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# WAVE PROPAGATION IN ICE – A LABORATORY STUDY

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## ABSTRACT

The opening up of the Arctic increases the possibility of shipping and offshore engineering. The challenge, however, is the insufficient understanding of the air-ice-ocean system. In particular, more open water in the Arctic has increased the wave intensity. As a consequence, wave propagation through the dynamically changing ice covers in the Marginal Ice Zone (MIZ) has become an important topic for all maritime operations in the Arctic.
Waves and ice covers mutually affect each other. At the formation stage, waves create grease/pancake ice from open water. As the ice edge extends, waves damp out to allow the pancake ice field consolidate into a solid ice cover. At a later stage, waves may fracture an existing solid ice cover.
While field data, in-situ or remotely sensed, are required to parameterize and validate models for the "new Arctic ocean", laboratory experiments provide a much more controlled and less expensive alternative. At present, there are only a few international field campaigns planned. For engineering needs, well-controlled test conditions and the investigation of a broad range of parameters are required.
At present there are several engineering projects/activities in ice-covered waters: wind farms, oil/gas rigs, ice navigation route planning, and oil spill mitigation. These will be located in the MIZ, where dynamically changing ice conditions prevail.
Because different challenges exist for different projects/activities, all of them need to have an accurate prediction of the wave climate.
Results from a systematic investigation of wave attenuation and velocity change carried out in HSVA's ice tanks for various types of ice (frazil, pancake ice, ice floes of different sizes and thickness) are presented.

## INTRODUCTION

The extent of the Arctic sea ice has reduced significantly recent years. Instead of an ocean mostly covered by a continuous ice cover, the Arctic now has a large expanse of open water adjacent to a dynamically changing ice cover called the Marginal Ice Zone (MIZ). We expect that most of the future engineering activities will take place in this zone. Further increase in global temperature of 1-2$^{o}$C may continue to accelerate the Arctic ice reduction in the future (Wang and Overland, 2009). At the same time, storm frequency and intensity have both increases in this region (Young et al. 2011). Along with the opening of the Arctic, the activities related to Arctic shipping and installation of offshore structures for extraction of oil and gas increase.
Today there is the insufficient understanding of the air-ice-ocean system. In particular, more open water in the Arctic has increased the wave intensity. As a consequence, wave propagation

through the dynamically changing ice covers in the MIZ has become an important topic for all maritime operations and offshore engineering activities in the Arctic.

Waves and ice covers mutually affect each other. At the formation stage, waves create grease/pancake ice from open water (Figure 1a). As ice edge extends, waves damp out to allow the pancake ice field (Figure 1b) consolidate into a solid ice cover. At a later stage, waves may break an existing ice cover. Further wave actions, depending on the wave intensity, may leave the ice cover as a scattered puzzle of ice floes (Figure 1c), continue to pulverize the ice floes into a brash ice field, or shape them into anything in between.
On the other hand, ice covers attenuate waves and change their velocity. Both attenuation and speed change depend on the mechanical properties of the ice cover. However, the mechanical properties of different ice covers, particularly as a collection of frozen/broken/refrozen conglomerate as often present in the MIZ, are unknown.

(a) (b) (c)

Figure 1. Formation of pancake ice in a wave field in the Kara Sea (a), pancake ice (b) and newly fragment ice sheet (c); Photo (b) source: National Institute of Water and Atmospheric Research (NIWA), The University of Waikato, Hamilton, New Zealand.

Today little data is available to build a necessary knowledge base for wave propagation in the MIZ. A few field studies during Marginal Ice Zone Experiments (MIZEX) and some isolated field campaigns in the Antarctic region have only shown that wave attenuation is strongly dependent on frequency (Wadhams et al. 1986, 1988). High frequency waves can be damped down over a distance of several meters, while swell propagates undisturbed for hundreds of kilometers. Remote sensing data showed that oblique waves may change their direction upon entering an ice cover, which indicates that the wave speed is changed between the open water and inside an ice cover (Liu et al., 1991).
Only few laboratory studies of wave propagation under ice sheets have been executed. Wave experiments conducted in a small wave tank at the University of Washington have shown that that a change of wave velocity and attenuation both happen in grease ice fields (Newyear and Martin, 1997; 1999).
Another experiment in a larger wave tank in Japan showed that wave speed slowed down in pure elastic synthetic ice covers when the floe size was reduced (Sakai and Hanai, 2002).
Since 1997 several studies were carried out at HSVA over the years to investigate wave-ice interaction associated with pancake ice formation. This paper gives an overview of “waves in ice” experiments carried out in the ice tanks of the Hamburg Ship Model Basin (HSVA) over the last 18 years.

