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Loads on Structure and Waves in Ice (LS-WICE) Project, Part 1: Wave Attenuation and Dispersion in Broken Ice Fields

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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 three parts to this investigation: ice fracture under wave actions, wave attenuation/dispersion in broken ice covers, and ice-structure interaction under wave conditions. This paper focuses on the wave attenuation/dispersion part of the investigation. A level ice sheet was produced first. The physical and mechanical properties were measured in the Large Ice Model Basin (LIMB) before passing through a range of waves to obtain the attenuation/dispersion relation. Wave measurements were monitored with pressure transducers and ultrasound sensors. The test sequence began with a continuous ice sheet followed by broken ice sheet. The broken ice sheet was produced by cutting the continuous ice sheet into uniform size floes. A range of floe sizes and wave periods were tested. Results of the data obtained and their implications to wave propagation in the marginal ice zone populated with different broken ice floes will be presented.

KEY WORDS: Ice; Waves; Attenuation; Dispersion.

INTRODUCTION

Reduction of sea ice coverage in the Arctic has opened up shipping and offshore engineering developments. The safe operation of these developments and effective environmental protection strategies rely on better predictions of the Arctic marine condition. One of the most obvious needs is a better wave model, which can take into account the dynamically changing ice cover, in particular in the marginal ice zone. After several decades of intensive development, global wave models such as WAVEWATCH III (Tolman, 2014) have reached a satisfactory level for open water regions. However, under partially and fully ice covered seas, these models need much more work.

The project LS-WICE "Loads on structures and waves in ice" was granted by the Hydralab+ project under the Horizon 2020 EU-Framework programme for research and innovation (H2020-INFAIA-2014-2015). The current Hydralab+ project runs from September 2015 until August 2019, in which 24 partners and 9 associated partners form a network of research institutes. The goal of this network is to strengthen the experimental hydraulic and ice engineering research to better address climate change adaptation issues.

The LS-WICE experiments were carried out by an international group of researchers from Norway, Poland and USA in the Large Ice Model Basin (LIMB) at the Hamburg Ship Model Basin (HSVA).The test facility in the LIMB was a 72 m long, 10 m wide and 2.5 m deep ice tank. Four flap type mobile wave generator modules cover the total 10 m width of the ice tank. The maximum wave height of this facility is limited to 0.25 m and the maximum wave period is 3 s. At the end of the basin a parabolic shaped beach especially designed for this project was installed in order to minimize wave reflection. Ice sheets were produced under air temperature of about -22 deg Celsius.

Figure 1 shows the elevation and the plan view of the LIMB and Figure 2 shows the mobile wave generator modules and the parabolic shaped beach at the end of the ice tank.

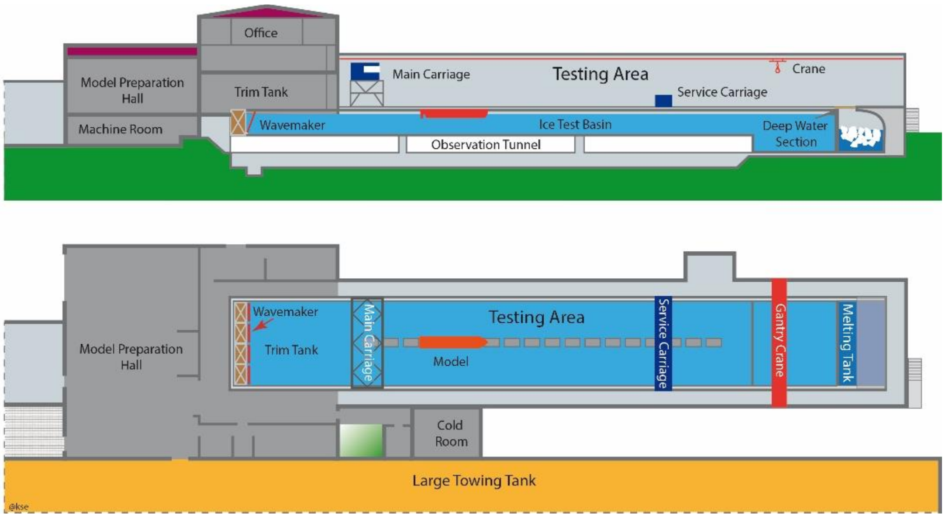

Figure 1. Elevation view (top) and plan view (bottom) of the LIMB.

