SIGNIFICANCE OF TIDAL CHANGE ON ABRASION AREA OF STRUCTURES DUE TO SEA ICE MOVEMENT

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ABSTRACT
When ice movement is very active, hydraulic structures in ice-covered areas suffer abrasion. Especially for offshore structures of reinforced concrete, it is necessary to determine the required cover thickness with high accuracy. This paper describes a method for estimating the size of the active abrasion area, considering local ice pressure distribution, change of water level due to tide, and scatter of physical properties of sea ice. Sample calculations are made for offshore structures in eastern Sakhalin under natural conditions.

KEY WORDS: Sea ice; Abrasion; Local ice pressure, Offshore structure, Tidal change.

INTRODUCTION
Structures in ice-covered areas generally suffer abrasion due to ice movement. In particular, a method is required for estimating the abrasive area of surfaces of offshore structures built in Sakhalin for development of natural resources offshore, because the movement of sea ice is very active due to the eastern Sakhalin current. Offshore structures made of concrete also need to be lightweight because of the long carriage distance required for their installation. Therefore, it is necessary to determine the thickness of cover concrete with high accuracy. This paper investigates the effects of vertical displacement of sea ice due to tidal change as well as randomness of physical properties of sea ice on the abrasion amount under active sea ice movement.

FACTORS INFLUENCING ABRASION
Saeki et al. (1985) conducted systematic experiments on the amount of abrasion by sea ice of several materials and showed that the average abrasion amount (A) can be calculated from:
Average abrasion amount \( A \) depends on a factor \( m_v \) based on the structural material (called average abrasion velocity in units of \([\text{mm}/(\text{km})]/[\text{kgf/cm}^2]\)), average contact pressure \( \sigma_v \) in units of \([\text{kgf/cm}^2]\) and abrasion length \( L \) [km]. Hanada et al. (1995) summarized factors \( m_v \) for several materials against sea ice obtained from laboratory abrasion tests (by Saeki et al., 1985; Asai et al., 1986; Itoh et al., 1990, 1992) as shown in Table 1.

Table 1 Factors \( m_v \) for several materials (against Sea Ice)

<table>
<thead>
<tr>
<th>Materials</th>
<th>Average abrasion velocity ( m_v ) [mm/(km)/(kgf/cm²)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>0.00178</td>
</tr>
<tr>
<td>Steel</td>
<td>0.00030</td>
</tr>
<tr>
<td>Urethane</td>
<td>0.00030</td>
</tr>
<tr>
<td>Zebron</td>
<td>0.00078</td>
</tr>
<tr>
<td>LDPE (Low Density Polyethylene)</td>
<td>0.00022</td>
</tr>
<tr>
<td>HDPE (High Density Polyethylene)</td>
<td>0.00030</td>
</tr>
<tr>
<td>Sand stone</td>
<td>0.00049</td>
</tr>
<tr>
<td>Pyroxenic Andesite</td>
<td>0.00084</td>
</tr>
<tr>
<td>Quartzous Andesite A</td>
<td>0.00065</td>
</tr>
<tr>
<td>Quartzous Andesite B</td>
<td>0.00177</td>
</tr>
<tr>
<td>Granite</td>
<td>0.00216</td>
</tr>
</tbody>
</table>

(Nota) 1 [kgf/cm²] = 0.098 [MPa], Temperature of sea ice is –10 degree in centigrade.

These factors were measured at 10 [kgf/cm²](=0.98MPa) average contact pressure \( \sigma_v \) and –10 degrees centigrade sea ice temperature. The precipitation of \( \text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O} \) at –8.2 degrees centigrade as well as \( \text{NaCl}_2\text{H}_2\text{O} \) at –22.9 degrees centigrade from brine act to increase abrasion. The average contact pressure \( \sigma_L \) [kgf/cm²] is calculated as normal force divided by apparent contact area. In fact, higher pressure acts at the center of the contact area (Saeki et al., 1984) and in turn increases abrasion there. Therefore, an approximation curve for ice pressure distribution, which was proposed by Takeuchi et al. (2000, 2004) through data obtained by a plane pressure panel sensor in ice/structure interaction, is available for local ice pressure \( \sigma_L \) in Eq.2.