## WAVE-ICE EXPERIMENTS IN THE ARCTIC ENVIRONMENTAL TEST BASIN

### *INTERICE Project*

During the INTERICE-project Eicken et al. (1998) performed in 1998 experiments in a wave field which mainly addressing the effects of wind, current and wave conditions on the formation of pancake ice, the evolution of ice cover morphology and ice microstructure and salinity of frazil ice. Wave damping and its effect on the wavelength spectrum in different ice types was also investigated. It was found that the frazil and pancake formation process depended on the presence of wind. Stable, uniform pancake ice covers were formed in the absence of no wind, while under the presence of wind and under same wave conditions a frazil layer continued to thicken without clear formation of pancakes. Given time, formed pancakes coagulated with neighbors to form composite pancakes. The appearance of composites coincided with an significant increase of wave damping. More details of the pancake ice evolution in the experiments can be found in Leonard et al. (1998).
In 2001 an experiment to study pancake ice growth in a wave field has been conducted in the Arctic Environmental Test Basin (AETB). For the tests a twin wave tank facility was built. Two wave generator in the twin tanks with identical geometry produced different waves ranging from 0.5-0.9 Hz in the same cold room. Data obtained in the experiment are used to identify the ice production rate that may be attributed to wave actions and to determine the relation between the ice cover morphology and wave characteristics (Shen et al., 2004).

### *RECARO Project*

In the framework of the *REduced ice Cover in the ARctic Ocean* (RECARO) project a number of different experiments involving waves of different frequencies and amplitudes were conducted in the AETB (Figure 2). The simultaneous measurements of the same oceanic and cryospheric parameters during the ice formation process should provide new insight into a large variety of questions relating to the different regimes of ice formation: *ice growth, brine drainage, pancake ice formation, mechanical strength/crystal properties, optical properties* and *wave attenuation* (Wilkinson et al., 2009).
RECARO wave experiments were carried out by Wang and Shen (2010) to isolate the mechanical actions of the waves from thermodynamic effects. A a study was done in a pancake ice field to show that both wave attenuation and speed change took place.
At the beginning of the experiment the water surface was ice free and maximum cooling was applied to rapidly decrease the air temperature. At the same time the wave paddles were active to generate frazil ice. After 28 hours the ice cover consisted of 90 mm thick layer of grease and pancake ice mixture. It was observed that the size of pancakes increased towards the beach.
Before starting the wave experiment the wave generators were switched off to calm down the water surface. The air temperature was kept constant at -12° during the 3 hours lasting wave experiments. In each test run the frequency and paddle stroke in both tanks were identical and each frequency test run was repeated three times to ensure consistent results.
Before each test run the undrained ice thickness was measured at 4 locations using a sampling cylinder and the drained ice thickness was also measured by scooping up a portion of ice every 2 m beginning from 3 m away from the paddles to 13 m before and after the complete set of experiment. Time series from seven pressure transducers submerged 250 mm below static-water-level were recorded with a sampling rate 10 Hz for 1 minute (Wang and Shen, 2010).
The wave frequency was read from the wave generator controller and also determined from the pressure transducers. Four different frequency estimators were applied to the entire set of selected time series after deleting the calm water part. The result was that the standard

deviations of the estimated frequencies for all cases was negligibly small and the mean frequencies were close to the wave generator frequency readings as shown in Table 1 and 2. Consequently the mean frequencies were adopted for the subsequent analysis (Wang and Shen, 2010). With the wave experiments carried out by Wang and Shen the validity of a two-layer viscous model for grease-pancake ice mixture should be verified.

