ANALYSIS OF ICE BOTTOM TOPOGRAPHY ON OKHOTSK SEA COAST OF HOKKAIDO - OBSERVATION RESULTS IN 2004 -

Shinji Kioka¹, Yasuji Yamamoto¹, Shigeki Sakai² and Takahiro Takeuti³

¹Civil Engineering Research Institute of Hokkaido, Sapporo, Japan
²Iwate University, Iwate University, Iwate, Japan
³Hachinohe Institute of Technology, Hachinohe, Japan

ABSTRACT
We have conducted sea ice surveys using Ice Profiling Sonar (IPS) and Acoustic Doppler Current Profiler (ADCP). This paper reports on the quantitative analysis results on the sea ice data, especially on ice bottom topography, obtained in 2004. and the renewed knowledge obtained by comparing the data with past results. From results of analysis of the sea ice bottom topography (draft profile) with non-stationary characteristics by the locally stationary AR model, we were able to make the assumption that although the average power (variance of draft depth) of each subinterval (span) considered locally stationary was different, the normalized spectra of the subintervals were identical, which indicated similar results as the previous data. We were able to obtain an important conclusion that the typical normalized spectrum of ice bottom topography (underside profile) might be common regardless of annual variations in ice draft.

KEYWORDS: IPS, ADCP, sea ice, draft, bottom topography, spectrum

INTRODUCTION
When designing and constructing offshore/coastal structures, pipelines and other underwater and buried structures or winter navigation through pack ice, interaction with sea ice must be fully taken into consideration. It is also necessary to acquire information on the ice bottom topography (ice bottom roughness, unevenness) in advance for oil spill contingency plans such as prediction of the range of oil spreading under an ice cover or recovery of oil in ice-infested waters. In particular, with the recent progress of oil and natural gas development along the Sakhalin continental shelf, transport of oil and natural gas to Japan by vessels as well as accompanying oil spills or other accidents are expected in the future. However, hardly any field observations are available in Okhotsk Sea coast of Hokkaido. We have therefore conducted surveys of the drift speed, draft depth and other details of sea ice using Acoustic Doppler Current Profiler(WH-ADCP by RD Instrument, U.S.A) and Ice Profiling Sonar (IPS-4 by ASL Environmental Sciences, Canada) since 2001. We have quantitatively analyzed those sea ice data and developed a practical simulation method for ice bottom topography (Yamamoto et al.,2002, Kioka et al.,2004a,b). Our
main goal is to clarify the statistical distribution of the above sea ice data from the accumulated data. We also aim to develop a general-purpose method for simulating the fundamentally complex draft depth or bottom topography of sea ice by using a small amount of statistics collected from enormous volumes of data, and to feed back the results to solve the above technical issues.

This paper will report on the results of the quantitative analysis of sea ice data, especially on bottom topography, obtained in 2004, and on the updated information obtained by comparing the results with the past analysis results of sea ice data.

**OBSERVATION METHODS**

The observation site in 2004 was 1.5 km off the Shinobutsunai, Okhotsk Sea of Hokkaido as shown in Fig.1. An Acoustic Doppler Current Profiler (ADCP) and an Ice Profiling Sonar (IPS) were installed at a depth of 16 m for observation of the draft and drift speed/direction of sea ice passing over the observation equipments. Fig.2 shows outline of the observation methods using the ADCP and the IPS. Theories and survey methods of these measuring instruments were detailed by Sakikawa et al. (2002), Belliveau et al. (1989) and Birch et al. (1999).

**OVERVIEW OF OBSERVATION RESULTS**

**Data subject to analysis**

Data obtained on February 27 and 28 were chosen for analysis since the requirements for (1) existence of sea ice at the observation site, (2) relatively continuous section as well as good data without noise or missing values and (3) section where prominent direction of sea ice drift is southeast due to reasons described later. Although the spectrum characteristics of the bottom
topography of sea ice may differ by direction when one direction of ice drift is prevalent (Kioka et al., 2004a), the primary purpose of this study is to estimate the spectrum in the prominent direction of sea ice drift as mentioned later. The presence of sea ice was confirmed using the sea ice information provided by the Institute of Low Temperature Science, Hokkaido University, and the Ice Information Center of the 1st Regional Coast Guard Headquarters. Data from 2001 (February 8 to 19), which have already been reported (2.4 km off Mombetsu, 18-meter deep) (Yamamoto et al., 2002, Kioka et al., 2004a), were used for comparisons with past data. Data could not be obtained in 2002 and 2003 due to malfunctions of IPS. Sea ice data in the northeastern Sakhalin (Birch, 1999) were also examined as a reference.

