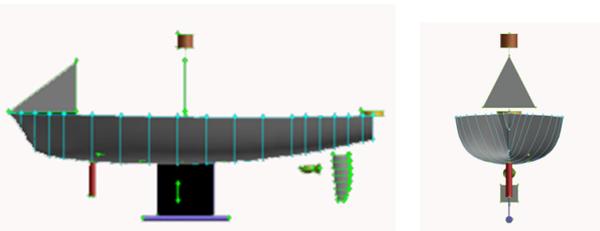


Fig.8 New model of SOTAB-II

We are now designing a new model of SOTAB-II with a sailing yacht shape to reduce the hydrodynamic drag force acting on the body under the waterline as shown in Fig.8. In this model, the direction of the sail surface is fixed normal to the longitudinal direction of the yacht shaped body and the azimuth angle is controlled to become parallel to wind direction. Oil slick will be detected by a UV optical sensor mounted on the top of the mast.

In order to enhance the effectiveness of the system using SOTAB-II, we estimate how many SOTAB-IIs we would need for an oil spill accident. Followings are the assumptions to estimate the number.

1. The amount of the oil (V_0) spills initially at the beginning of oil spill accident.
2. Such spilled oil spreads in a circle with radius of 1 m in 24 hours. We arrange SOTABs around the edge of this circular spilled oil with the interval of 500 m, where the radius of diffusion is calculated by using the following equations[3].

$$l_{1,t} = C_1 \left(\Delta g V_E^2 t^2 \right)^{1/4} \quad (0 \sim 1 \text{ hour}) \quad (1)$$

$$l_{2,t} = C_2 \left(\frac{\Delta g V_E^2 t^{3/2}}{v_E^{1/2}} \right)^{1/6} \quad (1 \sim 24 \text{ hours}) \quad (2)$$

, where each coefficient are as follows.

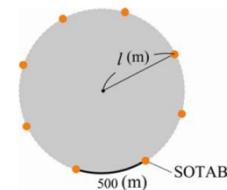
$$\Delta = \left(1 - \frac{\rho_E}{\rho_W} \right) \quad (3)$$

$$\frac{\mu}{\mu_0} = \exp \left(\frac{2.5W}{1 - 1.085W} \right) \quad (4)$$

$$V_E = \frac{V_0}{1 - W} (1 - E) \quad (5)$$

$$\rho_E = W \rho_W + (1 - W) \rho_0 \quad (6)$$

- ρ_0, ρ_E, ρ_W : density of spilled oil, emulsified oil and water (kg/m^3), respectively
- g : gravity acceleration (m/s^2)
- t : time (hour)
- ν_E : kinematic viscosity of emulsified oil (m^2/s)
- μ, μ_0 : viscosity of spilled oil and emulsified oil
- V_0, V_E : volume of initially poured and emulsified oil (m^3)
- W : rate of moisture component
- E : rate of evaporation



Figs. 9 Ideal arrangement of SOTAB for initially spilled oil spread in a circle for 24 hours

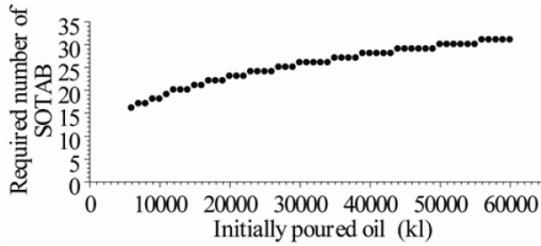


Fig.10 The required number of SOTAB corresponding to the initially spilled oil

Eq. (1) shows the radius of diffusion of spilled oil up to 1 hour. Then, the radius changes according to Eq. (2). Therefore, the radius of diffusion of spilled oil after 24 hours is $l_{1,1}+l_{2,24}$. The circumferences of initially spilled oil were calculated using the radiuses of diffusion l . Then, we calculated the number of SOTAB required in each case (Fig.10).

In case the “Nakhodka” oil spill occurred in 1997, the initially spilled oil was 6,700 kl, and 16 SOTABS will be required. On the other hand, in the case of Exxon Valdez that spilled oil oil in 1989 at the amount of 42,000 kl, 28 SOTABS will be required.