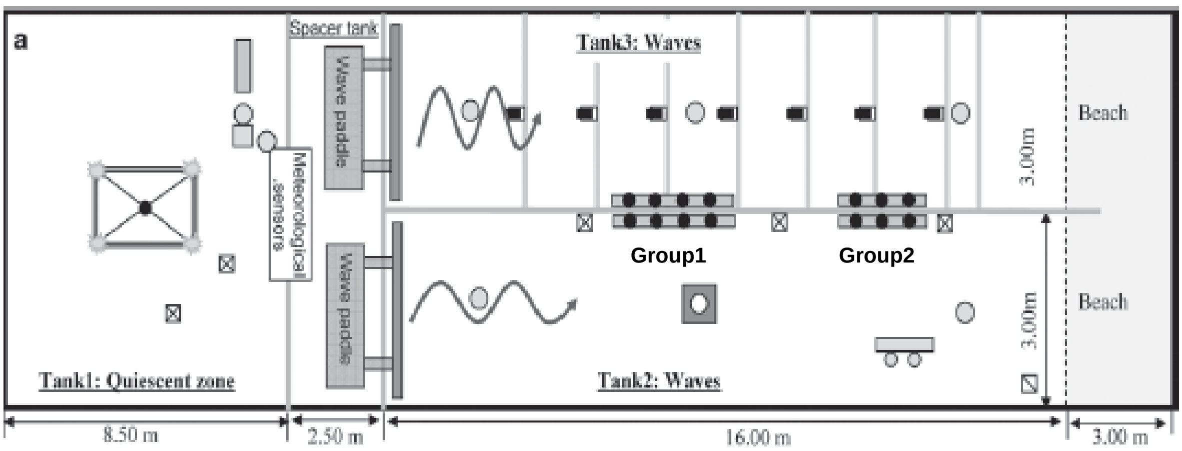


Figure 2. Schematic of the layout of the AETB during RECARO experiments.

### *Wave Number and Attenuation Rate*

The normalized wave number κ and attenuation rate α are defined as

$$\kappa = k/k_0 \qquad ; \alpha = q/k_0 \qquad (1)$$

where $k_0$ is the open water wave number obtained from open water dispersion relation $\sigma^2 = g\, k_0 \tanh(k_0\, d)$, where $d$ is the water depth, $\sigma = 2\,\pi\, f_M$ is the angular frequency and $g$ the gravitational acceleration.

The observed parameters for TANK 2 and TANK 3 are presented in tabular form in Wang and Shen (2010). The normalized wave number $\kappa$ and normalized attenuation rate $\alpha$ for various frequencies $f_M$ is shown in Figure 3 and Figure 4 respectively. The reading wave generator frequencies for five test runs were: 0.50 Hz, 0.65 Hz, 0.80 Hz, 0.90 Hz and 1.10 Hz for both tanks.

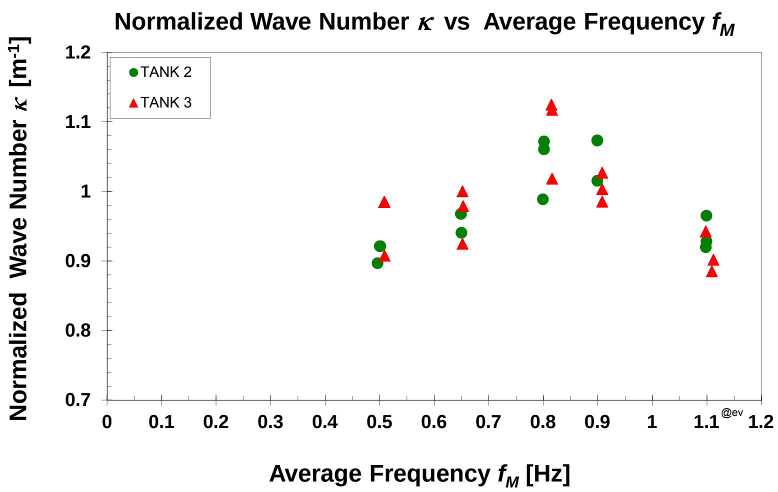


Figure 3. Normalized wave number $\kappa$ plotted for various frequencies $f_M$. The green circle is the normalized wave number in TANK 2, red triangle is the normalized wave number in TANK 3.