**Characteristics of the sea ice drift**

Fig. 3 shows the drift path of sea ice observed in 2004 (the period between February 17 and 28, when the sea ice concentration was relatively strong, was used as an example in this case). This figure simply shows a coordinate based on the drift speed/direction of sea ice at a fixed point. It was presumed from sea ice data of two different points -- data from the Institute of Low Temperature Science, Hokkaido University (11 km off Yubetsu, 60-meter deep; same measuring method as that used by the authors) and our sea ice data of 2001 (2.3 km offshore) -- that the prominent direction of sea ice drift was southeast. It can be seen from Fig. 3 that the southeast direction was the prominent direction in 2004, although there were slightly stagnant periods, such as between Feb. 21 and 22 and Feb. 24 and 26. The frequency distribution of the drift speed was exponentially and was almost the same as the past result. The median and maximum values were 0.17 and 1.5 m/s, respectively, in the data from 2004, and were 0.12 and 1.2 m/s in the past data (2001). Although the differences were not significant, the drift speed was slightly higher. While the drift speed depends greatly on the concentration of sea ice, currents (tides), wind velocity and other conditions, it may also be influenced by the coastal topography. In the observations from 2001, for example, a difference in speed depending on the distance from the coast (offshore sea ice is faster) was found compared with the above-mentioned sea ice data from the Institute of Low Temperature Science, Hokkaido University, and the influence of the coastal area was thought to be one of the causes.

**Ice Draft Depth and Ice Bottom Topography**

Fig. 4 shows an example of sea ice draft with distance obtained in 2004 (Feb. 26-27) using ADCP data along with IPS data, which can be regarded as the ice bottom topography. As the past results, the topography of sea ice bottom was not flat and had very large undulations. Figs 5 and 6 show the frequency distribution of the sea ice draft depth and the exceedance probability distribution including the past data (2001), respectively. The frequency distribution of sea ice draft depth was close to exponential, indicating identical results as the past data. However, average draft depth of 0.61 m and maximum draft depth of 8.0 m (9 m in the total measurement area) were observed, deeper than those of the previous data. Ice draft depth might vary significantly each year. Fukamachi et al. (2001) observed a thickness of 17 meters at 60 m water depth off Yubetsu,
Hokkaido, between March 6 and 10, 1999, by using the same measurement method as ours. Sea ice with relatively large draft was thus confirmed even on the Okhotsk Sea coast of Hokkaido, which is part of the southern limit of sea ice.

**QUANTITATIVE ANALYSIS ON SEA ICE DRAFT DEPTH/BOTTOM TOPOGRAPHY**

**Analysis Targets and Non-Stationary Characteristics of Sea Ice Bottom Topography**
When the sea ice bottom topography is represented as a waveform, it is important to determine whether this waveform has non-stationary characteristics. The decision whether to take into account non-stationary characteristics depends on the scale for which calculation is to be performed (e.g., calculation region for oil spill spread under the sea ice). If the scale is too small relative to the obtained data length, non-stationary characteristics may need to be taken into account. It would be desirable to incorporate the properties of level ice areas and open sea areas (where no sea ice exists). However, we do not have sufficient information on these factors to accurately analyze their effects. This study focuses on the sea ice bottom topography with macro-scale roughness, selected from areas where the waveforms show that the prominent direction of sea ice drifts is southeast. Excluded areas are those where sea ices are rotating, or where they are drifting almost perpendicular to the prominent direction of sea ice drifts. The data were divided according to the basic local span (1200 m) for the locally stationary AR model (presented in a later section). Each basic local span, the spans whose average draft is less than 10 cm are considered to be open water and are therefore excluded.