3. Assimilation Analyses of Environmental Simulation and Measured Data by Buoy Robots

A data fusion method incorporating real time measured data from buoy robots in the simulation models for not only gas and oil blowouts, but also spilled oil drifting on sea surface will be developed. Precision of prediction of oil and gas behavior using simulation models will be improved by incorporating real time measured data from buoy robots SOTAB-I and SOTAB-II.

3.1 Model Evaluation of Behavior of Oil and Gas from Deep-

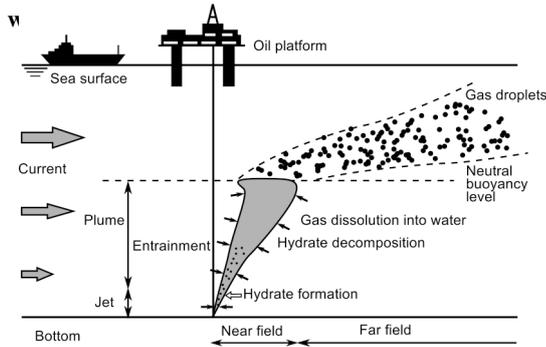


Fig.11 Schematic of deepwater gas blowout[4]

A model incorporating the phase changes of gas, associated changes in thermodynamics and its impact on the hydrodynamics of plume is evaluated taking hydrate formation, hydrate decomposition, gas dissolution, and non-ideal behavior of the gas into account.

The behavior of gas plume is initially dominated by its dynamics. This part is modeled with integral Lagrangian control volume concept where plume hydrodynamics and thermodynamics are considered for Lagrangian control volume. The Lagrangian control volume is defined as a volume with the local diameter of the plume,

moving along the plume trajectory with plume velocity. As the plume grows larger, its dynamics become less important due to entrainment. In stratified ambient conditions, a jet/plume may reach a neutrally buoyant level beyond which the jet/plume dynamics are no longer important, and the plume behavior is more governed by the advection and diffusion[4].

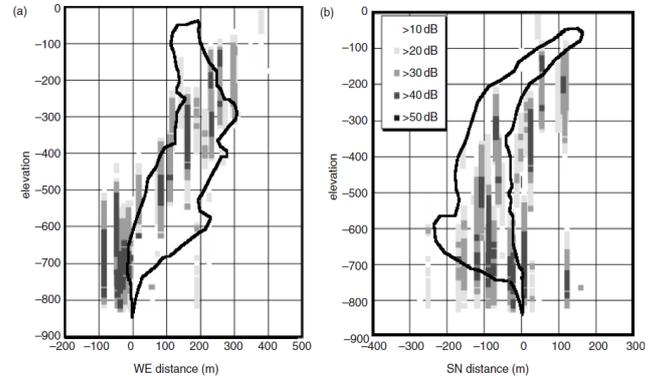


Fig.12 Side views of Echo Sounder data and CDOG simulated profile(thick line) at the DeepSpill experiment

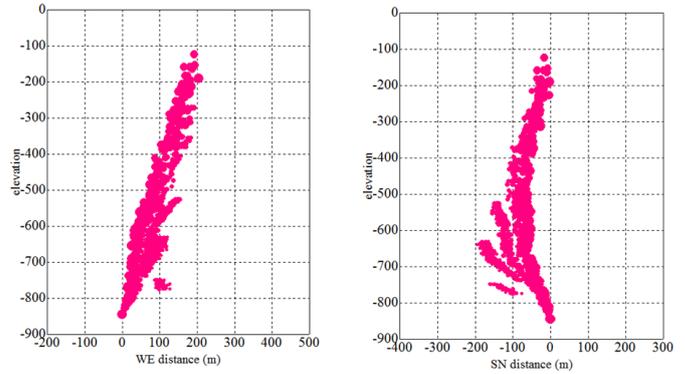


Fig.13 Side views of the simulated profile of behavior of oil droplets using the proposed model