\[
\sigma_L = \sigma_v \times k \left( \frac{z}{h} \right) = \sigma_v \times m_1 \times \exp \left\{ -m_2 \left( \frac{z}{h} \right)^2 \right\} \tag{2}
\]

where, \( k(z/h) \) is a multiplier of uniaxial compressive strength, \( z \) is distance from the center of ice thickness \( h \), and \( m_1 \) and \( m_2 \) are factors. The type of local ice pressure is characterized into two based on failure modes of brittle and ductile, depending on indentation velocity \( V \) divided by ice thickness \( h \). \( m_1 \) and \( m_2 \) are given as follows, considering a reference (being abraded) width of structure \( W_r \).

**<brittle case:** \( V/h > 3 \times 10^{-3} \) \((1/s)\)

\( m_1 \) is estimated as a function of \( W_r/h \) as shown in Figure 1 (a).

\( m_2 \) is taken as 100.

**<ductile case:** \( V/h < 3 \times 10^{-3} \) \((1/s)\)

\( m_1 \) is estimated as a function of \( W_r/h \) as shown in Figure 1 (b).

\( m_2 \) is taken as 15.

For the brittle case, the strong dependence of \( m_1 \) on \( W_r/h \) is due to a nonsimultaneous failure of ice at the ice/structure interface. This reflects the large drop from "extreme/sig-c" and "max/sig-c" to "average/sig-c" in Figure 1 (a). Using \( W_r/h=1 \), a multiplier \( k(z/h) \) can be plotted as a function.
 Figure 1(a) Effect of $W_r/h$ on $m_1$ (brittle) Figure 1(b) Effect of $W_r/h$ on $m_1$ (ductile)

of $(z/h)$, as shown in Figure 2. Therefore, if we have an uniaxial compressive strength ($\sigma_c$) of ice in the considered sea area, contact pressure ($\sigma_v$) calculated through local ice pressure ($\sigma_L$) in Eq.2 allows us to estimate an abrasion amount ($A$) in a small area from Eq.1. And, Eq.1 gives an “average” abrasion amount ($A$) because there is a pressure distribution inside the contact area in tests conducted by Saeki et al. (1985). But the contact width in their tests is 8 cm which is not so

Figure 2 Distribution of $k(z/h)$ in terms of $z/h$ ($W_r/h=1$)

Figure 3 Ice sheet and structure interaction

Figure 4 Configuration of ice/structure interaction, considering tidal change, local ice pressure distribution and randomness, on physical properties of sea ice.
large. Therefore, it should be noted that the use of Eq.1 includes an assumption in the calculation here. Since abrasion for the brittle case is much larger than that for the ductile case due to active movement of ice, most later calculations are for the brittle case.