**Analysis by Locally Stationary Autoregressive (AR) model**
As in the previous study (Kioka et al., 2004a), we also applied the locally stationary autoregressive
(AR) model to the analysis for the bottom topography of sea ice, which is applicable for non-stationary analysis. The algorithm for this model is essentially the same as that of the MEM method. The time (distance) axis is divided into basic local spans (1.2 km). After the model is applied to these basic local spans, the spans with similar waveform characteristics are combined. Akaike's Information Criterion (AIC) is the standard for determining similarity. Basic local spans, including combined ones, are regarded as stationary subintervals, since the waveform is assumed to be stationary in each basic local span. The basic local span was set to 1.2 km by assuming a calculating area (order of several hundred meters to several kilometers) of oil spill spreading under sea ice in the same way as in the past. Fig.7 shows the results of the analysis in which the locally stationary AR model is applied. The vertical axis shows wave number spectra, which is normalized by dividing the spectrum density by the variance of the draft depth, which is the 0-th moment of the spectrum. The other two axes are the wave number $k$ (cycle/m) and distance (km). The figure shows that the normalized spectra of the stationary subintervals tend to be similar. From a practical view points, we can assume that although the average power (variance of draft depth) of each subinterval is different, the spectrum characteristics of the subintervals are similar, and their normalized spectra can be assumed identical. This result roughly agrees with that in the previous result (Kioka et al., 2004a). This result also agreed with that by distance-wave number analysis using discrete wavelet transform (Kioka et al., 2004a). For practical application of this method, the typical normalized spectrum as well as the range of the variance and its frequency distribution should be estimated, which is a very straightforward process. The typical normalized spectrum is defined as the ensemble averages of the normalized spectra of the stationary subintervals. Fig.8 shows the typical normalized spectrum. Fig.9 shows the non-normalized spectra of each subinterval. The two bold lines represent the spectra of the greatest and smallest values of variance of the stationary subintervals multiplied by the typical normalized spectrum. The figure indicates that the curves of the non-normalized spectra of each stationary subinterval behave in a similar manner, although they deviate in a certain range. As shown in Fig.8,
dividing those non-normalized spectra with the variance greatly reduces the deviations. The bold curves cover the range of the original non-normalized spectra, thereby validating the concept of the “typical normalized spectrum”. This result was also the same with that in the previous study (Kioka et al., 2004a).

Fig. 10 shows comparison of the typical normalized spectrum in 2004 with that in 2001 (Kioka et al., 2004a). From this figure, we can see that the two are roughly the same, indicating the important conclusion that the typical normalized spectrum (roughness, unevenness characteristics) might be common regardless of annual variations in ice draft. Data regarding the sea ice draft depth in the northeastern part of Sakhalin (distance 2.5 km) (Birch et al., 1999) shown in Fig. 11 were also analyzed using the same method although the amount of data was smaller. Despite there being data equivalent only to one or two of the locally stationary subintervals mentioned above and the reliability is low, they were contained in the figure as a sample (not the typical normalized spectrum) obtained for reference. Compared with the coastal areas of Hokkaido, there seems to be a slightly higher concentration of energy in the low wave number range. If these are regarded as one sample, however, it is considered within the original range of variance as can be presumed from Fig. 8. Since the waveform characteristics with strong positive skewness were also similar, it is presumed that there is similarity among roughness characteristics of deformed ice, suggesting that the typical normalized spectra might be common regardless special and temporal component.

The discussion above assumes normality of data (Gaussian process). However, the actual distribution has the skewness. It is not proper to apply the spectra in their current form to various statistical estimates. Here, we attempt to normalize our data as much as possible. As one method, the generally known data transformation method that includes logarithmic transformation is a *Box-Cox transformation*, which is given by the following formula:

\[
z_n = \begin{cases} 
\lambda^{-1} \left( y_n^\lambda - 1 \right) & \lambda \neq 0 \\
\log y_n & \lambda = 0
\end{cases}
\]

(1)

\(\lambda\) is a variable parameter that is selected such that the value of AIC is minimized when the transformed data are assumed to follow normal distribution. The value of \(\lambda\) was -0.1 if this rule is strictly applied. However, we can choose 0 for convenience, which means employment of logarithmic transformation. This concept was also the same with that in the previous study (Kioka et al., 2004a). The data to which logarithmic transformation was applied were analyzed by the method explained above. As in the previous study (Kioka et al., 2004a), this spectrum was also not very different from that before the transformation. All these results were similar to those presented in Figures 8 and 9, including the above-mentioned statement.
Relationships among the average value, standard deviation of sea ice draft depth and the significant amplitude of bottom topography