Blowout of oil droplets is modeled to compare the DeepSpill experiment[5] conducted in the Norwegian Sea at the Helland Hansen site (65°00’N 04°50’E) in 844 m of water roughly 125 km off the coast of central Norway. In the simulation, water temperature, salinity and ambient current velocity are imposed at each sea level. The distribution of oil droplet size is also given. The model represents the behavior of oil droplets using unsteady motion of oil droplets in the vertical direction and diffusion of oil droplets in horizontal plane. To evaluate the validity of the model, the experimental and simulation results using the side views of Echo Sounder data and CDOG simulated profile(thick line) at the DeepSpill experiment[6] for the case of mixture of oil and gas (volume ratio is 1:42, mass ratio is 1:45(gas hydrate)) are compared(Figs. 12 and 13). The proposed model should include breakup and coalescence of oil and gas bubbles for the next stage.

3.2 Assimilation of Weather Research and Forecasting(WRF) in the Model of Drifting of Spilled Oil on Sea Surface

A combination of Princeton Ocean Model(POM) for ocean modeling and WRF Model is used for the prediction of drifting of spilled oil on sea surface in this study. To raise the accuracy of prediction of drifting of spilled oil on sea surface, this study adopts variational data Assimilation method for WRF Model and POM

using data from SOTAB-II and others.

This paper deals with a simulation of the drifting of spilled oil after the incident of the Russian tanker Nakhodka in the Sea of Japan in January 1997 to evaluate the effectiveness of data assimilation method. The model grid area was set from latitude 33°N to 52°N and from longitude 127°E to 142°30'E (Fig 14).

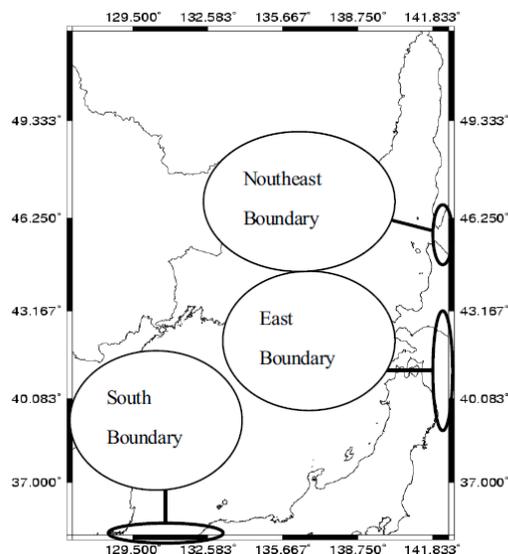


Fig.14 Japan Sea area for simulation

The grid step was set as 1/6 degree in both the longitudinal and latitudinal directions for POM. In vertical direction, the sigma coordinate system was used. The time step was set as 12sec, and the period of this calculation was set from January 1st to January 30th in 1997. We set six open boundaries as shown in fig 14, and monthly average water temperature, salinity and sea levels were imposed at these boundary points. The inflow from Tsushima Strait and the outflow from Tsugaru Strait and Soya Strait were considered. In this study, the wind stress was given to sea surface. The initial and boundary conditions were given from NCEP/NOAA data. Table 1 shows the comparison of ratio of collected spilled oil by prefectures in Japan after Nakhodka accident between measured, simulated without data assimilation, and simulated using 3-D variational data assimilation method[7]. We find that the data assimilation increases the accuracy of prediction of amount of drifted oil on shore.

Table 1 Comparison of ratio of collected spilled oil at prefectures in Japan after Nakhodka oil spill accident

Name of Prefecture	Measured(%)	Without Data Assimilation(%)	3-D Variational Data Assimilation(%)
Shimane	0.60	9.19	4.98
Tottori			
Hyogo	2.90	2.16	1.37
Kyoto	7.30	9.26	5.11
Fukui	37.30	54.50	47.28
Ishikawa	44.30	21.08	30.60
Niigata	7.60	4.24	10.26
Others		1.12	1.94
	RMS Error(%)	12.41	7.31

4. Concluding Remarks

Sea experiments will be carried out using SOTAB-I in the areas of Gulf of Mexico and off Niigata where methane gas is spilled, and using SOTAB-IIs in the area of Norway where actual oil is dispersed.

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