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Wave propagation in frazil/pancake, pancake, and fragmented ice covers

Xin Zhao, Hayley H. Shen *

Department of Civil and Environmental Engineering, Clarkson University, Potsdam, NY 13699, USA

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ABSTRACT

As waves propagate under ice covers, their length and amplitude, as well as the directional distribution of energy may change. These changes depend on the wave frequency and properties of the ice cover. There are several theories for these phenomena, but very limited data to validate these theories. In 2008 a laboratory study at the Hamburgische Schiffbau-Versuchsanstalt GmbH (HSVA) the wave dispersion, including both wavelength change and wave attenuation, was measured for a grease/pancake ice field. The results were compared to those from a grease ice field formed in a smaller wave tank at the University of Washington. It was shown that wave propagation under a grease ice cover followed that of a viscous layer model, but under a pancake ice field it did not. A more extensive experiment was conducted again in 2013 at HSVA to further investigate the wave dispersion. The results reported here are from that experiment with three different types of ice covers: frazil/pancake ice, pancake ice, and fragmented ice floes. The wave number and attenuation are obtained for several monochromatic waves over a range of frequencies. Using an optimization procedure to inversely determine the model parameters, we estimate the equivalent viscoelastic properties of these ice covers. We show that different ice covers require different parameterization to reflect the observed dispersion, hence a possibility of a direct relation between ice morphology and its equivalent mechanical parameters.

1. Introduction

Sea ice reduction has increased the amount of open water in the Arctic. Opportunities in mining and shipping require better knowledge of this new environment. As a consequence, wave propagation through ice covers has become an important topic for maritime operations in the Arctic. Operational wave models previously included ice in a rudimentary way (Tolman, 2003). These models have begun considering many physical processes that have been studied theoretically and through direct observations (Squire, 2007). For instance, WAVEWATCH III® (WW3) now includes ice effects by considering viscoelasticity from the ice cover, or the eddy viscosity from water (Tolman and WAVEWATCH III® Development Group, 2014). Presently, these effects are modeled theoretically using parameters that need to be determined by measured data.

While field data, in-situ or remotely sensed, are required to parameterize and validate models for new conditions in the Arctic Ocean, laboratory experiment provides a much more controlled and less expensive supplement. In 2008, an opportune test was conducted during a large multi-group ice growth experiment at HSVA (Wilkinson et al., 2009). In that test, wave propagation through a grease/pancake ice field was measured. The results were compared with a model that assumed ice covers as a pure viscous material. Though this model agreed well with laboratory data taken with a soft grease ice cover under warm temperature (Newyear and Martin, 1999), it did not agree well with the grease/pancake ice cover under cold temperature (Wang and Shen, 2010a). More extensive tests were not feasible in 2008.

In 2013, an experiment was conducted at HSVA again. As a separate part of a larger study led by Jeremy Wilkinson of the British Antarctic Survey, a two-day experiment was performed to measure wave–ice interactions for three different ice covers: frazil/pancake ice, pancake ice, and fragmented ice floes.

Three former laboratory studies are closely related to the present investigation. The first was a study of wave propagation through a grease ice field mentioned earlier (Newyear and Martin, 1999), in which it was found that the wave dispersion data agreed with a viscous layer model (Keller, 1998). By matching the measured wave number and attenuation, the effective viscosity of a grease ice layer was determined to be on the order of 10^4 times that of water. The second was a study of wave propagation through polyethylene sheets (Sakai and Hanai, 2002). The total length of the polyethylene cover was kept the same but in each wave test the sheets were cut into successively smaller segments. It was found that by reducing the size of the segments without changing the cover's overall dimension the wave speed was reduced. The thin elastic plate theory (e.g. Wadhams, 1986) was used to fit these data, from which it was shown that the equivalent rigidity of the cover reduced with decreasing floe size. The third was a study of wave propagation through a grease/pancake ice field (Wang and Shen, 2010a), also mentioned earlier, where they propagated waves through a mixture of frazil and pancake ice field. They found that the viscous layer theory did not agree with the data. These three laboratory studies

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* Corresponding author. Fax: +1 315 268 7985.
E-mail address: hhshen@clarkson.edu (H.H. Shen).

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indicate that a pure viscous model may not be sufficient to describe different ice cover types. A rigidity parameter, which might be floe size dependent as shown by Sakai and Hanai (2002), is also required. A viscoelastic model is a candidate because it allows for two parameters: the rigidity and the viscosity, to be included in the dispersion response (Wang and Shen, 2010b). In the present paper, the 2013 HSVA data are used to illustrate the data processing and the inverse method to determine the rigidity and viscosity parameters from the measured dispersion data.

2. The experiment

The sketch of the facility used in the 2013 HSVA experiment is shown in Fig. 1. There were two wave tanks operating independent of each other. Data reported here is from tank 3 (Figs. 1 and 2). Tank 2 was dedicated to other purposes unrelated to the present study. Before the experiment, the voltage signals from the Omega PX pressure sensors were calibrated with the water elevation. In the following sections the 'raw data' refer to the calibrated water elevation. The tanks were filled with salt water. The water depth in the tank was 0.94 m and 0.93 m with corresponding nominal depth of all sensors at 0.24 m and 0.23 m for test 1, and tests 2 & 3, respectively. Three types of ice covers were formed during the experiment, as shown in Fig. 3. Detailed information of the facility, the pressure sensors, the formation of ice and collection of experimental data can be found in the experimental reports (Callinan et al., 2014a,b). Ice thickness and floe size were sampled with a mesh-scoop shown in Fig. 4. This tool was used in all our previous experiments (e.g. Shen et al., 2004; Wang and Shen, 2010a). Water was drained from the mesh bottom of the square scoop after inserting the tool sideways through the thickness of the ice cover and gently lifting the sample off the surface. The thickness of the whole ice cover, which consisted of a slushy bottom layer and one or more pancakes on top (if pancakes were formed), and the diameter of the pancake ice were estimated using the scale on the tool. Another sampling of the in-situ ice thickness as reported by Smedsrud and Skogseth (2006) was also used in the frazil ice stage. This method involved using an open cylinder to puncture through the ice cover vertically, then plugging the submerged end and lifting the cylinder off the wave tank. The ice thickness floating on top of the water in the cylinder was then estimated using the scale on the cylinder wall. After pancakes have formed the in-situ measurement was stopped due to the difficulty of puncturing the relatively rigid ice cover. Using the 2008 data from both methods, we determine that the drained thickness using the mesh-scoop was about 2/3 that of the undrained values using the cylinder.