Information necessary for simulation of the bottom topography is the variance (standard deviation) that indirectly reflects non-stationary characteristics, and the typical normalized spectrum. Therefore, it is significant to study the basic properties and range of the variance (Kioka et al., 2004a). Figure 12 shows average values ($h_{\text{mean}}$) and standard deviations ($R_{SD}$) of the data including the previous data (Kioka et al., 2004a). Each data point on the figure represents a result in each stationary subinterval. The straight line in the figure indicates that the average value is equal to the standard deviation. In fact it means the relationship between the average value and standard deviation of the population when the initial variables follow an exponential distribution. The figure shows that they are distributed around the straight line, suggesting that the draft data follow a roughly exponential distribution. Data from Sakhalin were also plotted as a reference. It can be seen that this data was at the upper limit of the data from the coastal area of Hokkaido and that the draft depth and its standard deviation in Sakhalin are greater than those of Hokkaido. This plot is, however, regarded as an extension of the data from the coastal area of Hokkaido, and their unevenness characteristics are presumed to be similar even though the scales are different as mentioned in the previous section.

It would be useful to describe the ice bottom topography (roughness) intuitively and visually using the standard deviation. The significant ocean wave height (highest one-third wave) is thought to the height that we subjectively perceive as the average wave height. Following this idea, this section discusses the relationship between the significant amplitude of bottom topography of sea ice and the standard deviation of the ice draft, a value that is a parameter of roughness. The ocean wave height distribution is defined by the zero-upcrossing method, but if the original water surface fluctuation is Gaussian, it is theoretically a Rayleigh distribution. In this case, the significant wave height is four times the standard deviation of the original water surface fluctuation. The fluctuation of sea ice draft is not Gaussian, but it roughly conforms to exponential distribution or logarithmic normal distribution with strong skewness. This fluctuation also has non-stationary characteristics, so logical analysis is difficult for this case. Thus, for each subinterval considered locally stationary above mentioned, the zero-upcrossing method was employed to calculate the amplitude (Fig. 13). The figure shows that the standard deviation and the significant amplitude are roughly proportional. The slope is about 3.4, which means that the standard deviation multiplied by 3.4 would give a subjective/intuitive topography (roughness). In fact, the significant amplitude of the topography calculated in this method represented a subjective/intuitive of the topography in most of the sections.

![Fig. 12 Average values and standard deviations of ice draft locally stationary subintervals](image1)

![Fig. 13 Standard deviations ($R_{SD}$) vs. significant amplitudes of sea ice draft in locally stationary subintervals](image2)

-315-
DISCUSSION AND FUTURE CHALLENGES

As in the previous study, we confirmed that the complicated sea ice draft profile (ice bottom topography) that is non-Gaussian and has non-stationary characteristics could be represented using only the typical normalized spectrum and variance (standard deviation) of sea ice draft that indirectly reflects non-stationary characteristics of sea ice draft. Also, thereby, we can easily simulate the ice bottom topography (draft profile) using only them. The simulation method has already been proposed (Kioka et al.,2004b). They serve as input and boundary conditions necessary for estimations of behavior and ice load along with drag forces, at times of interference between sea ice and a structure, or for estimating the abrasion at the surface of a structure. It will also be possible to apply it to performance design of structures based on the theory of probability in the future. Needless to say, information on the velocity and the sea ice concentration will also be necessary in that case. Estimating the bottom topography of sea ice is also important as a boundary condition for calculation of the range of oil spreading under an ice cover in case of the oil spill accident.

However, this is a fixed-point observation and two-dimensional data cannot be obtained based on this type of observation method alone. The spectrum characteristics may not be identical in a random direction especially in the case where the direction of sea ice drift is prominent in one direction. We need to get spatial and temporal information including ice profile data perpendicular to the prominent direction of ice drift. Also, the draft depth may also vary by location. Therefore, the spatial distribution of the variance must be clarified in some way even if the typical normalized spectrum can be assumed as identical. We have also planned to introduce an efficient system for constant measurements in order to obtain sufficiently reliable samples, in addition to examining the above measurement technologies and taking the sea ice concentration into consideration.

REFERENCES


-316-