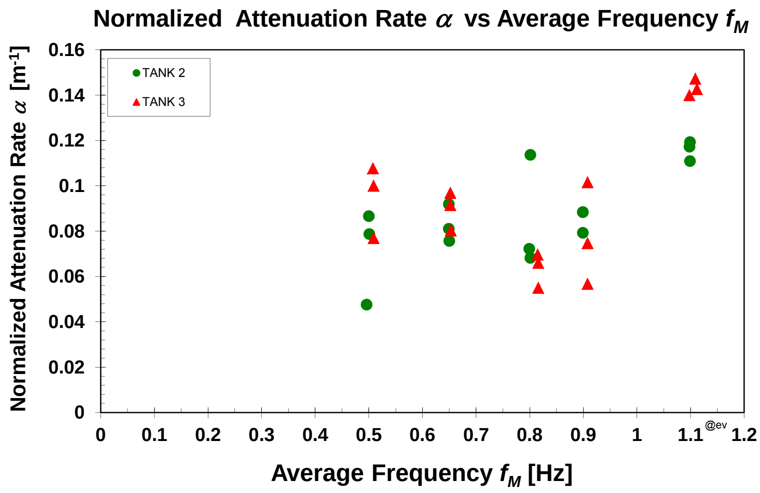


Figure 4. Normalized attenuation rate $\alpha$ plotted for various frequencies $f_M$. The green circle is the normalized attenuation rate in TANK 2, red triangle is the normalized attenuation rate in TANK 3.

In Figure 5 the normalized attenuation rate α is plotted versus ice thickness. Although the scatter of the data is large, a slight increase of attenuation rate α is observed with increasing ice thickness h.

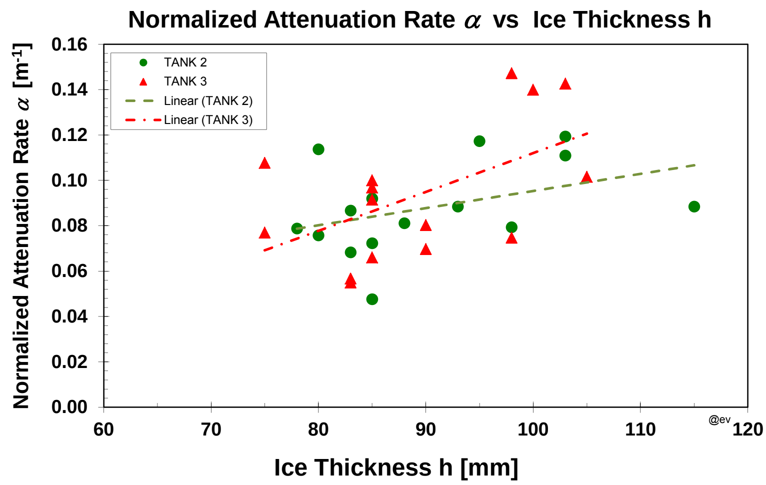


Figure 5. Normalized attenuation rate $\alpha$ plotted for various ice thickness h. The green circle is the normalized attenuation rate in TANK 2, red triangle is the normalized attenuation rate in TANK 3.

***Pancake Size and Ice Thickness***

The change of pancake size and ice thickness during the experiment was mainly caused by wave advection and less by thermal growth. The average drained ice thickness measured at the three locations 7 m, 9m and 11 m for Tank 2 was 67 mm and 83 mm before and after the experiment respectively, and 58 mm and 57 mm for Tank 3 (Wang and Shen, 2010).

In general the size of pancake ice varied with the distance from the wave generator where they were small and increased at larger distance from the wave generator.

