Loads on Structure and Waves in Ice (LS-WICE) Project, Part 2: Sea Ice Breaking by Waves

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ABSTRACT

A multi-group investigation was conducted at Hamburgische Schiffbau-Versuchsanstalt GmbH (HSVA) from Oct. 24 to Nov. 11, 2016 under the Hydralab+ Transnational Access project: Loads on Structure and Waves in Ice (LS-WICE). There are four parts to this investigation: wave attenuation/dispersion in broken ice covers, wave-induced ice-floe collisions, ice fracture under wave action, and ice-structure interaction under wave conditions. This paper focuses on the part of the experiment related to wave-induced ice breaking. During the preparatory stage of the tests, a continuous ice sheet was produced, and the mechanical and physical ice properties were determined at a number of selected locations in the Large Ice Model Basin (LIMB). Pressure transducers and ultrasound sensors located at different positions along the ice tank were used to monitor the wave propagation through the ice. Additionally, 3D motion of a few markers placed on the ice was tracked with an infrared camera system (Qualisys Motion Capture System). The progress of breaking was recorded with cameras placed above as well as sideways from the tank. The measurements consisted of two groups of tests, with a constant wave period in each group. The wave amplitude was increased stepwise, starting from a value too low to break the ice, until a major fragmentation of ice occurred. After each group of tests, the locations of cracks were determined and the floe-size distribution was estimated. The paper presents the data collected during the experiment, together with a short discussion of the observed breaking patterns and processes that created them.

KEY WORDS: Ice; Waves; Ice breaking; Floe-size distribution.

INTRODUCTION

Sea ice–waves interactions belong to the dominating processes shaping the features and behavior of the marginal ice zone (MIZ). In fact, mutual wave–ice interactions are a defining characteristic of this type of the ice cover, occurring within a certain distance from the ice edge. The details of these interactions depend on wave parameters, ice thickness and material properties (density, elastic modulus, etc.), but they also influence and are influenced by the floe-size distribution (FSD). The scattering and attenuation of the wave energy – and thus the width of the MIZ – very strongly depend on the sizes of ice floes, which in turn are a product
of wave-induced breaking. In general, FSD is only rarely taken into account in sea ice models, and only very recently equations have been proposed that describe the evolution of FSD in time (Horvat & Tzipermann, 2015) in a manner analogous to the evolution of the ice-thickness distribution, for which a mathematical description suitable for continuum sea ice models is well established. Although substantial effort has been put recently in developing parameterizations of sea ice–wave interactions for numerical models (e.g., Dumont et al., 2011; Williams et al. 2013), our understanding of the details of many important aspects of these interactions still remains unsatisfactory. This is true for wave-induced ice breaking, for which only very rudimentary, approximate models exist (e.g., Langhorne et al., 1998; Squire, 2007; Squire et al., 1995; Kohout & Meylan, 2008). Moreover, lack of validation data restraints further development. The Hydralab+ Transnational Access project “Loads on Structure and Waves in Ice” (LS-WICE) belongs to the first experiments in which a group of tests was devoted to measuring and observing ice breaking by waves under controlled, laboratory conditions. Apart from measuring the wave characteristics at several locations along the ice tank, and the motion of the ice itself, we recorded the progress of breaking, making it possible to analyze the relationships between the wave propagation and the temporal evolution of the crack pattern. Other LS-WICE tests, devoted to wave attenuation in broken ice, kinematics of floes’ collisions, and ice–structure interactions are described in accompanying papers in this volume (Cheng et al., 2017; Li et al., 2017; Tsarau et al., 2017).

DESCRIPTION OF THE EXPERIMENT

An overview of the whole LS-WICE project, including the description of the facility (Large Ice Model Basin at HSV A) and the measuring equipment, can be found in the accompanying paper by Cheng et al. (2017) and will not be repeated here. For the ice-breaking group of tests, a continuous ice sheet was prepared and positioned as shown in Figure 1, by cutting it from the side walls of the tank (the ice strips at both sides, ~10 cm wide, have been removed in order to prevent affecting the ice motions by the interactions with wall and thus the breaking patterns obtained) and by pushing it by 6 m towards the melting tank so that the final ice edge position was at \( x = 20 \) m, approximately 18 m from the wavemaker. The thickness of the ice, measured at a number of locations in the tank, varied between 32.5 and 38.5 mm, with an average of 34.8 mm; the ice elastic modulus equaled 16 MPa; the bending strength varied from 41.5 kPa close to the ice edge to 67.1 kPa in the area close to the beach.

The locations of the pressure and ultrasound sensors used in this group of tests is shown in Figure 1, together with the locations of five markers of the Qualisys Motion Capture System that were placed on the ice along the central axis of the tank, ~1.5 m apart from each other. In order to record the time evolution of the ice breaking pattern, large parts of the ice sheet were continuously monitored with an AXIS camera mounted at the ceiling and two sideward-looking GoPro cameras mounted at the walls. Additionally, static images of the entire ice sheet were taken after two tests in which major ice breaking was observed in order to determine the resulting floe-size distribution.