Figure 2. Mobile wave generator modules (left) and parabolic shaped beach (right).

The test program was executed in open water and in 4 ice sheets. A cylindrical structure (0.69 m diameter) was stationarily anchored in ice sheet no. 4 in order to measure the ice and wave forces acting on the cylinder as shown in Figure 3. Each of these tests had different purposes. The open water case was performed to characterize the wave tank behavior and to calibrate all sensors. Ice sheet no. 1 was constructed to perform the break-up test. Ice sheets no. 2 and no. 3 were used to test wave attenuation and dispersion under different monochromatic waves. Ice sheet no. 4 was produced to test ice-structure interaction in the presence of a wave field.

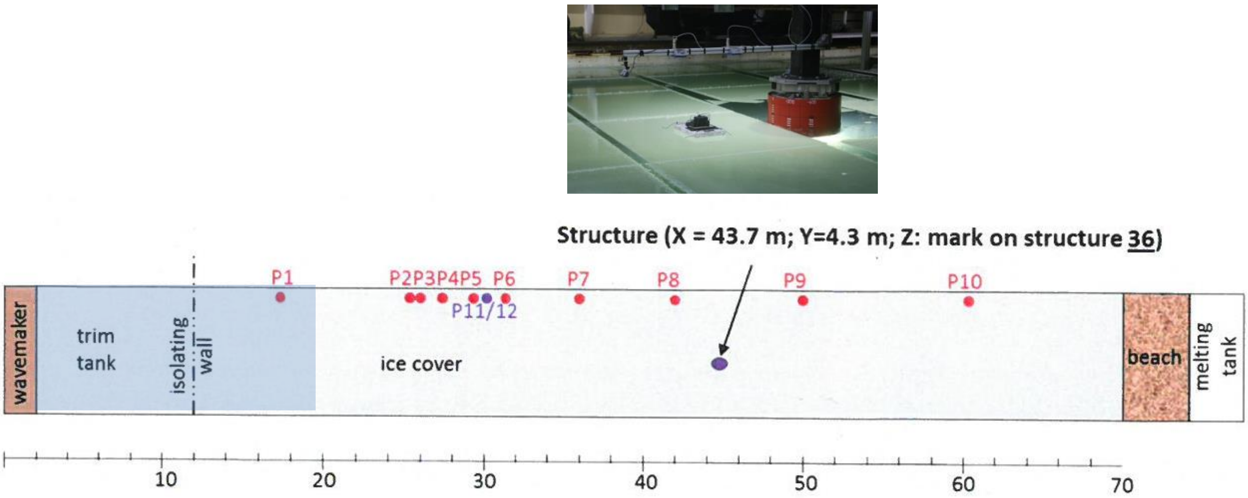

Figure 3. Layout of the wave tank and location of pressure sensors in open water tests (note: locations of sensors changed everyday.)

The wave field was monitored by two types of sensors: ultrasound and pressure, one determined directly the surface elevation and the other the dynamic pressure which was related to the surface elevation. The ultrasound sensors were UltraLab (model ULS Advanced USS 13-HF, IP65, M30x1.5). The pressure transducers included ten BD (model LMP307, 0.1 bar range), and two Omega (PX437 and PX438, range 0.14 bar range). A Qualisys Motion Capture System together with markers that were placed on the ice along the central axis of the tank to monitor the motion of ice surface. 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 with a Canon EOS 550D digital reflex camera after two tests in which major ice breaking was observed in order to determine the resulting floe-size distribution.

The study presented in this paper concerns only the wave attenuation and dispersion part of the LS-WICE project. There are three accompanying papers at this conference each addresses a different topic (Herman et al., Tsarau et al., and Li et al., see this Proceedings). This paper is motivated by this purpose: to determine the effect of ice in the marginal ice zone on wave propagation.