These experiments have shown that wave propagation changes significantly when pancake ice is present. The range of frequencies tested was narrow ($0.501< f_M < 1.098$) and it is believed that a more extensive investigation with a broader frequency range and better controlled ice properties will give a clearer picture of the role played by pancake ice. When the frequency range is extended to $f_M \sim 1.6$ Hz the results can be compared with those measured by Newyear and Martin (1997).

***Oil Detection under Sea Ice - Project***

In December 2013 experiments with oil spills in ice were executed at the Hamburg Ship Model Basin (HSVA) in the Arctic Environmental Test Basin (AETB). The project entitled "O*il* D*etection under* S*ea* I*ce* (ODSI)" was performed to understand the behaviour of oil under young ice, as well as the possibility to remotely detect the presence of oil under and within young ice types. The young ice types grown for the experiments were: (1) frazil ice, (2) nilas, and (3) pancake ice. The aim of the experiments in the Artic Environmental Test Basin was to grow these ice types and characterise the behaviour of spilled oil and evaluate potential detection approaches under these ice types. As part of this project tests were also performed to investigate wave-ice interactions for three different ice covers. Details about the oil spill experiments can be found in Wilkinson et al. (2014). This paper focusses on the wave-ice interaction investigated by H. Shen et al. from Clarkson University, NY.

***Experimental Set-up***

The tests were carried out in the AETB, a refrigerated cold room in which air temperature can be regulated down to -20°C. For the current experiments, air temperature was set to approximately -15°C. The wave basin is in total 30 m long, 6 m wide and 1.2 m deep. The basin is further divided by a wooden bulkhead into two 3m-wide flumes. Locations of instrumentation, sampling station, and other key elements and activities of the experiment are referred to by meter marks on the wall. Two separate flap-type wave makers are installed in each of the tanks near the 12 m mark. Circular profiled stainless steel beaches are located with their foot near the 27 m mark of the tanks. The layout of the basin and installation locations for the pressure transducers are illustrated in Figure 3. The flap-type wave generators and the beaches in Tank 2 and 3 are shown in Figure 4.

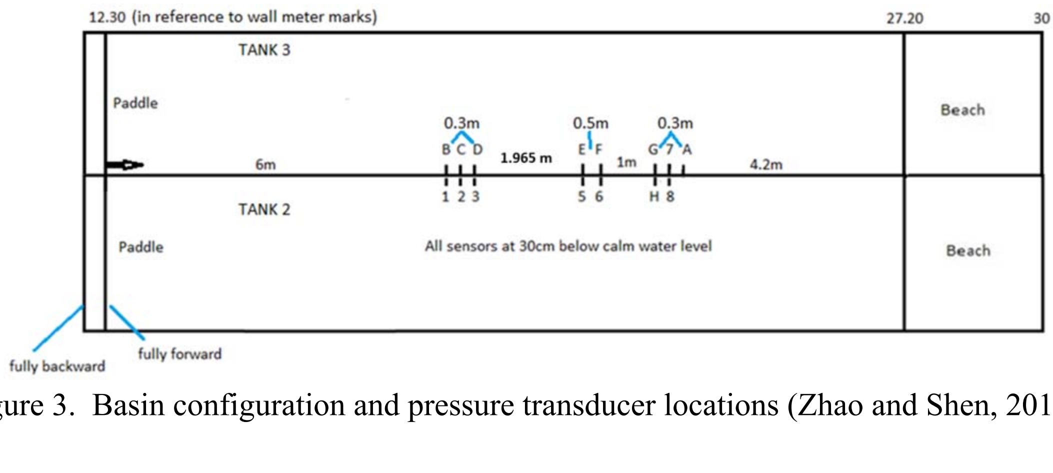


Figure 3. Basin configuration and pressure transducer locations (Zhao and Shen, 2015).

