EXPERIMENTAL STUDIES OF ICE RIDGE LOADS ON STRUCTURES

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Experiments to investigate the loads from ridge keels on structures have been performed at Hamburgische Schiffbau-Versuchsanstalt (HSVA) in Germany in scale 1:20. Four ice ridges were built and tests were performed with ice temperature and interaction speed as variables. The structures included two 0.7 m by 0.7 m underwater cubes and one 62°-sloped cone with a water line diameter of 0.6 m. The results indicate that colder ridges exerted higher loads on the structures for slow interaction speeds, but this effect disappears at higher speed. The horizontal loads on the sub sea structures reached a steady state and correlated to the keel profiles. Side tests comprised of seven punch tests, retaining wall tests, oedometer tests and two piling tests were also performed to characterize the mechanical properties of the rubble. A wedge extrusion was observed in the retaining wall test and the time series showed that the plate load seemed to be correlated to the penetration speed. The oedometer test showed the typical behaviour of a loose soil and the compaction behaviour was characterized.

1. INTRODUCTION

Gudmestad and Liferov (2007) discussed the use of sub-sea technology in the ice-covered waters. The design to resist ice actions requires knowledge about the loads that ice ridge keels can exert on bottom-based structures. It is often assumed that the limiting load from ridge keels is associated with either local or global failure. Liferov and Høyland (2004) reported medium scale keel interactions with a solid nearly vertical object. They observed that the keel failure was progressive, occurring while the ice ridge moved forward.

Analytical and numerical models exist, or can be developed, to calculate keel loads on structures. Ice model basin testing is believed to be the first mean to provide input for validation of these models. For a number of reasons, physical-mechanical properties of the model keels are rarely well documented. This negatively affects the confidence in the obtained load values. Therefore, the following objectives were targeted during the present research test campaign at HSVA: Investigate and document ridge behaviour and keel failure mechanisms during the interaction with structures and measure physical and mechanical properties of the keels by different supplementary methods.

2. EXPERIMENTAL SETUP

The HSVA ice tank is 78 m long, 10 m wide and 2.5 m deep. A 5 m deep section of 10 m by 12 m is located at the end of the tank. For the purpose of modeling shallow water conditions bottom elements (false bottom) were inserted into the tank to reduce the water depth. The structures were fixed on the false bottom, which was displaced along the tank by a motor driven carriage able to provide a maximum towing load of 50 kN. The dimensions of the structures, the level ice thickness, the drift speeds and the keel depths were scaled with a Froude scaling of 1:20. Two types of structures were studied: cubical shape for sub-surface keel interaction and simple conical for surface ridge interaction. A plan view of the testing procedure is shown in Figure 1. The principal dimensions of the structures are given in Figure 2.
Four ice sheets (corresponding to test series 1000, 2000, 3000 and 4000) were produced with one ice ridge per ice sheet. The ridges 2000 and 4000 were built from colder ice and tested soon after their production, with very little consolidation (degradation) time allowed. Ridges 3000 and 4000 were tested with an interaction speed of 0.22 m/s, whereas the interaction speed was 0.045 m/s for the ridges 1000 and 2000.

The retaining wall test was proposed to test ice rubble behaviour in the keel under controlled boundary conditions. A general illustration of the retaining wall box seen from below is given in Figure 3. A velocity-controlled piston displaced the pushing plate over a 790 mm course. There was a 10 mm gap between the pushing plate and the inner sides of the retaining wall box. Wheels attached to the pushing plate helped guiding it into the box. The cross section dimensions of the box were 700 * 700 mm, with 15 mm thick walls. The box was 2176 mm long and there was 1670 mm from the initial position of the pushing plate to the end of the box. Figure 4 is a picture of the retaining wall box being lowered into the ice ridge.