BACKGROUND OF THE STUDY

Sakai and Hanai (2002) reported an interesting experiment that showed floe size effect on wave dispersion. The experiment used a polyethylene sheet floating on water. The phase speed of a range of wave period propagating over this sheet was measured using ultrasound sensors. The first set of measurements was conducted using an intact sheet. The sheet was then cut successively into smaller and smaller strips. After each reduction of strip size, keeping the entire cover the same length, the same wave tests were conducted. The results showed clearly a decreasing wave speed as the strip size reduced, suggesting a reduction of the "equivalent" elastic modulus of the fragmented floating cover. This study inspired a couple of subsequent laboratory investigations. However, instead of focusing only on the floe size, these later studies included other effects. In Wang and Shen (2010), pancake ice mixed with frazils was used. In Zhao and Shen (2015) grease ice, pancake ice, and randomly fragmented ice covers were used. These tests showed that wave speed might change in different ice covers, particularly in fragmented ice covers. Furthermore, wave attenuation was clearly detected in all cases. However, due to the size of the wave tank, only very narrow range of wave period could be tested. These past studies encouraged a systematic investigation using real ice cover but in such a way that only floe size was allowed to change, as reported in this paper.

DESCRIPTION OF THE EXPERIMENT

We focused on the effect of floe size (D) relative to wavelength (λ) on wave propagation. Parameters to be determined from these two inputs include the wavelength and the attenuation rate.

The procedure of producing the ice cover with different floe sizes is described below. A level ice sheet was formed by seeding first to create a granular layer. Sustained cooling thickened this top layer by columnar growth until the whole sheet reaches about 0.035 m thickness. The Young's modulus, flexural strength, ice thickness, density and salinity were then obtained.

The intact ice cover was first freed by cutting a narrow strip about 0.1 m from the walls. A sequence of wave tests with different wave periods was first applied to the intact level ice cover. The intact level ice was then cut longitudinally into six 1.5 m wide strips parallel to the wave tank wall. Transverse cuts were applied to create floes of uniform sizes. We started with cuts of 6 m long floes. After applying a set of wave tests with different periods, these floes were further cut into 3 m, then 1.5 m, and finally 0.5 m floes. Each time a pattern of uniform size floes was produced. Figure 2 shows the floe field for the 6 m case and the 0.5 m case.

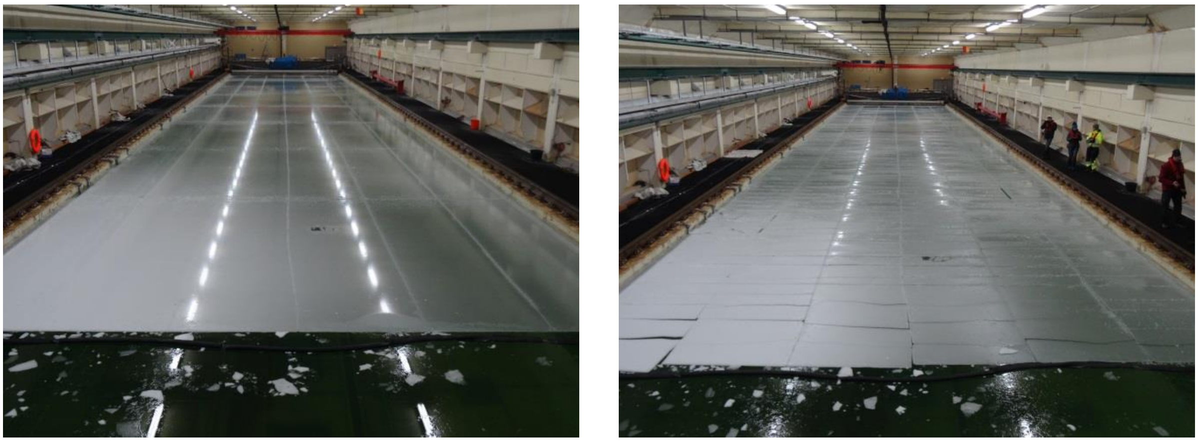

Figure 4. The regular pattern of ice floes tested were 1.5 m wide. The length of the floes started with 6 m, as shown in the left side photo and ended with 0.5 m, as shown in the right side photo, both taken just after the cutting prior to the wave tests.The whole ice cover was refrained from spreading by the boom at the leading edge. The first row of the 6 m long floes was broken by waves as evident from the right side photo.