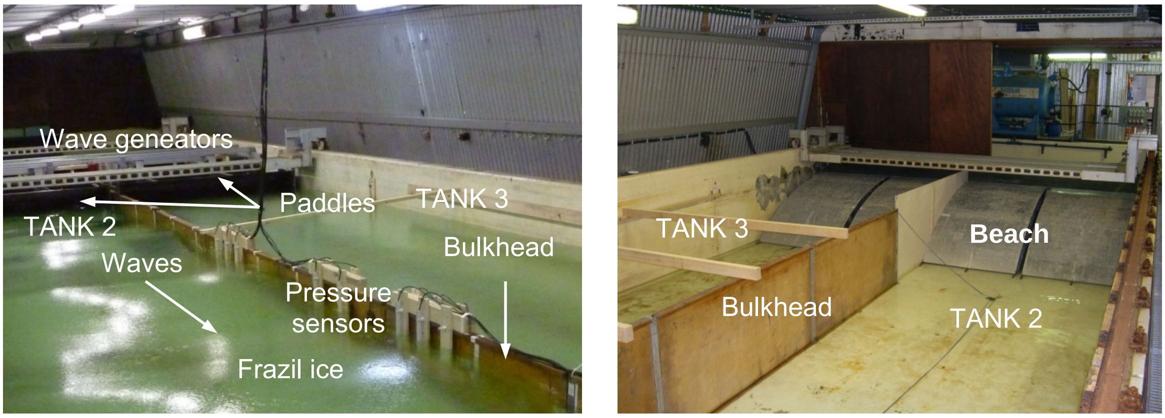


Figure 4. Arrangement of flap-type wave generator and beaches in TANK 2 and TANK 3

***Test Procedure***
***Open Water Tests***

The experiments were conducted using a 34 ‰ NaCL solution. The amplitudes in both fresh and saline water were almost of the same identical magnitude. Because the pressure transducers were calibrated in fresh water the calibrated conversion from voltage to centimeter was multiplied by 1.03 to get the correct water level. After installation of the pressure sensors in both tanks they were tested in two test runs in open water both under calm water and wave conditions.

The water depth data was recorded for one minute using a LabView virtual instrument and the results were compared to the actual water depth. Data was then recorded under wave conditions over one minute. It was noticed that if the wave maker was moving in TANK 2 but not in TANK 3, energy transfer occurred through a gap in the bulkhead close to the wave generators. When the paddle cycles back it pushes water from TANK 2 into TANK 3 and the energy from this water transfer propagates the entire length of TANK 3 (Callinan et al., 2014a, Callinan et al., 2014b). A spectrum analysis from Matlab showed that this would cause less than 2% energy leak into the calm water TANK 3. When both wave makers were working but at different amplitude, it was observed that energy crossover appeared in both tanks. Figure 5 shows the case where TANK 3 was operating at 0.5 Hz and TANK 2 at 0.65 Hz but at much lower amplitude. Thus only those cases were analysed in TANK 3 when in TANK 2 was calm water condition or was operating at low amplitude.

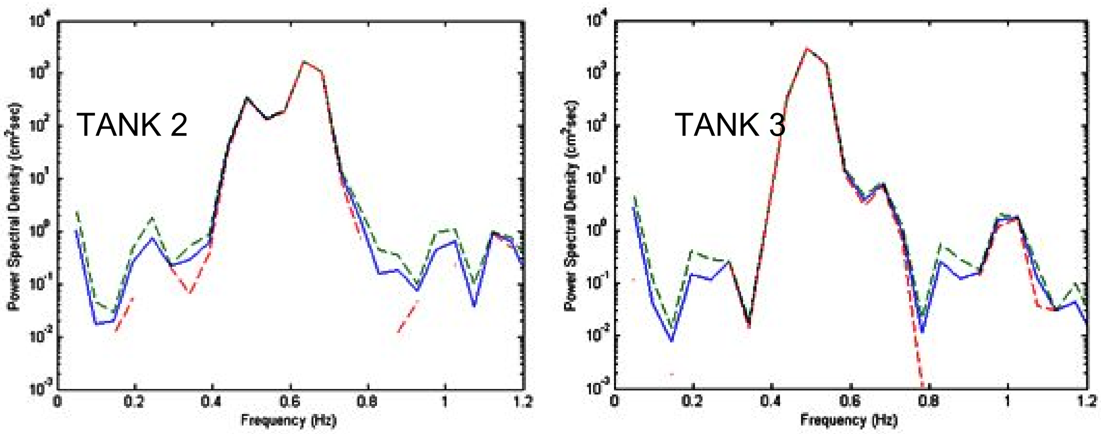


Figure 5. Power spectral density with 95% confidence interval nearest the wave makers for TANK 2 (left) and TANK 3 (right) when both were operating, TANK 3 at 0.5 Hz and TANK 2 at 0.65 Hz (after Callinan et al.,2014).