The oedometer test was performed to test the properties of the model rubble ice in compaction. It was performed in a cyclic way (loading-unloading-reloading) with a load level increasing for each step. Figure 5 shows the oedometer machine being constructed. Figure 6 shows an illustration of the volumetric box containing the rubble and covered with the velocity-controlled piston. The volumetric box was a steel cylinder of 520 mm diameter and 500 mm high. The bottom of the box was closed and the bottom of the side was drilled with water evacuation holes. The piston was pressing onto a 500 mm diameter wooden plate sliding in the box.
3. MAIN RESULTS AND CONCLUSION

Figure 8 shows the ridge profiles and the loads acting on the portside cube plotted against the position of the front face of the structure, for the test series 1000 and 4000 respectively. The same plots were generated for each interaction event with the cubes. In a general case, the $x$-loads seemed to correlate to the keel profile. They decreased before the valleys of the keel and increased in the vicinity of the peaks. This can be observed in Figure 8 (b). However, some particularities contradicted the previous affirmation, i.e. the final $x$-load peak in Figure 8 (a). On the underwater video, this peak load occurred at the beginning of a 0.2 m increase of the depth of the rubble mound in front of the structure.

The effect of the ridge temperature on the effective pressure was investigated (Table 1). The effective pressure was here defined as the $x$-keel load divided by the area of interaction. The $x$-keel load is equal to the $x$-total load for the cubes, and to the $x$-bottom load for the cone. For the cubes, the area of interaction is computed as the product of the cube width and the distance from the roof to the average keel depth (Table 1). For the cone, the area of interaction is the projected area of the cone interacting with the keel (average keel depth). It appears that a temperature effect is visible for the slow interaction tests (1000 and 2000), where the colder ridge produces a higher effective pressure. At higher interaction speed, no temperature effect could be observed.

<table>
<thead>
<tr>
<th>Test series</th>
<th>Portside Cube (average)</th>
<th>Starboard Cube (average)</th>
<th>Cone bottom (maximum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>1630 Pa</td>
<td>1530 Pa</td>
<td>2840 Pa</td>
</tr>
<tr>
<td>2000</td>
<td>4760 Pa</td>
<td>4760 Pa</td>
<td>4210 Pa</td>
</tr>
<tr>
<td>3000</td>
<td>4285 Pa</td>
<td>/</td>
<td>4210 Pa</td>
</tr>
<tr>
<td>4000</td>
<td>4120 Pa</td>
<td>/</td>
<td>4207 Pa</td>
</tr>
</tbody>
</table>
The underwater video of the retaining wall test showed a wedge failure mode of the rubble as indicated in Figure 9. The force time series also showed an increasing effective pressure (from 1100 to 5200 Pa) for a decreasing plate penetration speed (from 7 to 1 mm/s).

Figure 10 presents a typical curve derived from the oedometer test. The pressure is plotted against the volumetric strain. The time series gave a good indication of the effect of the compaction on the volumetric hardening of model rubble ice. For each one of the cycles shown in Figure 10 the steep linear part corresponded to the elastic domain. Upon loading, the stress reached a critical value (isotropic yield stress) where the slope of the curve suddenly changed. From that point the stress path becomes different upon unloading, the plastic domain was reached. Figure 10 showed that the yield stress and the size of the elastic domain were depending on the volumetric strain.

A closer look at Figure 10 shows that the slope of the elastic part of each cycle is increasing with the compression of the rubble. The bulk modulus was estimated to be 0.6 MPa for the first cycle and 1.14 for the last one. The corresponding Young modulus of the rubble was computed with equation (1).

\[
E = 3K \cdot (1 - 2\nu)
\]

where \(E\) is the Young’s modulus, \(K\) is the bulk modulus and \(\nu\) is the Poisson’s ratio, selected as 0.3, a typical value for granular materials. The Young modulus of the rubble for the first and last cycle was computed to be respectively 0.7 and 1.14 MPa. The estimated range of the Young’s modulus of HSVA’s rubble ice was in good agreement with the Young modulus estimated by Liferov et al (2003).

ACKNOWLEDGEMENT

The authors would like to thank NTNU and StatoilHydro for providing the means to realize these experiments. They also express their gratitude to Dr. Knut Høyland and Ada Repetto for their help and scientific advises. Andrea Haase, Hanne Hagen and Christian Lonøy are also particularly acknowledged for the precious help they provided during the test period. The authors would like to thank the Hamburg Ship Model Basin (HSVA) and the ice tank crew, for the hospitality, technical and scientific support and the professional execution of the test programme in the Research Infrastructure ARCTECLAB. This work has been supported by European Community's Sixth Framework Programme through the grant to the budget of the Integrated Infrastructure Initiative HYDRALAB III within the Transnational Access Activities, Contract no. 022441.

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