As shown in Fig. 3, three types of ice covers were tested: test 1 is frazil/pancake ice, test 2 pancake ice, and test 3 fragmented ice. Frazil/pancake ice is typical in the early stage of an ice cover formed in a wave field. The mixture of frazil crystals and small pancake-shape ice floes gradually coagulates into well-defined circular pancakes. They eventually freeze together to form a continuous sheet. These ice sheets may fracture under storms to form a fragmented ice cover. More on the ice formation process and corresponding images may be found at http://nsidc.org/cryosphere/seaice/characteristics/formation.html and http://aspect.antarctica.gov.au/home/glossary-and-image-library.

Test 1 was conducted first with a mixture of frazil/pancake ice cover. Test 2 was done after a period of freezing to mature the frazil/pancake into a field of pancake ice. After test 2, the wave was turned off to allow the ice cover to consolidate. This sheet was manually fractured to form a fragmented ice field for test 3. The ice cover thickness and the diameter of the typical pancake are shown in Table 1. Within each test, the frequencies used were roughly from 0.5 to 1.1 Hz. The range of frequency is dictated by the length of the wave tank, the stability of the wave maker, and the attenuation of wave. Lower frequencies would produce waves too long for the length of the wave tank. Higher frequencies impede safe operation of the wave paddle. They also result in waves that damp too quickly to be measured. At each frequency we repeated the test run at least once whenever possible. Under some ice conditions, high frequency waves were damped significantly before they reached the sensors hence no measurements were obtained. We used a stop–go procedure to avoid the reflected wave from the beach. Only the first part of the time series shortly after the arrival of the waves at the sensor locations was utilized. The sampling frequency was 100 Hz, and each wave run was 60 s, starting from the quiescent condition. Each run was followed by a 2 min resting period. A longer rest period was impractical. The sensors registered mainly noise after this period.

3. Data processing

The same data processing procedure is applied to all runs. We first apply an eleven point running average filter to the raw data. To avoid phase-shift, the average is centered at each point. The filter width is 0.1 s, corresponding to a low pass filter of 10 Hz cutoff. Hence it removes

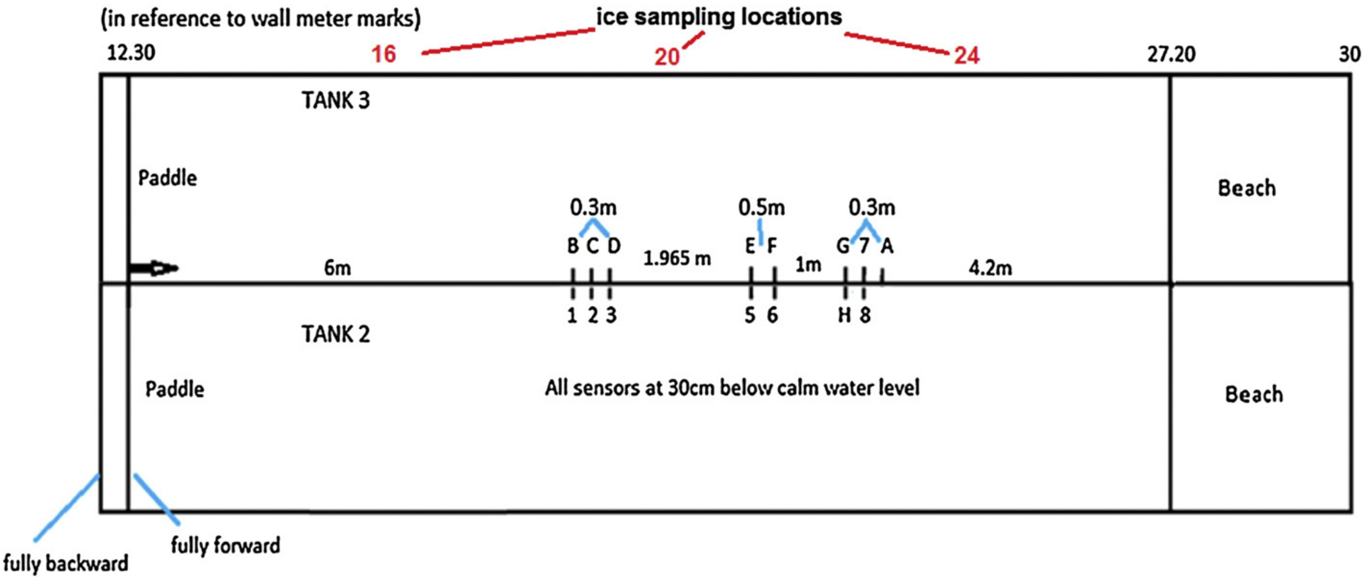

Fig. 1. Basin configuration and pressure transducer locations.