***Creation of Ice Conditions***

The three different ice conditions used in these experiments were created in succession in TANK 3, as ice concentration increased over the course of the testing days.

The frazil/pancake ice mixture was created first after air temperature was set down to -15°C in the afternoon of December 11. The wave maker was set at a frequency of 0.8 Hz with a moderate stroke and run overnight in order to facilitate the growth of frazil ice. The following morning, December 12, a frazil/pancake ice mixture was present in the tank and testing could commence. This ice condition is shown in Figure 6a.

The second ice cover was created at the end of December 12. The frequency and amplitude of the wave maker were changed prior to leaving the facility on that day. Frequency was reduced to 0.2 Hz and stroke was doubled to the setting in the previous night. This change allowed the already present pancake ice to increase in diameter and thickness overnight. Experiments were conducted in the morning of December 13. This ice condition is shown in Figure 6b.

After this pancake ice test, the wave maker was turned off for over an hour allowing the pancakes to freeze together creating a somewhat solid ice cover. This ice cover was broken apart by using a shovel to create a fragmented ice cover as shown in Figure 6c.

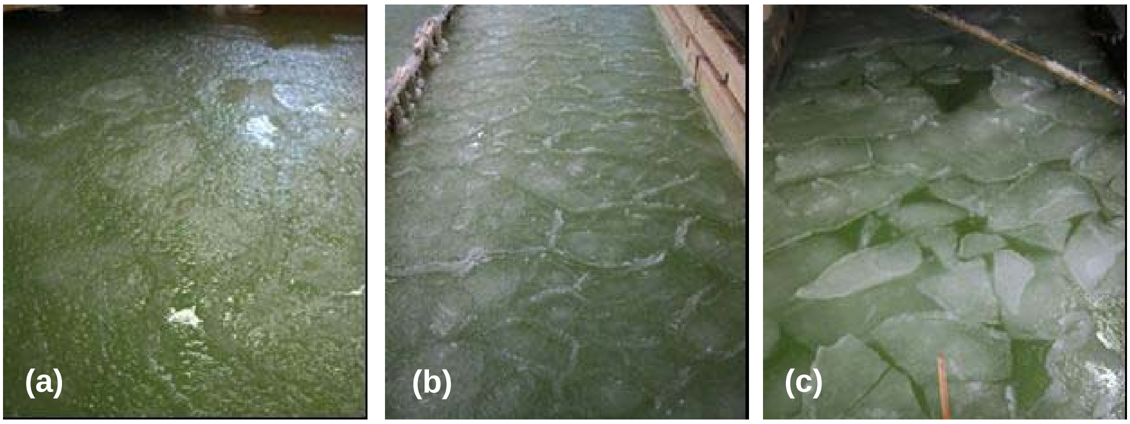


Figure 6. Frazil/pancake ice mixture (a), pancake ice (b), fragmented ice floe (c), ref.: Callinan et al. (2014b).

***"Waves in ice" Experiments***

TANK 2 was heavily instrumented for the oil spill test prepared for the second week. In the first week TANK 2 was going through pre-test preparations for various instruments, hence wave-ice study was carried out only in TANK 3. On December 13 TANK 2 was occasionally free from instrument preparation. When this happened wave-ice tests were also done in TANK 2. A series of tests was run in TANK 3 for the different ice conditions. The frazil/ pancake ice mixture was tested in the morning and afternoon of December 12. Pancake ice and the fragmented ice floe were tested on December 13.