The wave tests included wave periods between 0.9 to 2 s, starting from long wave to minimize the risk of breaking floes. However, the 6 m floes were proven to be too long to keep their integrity. The first row of these floes did break, as can be seen from Figure 4 (right side photo).

A stop-go wave test was performed. Each run lasted between 80 to 90 s, sufficient for each of the wave tested to travel the entire wave tank and return to ice edge. However, because no beach could perfectly absorb wave energy, to avoid effects from reflection, only a portion of the wave record before any wave reflection will be used for further analysis.

RESULTS

A typical set of pressure sensor data are shown in Figure 5. In Figure 5(a). from bottom to top the curves represent measured dynamic pressure from P1 to P9, respectively. Wave height in the open water (measured by P1) is clearly higher than that by the first sensor under ice cover (P2), suggesting some wave energy was reflected by the ice cover. Attenuation is clear by comparing the wave height from successive sensors. However, dynamic pressure defined as $\rho g \eta \frac{\cosh k(h+z)}{\cosh kh}$ is influenced by the sensor location z (with origin at the calm water level and positive upward), where η is the water surface elevation, h the water depth, ρ the water density and g the gravitational acceleration (Dean and Dalrymple, 1984). Data presented in Figure 5(a). need to be corrected by the small but not negligible differences between sensors before attenuation may be correctly measured. Phase shift between sensors can be seen from Figure 5(b). The time lag and distance between a pair of sensors will be used to determine the wave phase velocity first. From which the wavelength can be calculated using the relation $c = \lambda/T$, where c is the wave phase velocity and T is the wave period.

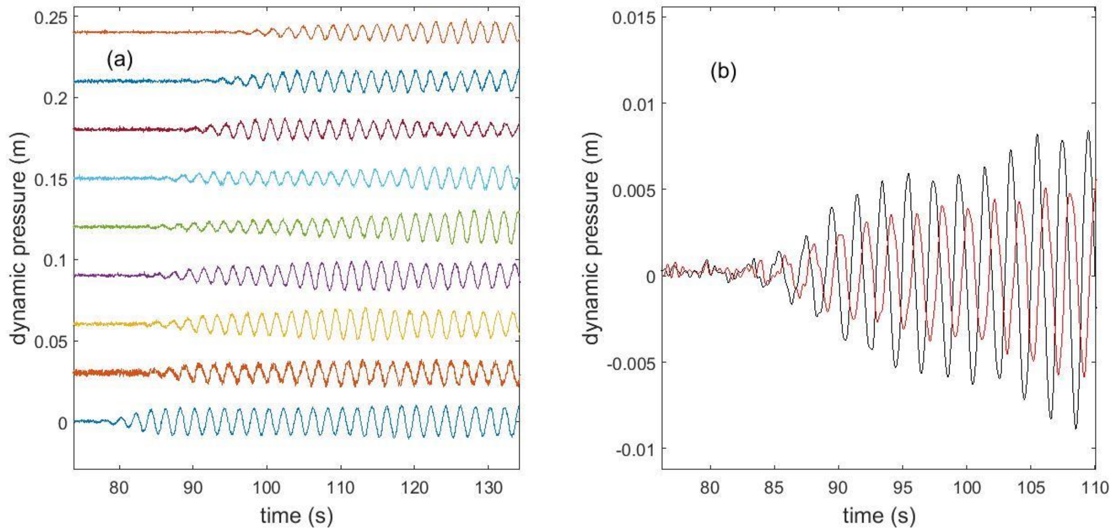

Figure 5. A sample test data. The vertical axis is the dynamic pressure divided by ρg. (a) All pressure data were vertically shifted to aid visualization; (b) A pair of pressure sensors, where both wave height and phase difference are clearly seen. The wave period in this case was 2 s and floe size 3 m.