**CALCULATION METHOD**

Let us consider the abrasion amount at the chamfer as described in Figure 3, since abrasion occurs more at a chamfered part than on other areas of an offshore structure. When an ice sheet moves toward the structure at velocity \( V \), abrasive line and contact pressure are \( \sqrt{2w_r} \) and \( \sqrt{2P} \), respectively. Thus, the product of \( (L) \) and \( (\sigma) \) becomes \( (w_r \times P) \). Further, the configuration of ice/structure interaction is as shown in Figure 4, considering tidal change and local ice pressure distribution. In the real world, ice properties vary with time and location. At time = 0, the ice sheet is located at \( (z=0) \), and has ice density \( (\rho) \), uniaxial compressive strength \( (\sigma_c) \), ice temperature \( (T_i) \) and ice salinity \( (S) \). Similarly, at time = \( t \), the ice sheet is located at \( (z=z_t) \), and has ice density \( (\rho_t) \), uniaxial compressive strength \( (\sigma_{ct}) \), ice temperature \( (T_{it}) \) and ice salinity \( (S_t) \). Here, we considered the sea ice on the eastern coast of the northern part of Sakhalin island, which has a large amount of natural resources. The calculation conditions used here are shown in Table 2 (JOLA, 2002; Beketsky et al., 1997; Truskov et al., 1993). Random values are taken on uniaxial compressive strength following a lognormal distribution, and ice density and ice thickness following a normal distribution (Takeuchi et al., 1995; Masaki et al., 1996). Randomness of ice salinity and ice temperature is included in that of uniaxial compressive strength. An increase in abrasion amount \( (dA_z) \) at point \( (z) \) during time interval \( (dt) \) can be calculated from Eq.3 and Eq.4. Tidal change is taken as a sine curve \( W(t) \) as in Eq.5 here.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Uni-axial compressive strength ( (\sigma) ) Following Log-normal Distribution</td>
<td>1.5 [MPa] (constant; average) ( (\text{CASE-A}) ) Standard Dev. 0.393[MPa] equivalent to Coefficient of variation 0.262</td>
<td>( (m) ) brittle (( W_r \times P ))</td>
<td>100</td>
</tr>
<tr>
<td>Ice thickness ( (h) ) Following Normal Distribution</td>
<td>1.3 [m] (constant; average) Standard Dev. 0.14</td>
<td>( (m) ) ductile</td>
<td>15 as a reference</td>
</tr>
<tr>
<td>Ice Density ( (\rho) ) Following Normal Distribution</td>
<td>0.8730 [g/cm(^3)] (constant; average) Standard Dev. 0.0237</td>
<td>Movement velocity ( (v) ) for brittle</td>
<td>2778 [m/hour] (equivalent to 1.5 [knot])</td>
</tr>
<tr>
<td>Tide</td>
<td>Sine curve</td>
<td>Movement velocity ( (v) ) for ductile</td>
<td>3<em>10(^{-3}) 3600</em>(h) [m/hour] as a reference</td>
</tr>
<tr>
<td>Half amplitude of tide ( (A_1) )</td>
<td>0, 0.25, 0.5, 0.75 [m]</td>
<td>Materials considered here</td>
<td>Concrete, Steel (Urethane)</td>
</tr>
<tr>
<td>Period of tide ( (T_P) )</td>
<td>24 [hour]</td>
<td>Time interval for calculation ( (dt) )</td>
<td>0.1 [hour] (equivalent to 360 [second])</td>
</tr>
<tr>
<td>Reference width of structure ( (W_r) )</td>
<td>1.3 [m] (constant)</td>
<td>Duration of total calculation</td>
<td>15 [day]</td>
</tr>
<tr>
<td>( (m) ) brittle</td>
<td>1.4 (average)</td>
<td>Calculation pitch in the vertical direction ( (dz) )</td>
<td>0.01 [m]</td>
</tr>
<tr>
<td>( (m) ) ductile</td>
<td>2.0 (average)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Calculation conditions used here

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\[ dA_z(t) = m_v \times \left[ m_x \times \exp\left\{ -m_x \left( \frac{z-z_i}{h_z} \right)^2 \right\} \right] \times \sigma_c \times v \times dt \]  
\[ z_i = W(t) + h_i \left( \frac{\rho_w}{\rho_{sw}} - 0.5 \right) - h_i \left( \frac{\rho_w}{\rho_{sw}} - 0.5 \right) \]  
\[ W(t) = A_z \sin\left( \frac{2\pi}{T} t \right) \]

where \((\rho_{sw})\) is density of sea water.

In the calculation, the distribution of abrasion amount \((A_z(t))\) can be estimated by integrating Eq.3 with respect to time (pitch \(dt\)) at each position \((z)\) with pitch \((dz)\) in the vertical direction. Based on \((A_z(t,r))\) generated to number of \((r)\) at time \((t)\) using random values \((r=1-N_{\text{max}}; N_{\text{max}}=50000)\), average \((A_z^A(t))\) and extreme \((A_z^E(t))\) of abrasion at \((z)\) and \((t)\) are calculated from Eq.6 and Eq.7.

\[ A_z^A(t) = \frac{1}{N_{\text{max}}} \sum_{r=1}^{N_{\text{max}}} A_z(t,r) \]  
\[ A_z^E(t) = A_z^A(t) + 3 \times \left[ \frac{1}{(N_{\text{max}}-1)} \sum_{r=1}^{N_{\text{max}}} (A_z(t,r) - A_z^A(t))^2 \right]^{0.5} \]