The list of tests performed in this test group is given in Table 1. The purpose of tests 1100, 1200 and 1300, performed with a small wave height \( H = 10 \) cm for three different wave periods, was to analyze wave attenuation within the continuous, unbroken ice cover – thus, these tests are complementary to those described in Cheng et al. (2017) and devoted
Figure 1. Instrument setup during the ice breaking test: P1–P10 are single pressure sensors, P11/12 – a double pressure sensor, S1 and S2 – ultrasound sensors, q1–q5 – Qualisys markers, dashed black lines – fields of view of sideward-looking GoPro cameras (Silver and Black), dashed blue lines – field of view of the AXIS camera mounted on the ceiling.

Table 1. Summary of test runs performed during the ice-breakup experiment

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Wave height (mm)</th>
<th>Wave period (s)</th>
<th>Test duration (s)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td>10.0</td>
<td>2.0</td>
<td>90</td>
<td>no breaking observed</td>
</tr>
<tr>
<td>1200</td>
<td>10.0</td>
<td>1.6</td>
<td>90</td>
<td>no breaking observed</td>
</tr>
<tr>
<td>1300</td>
<td>10.0</td>
<td>1.2</td>
<td>90</td>
<td>no breaking observed</td>
</tr>
<tr>
<td>1400</td>
<td>20.0</td>
<td>2.0</td>
<td>90</td>
<td>no breaking observed</td>
</tr>
<tr>
<td>1410</td>
<td>30.0</td>
<td>2.0</td>
<td>90</td>
<td>no breaking observed</td>
</tr>
<tr>
<td>1420</td>
<td>40.0</td>
<td>2.0</td>
<td>90</td>
<td>no breaking observed</td>
</tr>
<tr>
<td>1430</td>
<td>50.0</td>
<td>2.0</td>
<td>90</td>
<td>no breaking observed</td>
</tr>
<tr>
<td>1440</td>
<td>70.0</td>
<td>2.0</td>
<td>115</td>
<td>first major crack at ( x = 44 ) m</td>
</tr>
<tr>
<td>1450</td>
<td>90.0</td>
<td>2.0</td>
<td>several minutes</td>
<td>major breaking; test continued until no breaking occurred</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>photos from the crane camera for FSD</td>
</tr>
<tr>
<td>1500</td>
<td>50.0</td>
<td>1.6</td>
<td>90</td>
<td>only a few new cracks observed</td>
</tr>
<tr>
<td>1510</td>
<td>70.0</td>
<td>1.6</td>
<td>several minutes</td>
<td>major breaking; test continued until no breaking occurred</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>photos from the crane camera for FSD</td>
</tr>
</tbody>
</table>

specifically to measuring wave attenuation in broken ice fields. Subsequently, in tests 1400–1450, the wave period was kept constant at \( T = 2 \) s, corresponding to deep-water wavelength \( L = 6.24 \) m, and the wave amplitude was increased stepwise until major breaking of the ice was observed. Finally, two additional tests with shorter waves were performed (\( T = 1.6 \) s, \( L = 3.99 \) m) that led to further breaking of the ice into smaller floes. In all tests, the wave steepness was small enough to justify the use of the linear wave theory (the ratio \( H/L \) was largest in test 1510 and equaled 0.0175).

RESULTS

Stages of Ice Breaking

For long waves used in tests 1400–1450 (Table 1), no breaking of the ice was observed for wave heights up to 50 mm (test 1430). Remarkably, the first major crack, which appeared in test 1440, did not develop in vicinity of the ice edge, but approximately in the middle of the ice sheet, i.e., at \( x \approx 44 \) m (Figure 2a.), after 93 seconds from the start of the wavemaker. In the following test 1450, which led to a fragmentation of the entire ice sheet, this first crack acted...
Figure 2. Snapshots of the ice sheet from the GoPro Silver camera after test 1440 (a), 1450 (b) and 1510 (c), after removal of fish-eye effects. The Qualisys markers are highlighted with yellow circles for better visibility. In (b) and (c), the location of the initial crack is marked with a dashed blue line. Additionally in (b), the time sequence of the crack formation in the initial phases of test 1450 is shown with lines of different colors (according to the color code in the upper left corner of the image).