In Figure 6. we compare the wave speed between two cases of different floe sizes, both are from $T = 1.4$ s. The left panel is from floe size 1.5 m and the right panel is from floe size 0.5 m. The arrival of the wave from P2 to P9 is faster for the ice cover consisting floes of 1.5 m than that from floes of 0.5 m. Attenuation is also observed to be greater in the case with smaller floes.

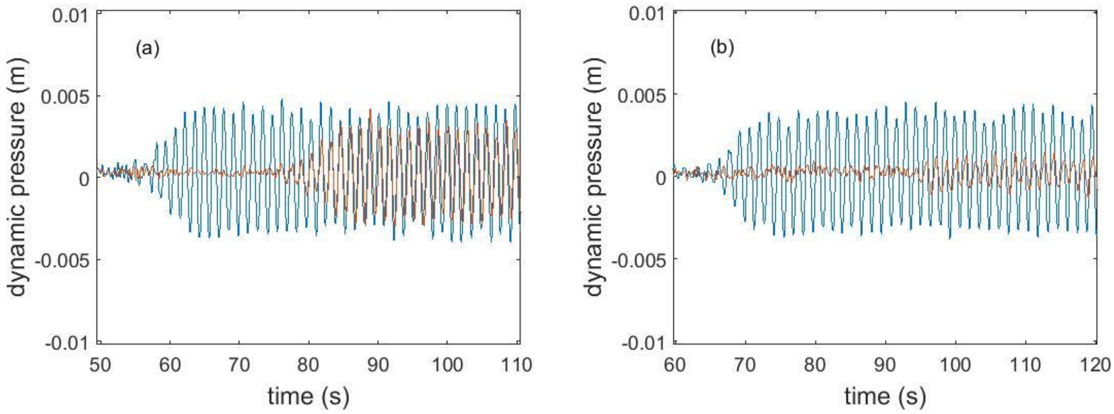

Figure 6. Comparison of wave arrival at P2 and at P9 for $T = 1.4$ s but different floe sizes: (a) 1.5 m (b) 0.5 m.

DISCUSSION AND CONCLUSIONS

In addition to laboratory studies mentioned earlier, a recent field experiment (Rogers et al., 2016) also showed that wave attenuation depended on the type of ice covers. Theoretical studies of how an ice cover might attenuate waves and change its dispersion relation are many. Squire (2007) provided a review of the theories up to that publication time. These theories have only been partially confirmed by a number of field experiments. Meylan et al. (2015) reported attenuation in the order of 10^{-5} (m^{-1}) in the Southern Ocean marginal ice zone with floes that were 2-3 m near the ice edge to 10-20 m about 200 km from the ice edge. The floes were 0.5-1 m thick first year ice. Doble et al. (2015) reported attenuation in the order of 10^{-3} (m^{-1}) in the Weddell Sea. The floes were newly formed pancake ice with size ~0.7 m and thickness 0.05-0.1 m. The space between floes was filled with frazil ice. The ice conditions of these two studies were very different from each other, and also very different from the much earlier study of Wadhams et al. (1988), in which they reported several field studies in the Arctic marginal ice zone including Bering and Greenland Seas. The range of attenuation was from 10^{-5} – 10^{-4} (m^{-1}). The ice covers consisted floes from 5-50 m with a range of thickness from 0.4 to 1.2 m in the Bering Sea and 3.1 m in the Greenland Sea. These studies strongly suggested that wave attenuation is a result of the combination of ice type and floe sizes.

To isolate ice effect on wave propagation from other mechanisms such as wind wave generation, nonlinear wave-wave energy transfer, and wave breaking, laboratory studies are necessary. The present study demonstrated a systematic approach to determine floe size effect on wave propagation. To scale up the results from a laboratory size wave and floes to the field, we need to determine the dominant length scales that can link the laboratory to the field conditions.

Detailed results of this study will be reported later in a journal paper. Wave-ice interaction may include many physical mechanisms as discussed in Shen and Squire (1998). In this experiment, the total attenuation from all processes present in the experiment is measured. Likewise, wave dispersion data are also the result of coexisting mechanisms. The dataset can potentially be used in many future studies.

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