**CALCULATION RESULTS**

**Constants on physical value of sea ice**

Using constant values of \((h), (\rho), (\sigma_c)\) and 4 cases of tide amplitude \((A_1)\) under brittle conditions, vertical distributions of abrasion for \((L)\) 1000.1 [km] are shown in Figure 5(a) for concrete and Figure 5(b) for steel and urethane. Abrasion amount is strongly influenced by material type, thus implying that it is better to locally use material having smaller abrasion velocity \((m_v)\) at an active area of structure. In addition, even though a tidal change is assumed to follow a sine curve here, active area and total amount of abrasion are strongly influenced by tidal change, especially \((A_1)\). Therefore, it is better to use precise data of tidal change in the considered sea area for the estimation.

**Variables of physical value of sea ice**

Using random values of \((h), (\rho), (\sigma_c)\) and 4 cases of half amplitude of tide \((A_1)\) under brittle conditions for concrete, 4 types of vertical distributions of abrasion for \((L)\) 333.36 [km] are shown in Figure 6(a), 6(b), 6(c) and 6(d). In particular, an extreme value of abrasion \((A_z^E(t))\) based on the use of 2 types of standard deviations \(0.393\text{[MPa]}\) for CASE-A, \(0.843\text{[MPa]}\) for CASE-B) on uni-axial compressive strength \((\sigma_c)\) is compared to abrasion based on the use of constant values of \((h), (\rho), (\sigma_c)\) (all-constant). For \((A_1)(=0m)\), abrasion slightly decreases for (CASE-A, CASE-B). However, the occurrence of \((A_1)\) slightly increases an extreme value of abrasion \((A_z^E(t))\) over the
Figure 5(a) Vertical distributions of abrasion Concrete

Figure 5(b) Vertical distributions of abrasion Steel & urethane

Figure 6(a) Vertical distributions of abrasion A1=0.0m

Figure 6(b) Vertical distributions of abrasion A1=0.25m

Figure 6(c) Vertical distributions of abrasion A1=0.50m

Figure 6(d) Vertical distributions of abrasion A1=0.75m
active abrasion area, in comparison with that for (all-constant). Furthermore, CASE-B shows slightly larger abrasion than CASE-A. Further, based on Figure 6(a), 6(b), 6(c) and 6(d), the relation between abrasion length \((L)\) and maximum abrasion amount \((A_{\text{max}})\) is plotted for (CASE-B) and (all-constant) in Figure 7(a) for concrete and 7(b) for steel and urethane. Maximum abrasion amount \((A_{\text{max}})\) increases linearly with abrasion length \((L)\). If there is a small tidal change, the effect of randomness on physical properties of sea ice on \((A_{\text{max}})\) is very small, even though the vertical distribution of abrasion changes depending on the randomness. Thus, the vertical position of sea ice influenced by tidal change becomes more important for an active area as well as the amount of abrasion. In addition, ice thickness variation (Kioka et al., 2004a; Kioka et al., 2004b) including ridge should be considered in the future analysis.

CONCLUSIONS

1) A method for estimating the active area and the total amount \((A)\) of abrasion is proposed considering tidal change and local ice pressure distribution. This gives information on countermeasures for reducing the abrasion amount, and the use of materials that have smaller abrasion velocity \((m_v)\) over a limited area of the structure, and that could reduce the weight of offshore structures made of reinforced concrete.

2) Randomness of physical properties of sea ice influences the vertical distribution of abrasion slightly, but has little effect on maximum abrasion amount \((A_{\text{max}})\). Therefore, in the calculation, the vertical position of sea ice influenced by tidal change becomes more important for estimation of abrasion.

3) In the calculation, it is assumed that ice fails in crushing during interaction with a structure. Field measurement of ice pressure in ice/structure interaction is very important for enhancing accuracy in estimating abrasion amount. Furthermore, it is better to consider a variation of ice thickness including ice deformation such as ridges, rubble and so in the future.
REFERENCES
JOIA annual report, (2002), JOIA.