as a “secondary” ice edge, from which breaking advanced in a down-wave direction in a manner similar to that at the “proper” ice edge. This is illustrated in Figure 2b, in which the sequence of crack formation is shown with lines of different color. Notably, whereas all cracks
numbered 2–6 in Figure 2b. formed during the first 40 seconds of test 1450, no single crack could be recognized on the up-wave side of the first crack during the first 60 seconds. Consequently, at the end of this test, the floes on the down-wave side of this initial crack were smaller than those on its up-wave side (Figure 2b.) and they experienced more intense flooding. Interestingly, a similar breaking sequence could be observed for the part of the ice sheet between the ice edge and the first crack, i.e., after a few floes separated from the main sheet in the ice edge region, a transverse crack formed roughly in the middle, and further breaking took place down-wave from this crack (not shown). In the subsequent test 1500, only a few new (mostly short) cracks developed, even though the overall behavior of the ice cover was visibly different than in previous tests, primarily due to the drift of the ice floes close to the ice edge in the up-wave direction, which led to a decrease of the ice concentration and thus changed the motion of individual floes (larger amplitudes of horizontal oscillatory motion, more frequent and more energetic collisions). Finally, in test 1510, strong breaking took place throughout the ice sheet, accompanied by a strong flooding (Figure 2c.) and progressive deterioration of the floes’ edges due to collisions – a process that produced many very small ice fragments filling spaces between larger floes.

**Ice Motion in Vicinity of the First Major Crack**

As can be seen in Figure 2, the Qualisy markers were placed along a line that was crossed by the first crack in test 1440, and remained in the zone of major crack formation throughout subsequent tests. (Note that although Figures 2 b,c suggest that the markers were directly at the edges of the floes, they remained firmly placed on the ice until the end of the last test.) A detailed analysis of the data from the pressure sensors and the Qualisy system is beyond the scope of this paper, but it is worth mentioning here some overall behavior of the ice sheet, visible in the time series of the vertical displacements of the Qualisys markers q1–q5 (Figure 3.). During the first ~55 s of test 1440, the amplitude of these displacements was nearly identical at all five locations (Figure 3a; note that the distance between q1 and q5 equaled approx. 6 m, i.e., one wavelength). The situation changed during the following ~20 s, after which a new pattern established (Figure 3b.), with increased amplitudes at q2 and q4 and decreased amplitudes at the remaining three markers – presumably due to wave reflection from the beach. In the videos, the first major crack became visible at time $t = 93$ s, i.e., the reflected waves presumably contributed to its formation.

![Figure 3. Fragments of time series of the vertical deflections (in mm) of Qualisys markers q1–q5 (see Figure 1. for their locations). Time is measured from the start of the wavemaker.](POAC17-051)
**Floe-Size Distribution**

Figure 4. shows a fragment of an image of the ice sheet obtained by: (i) stitching together overlapping images of the ice sheet taken with a downward-looking crane camera, (ii) transforming the result to a binary image of ice and water, and (iii) identifying floe boundaries. The floe-size distributions determined after tests 1450 ($N_f = 2269$ identified floes) and 1510 ($N_f = 3422$) are shown in Figure 4. A rank-order statistics is shown rather than binned histograms in order to avoid binning effects that would strongly influence the results, especially in the range of large floe sizes (as can be seen in Figure 5, in both cases less than 100 floes have surface areas larger than 1 m$^2$, and less than 10 floes have areas larger than 10 m$^2$). Moreover, because the shapes of the floes, especially the larger ones, tend to be irregular and elongated, the results are analyzed in terms of the floes’ surface areas instead of their radii? (obviously, this choice does not affect the shape of the curves in a log–log plot in Figure 5.). As can be seen, the floe sizes have an upper bound dependent on the wavelength, and the slopes of the distributions change gradually between the large and small floe regime. In the latter case, as can be expected, the slope is largely independent of the wave properties.

![Figure 4. A fragment of a binary image of the ice sheet after test 1510, with identified ice floes’ boundaries.](image1)

![Figure 5. Rank-order statistics of the surface areas (m$^2$) of ice floes after tests 1450 and 1510.](image2)
DISCUSSION AND CONCLUSIONS

Contrary to the expectations, we did not observe progressive breaking starting from the ice edge. Instead, the ice sheet first broke approximately in the middle of its length, and this first major crack presumably had a profound influence on the subsequent development of fractures. Thus, the breaking pattern in this experiment was very different, e.g., from that observed previously in preliminary tests at the same facility (Nils Reimer, HSVA – personal communication) or in the field (Squire et al., 1995; see also https://vimeo.com/106835989). Obviously, with just one case, it is impossible to determine whether this kind of breaking behavior is a repeatable feature or just a singular event caused, e.g., by unrecognized defects in the ice sheet that may have been created during ice preparation. The data from the pressure and Qualisys sensors suggest the role of reflected waves in the process. Moreover, it should be remembered that the ice sheet was not frozen to the beach at its down-wave end, i.e., it was a freely floating floe roughly ten wavelengths long rather than shore-fast ice, for which most models are developed.

A more in-depth analysis of the experiment described here will be presented in a subsequent paper, together with results of numerical modeling with a new version of the Discrete-Element bonded-particle Sea Ice model (DESIgn; Herman, 2016), extended to include a wave model coupled with an ice model.

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REFERENCES


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