The pressure sensors were placed at a nominal depth of 27 cm below calm water level. Each test lasted one minute. Data was logged using a LabView 2012 Virtual Instrument with a 100 Hz sampling frequency. Data logging began with quiescent water. Approximately 10 seconds following the start of data collection, the wave maker was turned on. The wave maker was allowed to operate for 30 seconds and then was turned off. Following the test, three minutes were allowed to pass in order for the water surface to calm (Callinan et al. 2014b).

The wave generator was used at five different frequencies ranging from 0.5 Hz to 1.1 Hz. Two experimental runs were conducted for each frequency during each of the tests. Four different tests were run (2 frazil/pancake ice mixtures, pancake ice, and fragmented ice floe) and each

took approximately one hour to complete. There was no big difference in the ice condition between the two frazil/pancake tests.
These thickness and diameter data are given in Figure 7. It is apparent that both thickness and pancake diameters are not uniform. The variability cannot be measured because the sampling was too sparse. Therefore the average of these measurements near the time of the wave tests was taken for the data analysis part.

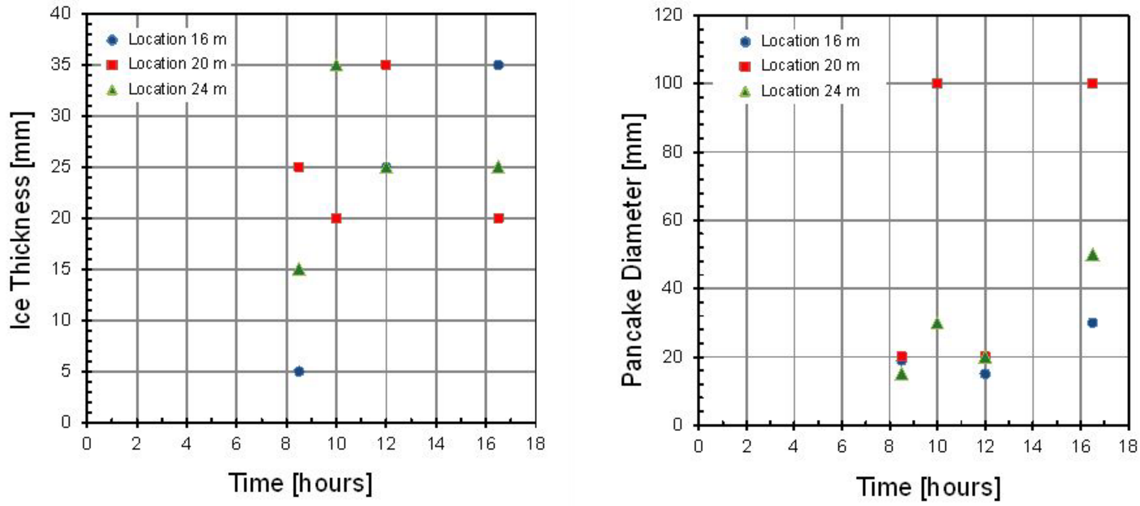


Figure 7. Ice thickness and diameter of pancakes of ice cover produced on December 12, 2013

***Summary of Experiments carried out in AETB***

The main conclusions from the various projects (INTERICE, RECARO and ODSI) can be summarized:

1. Pancake ice is fragile and of non-uniform thickness. To prepare a sample suitable for usual mechanical testing equipment is very difficult. The formation of an ice cover in a wave field can render a collection of pancakes dispersed in a frazil slurry, a brash ice cover of many different floe sizes, or a relatively uniform field of polygons interspersed in water. Each of these may have different viscous properties. The shear modulus and the viscosity parameter are both difficult to measure.

2. The range of wave period is severely restricted by the size of the wave tank. The reflexion of waves limits the duration of the test runs resulting in much less certainty of wave measurements. Therefore a larger ice basin would improve the possibilities to expand the range of wave height and wave period.

3. We often underestimate the time required for a careful laboratory experiment. It is found that although a lot simpler than field studies, laboratory work is still time consuming. For example, growing an ice cover takes certain time depending on the required ice thickness. Tests need to be repeated to check for variability.
   For the execution of experiments there was often not sufficient time scheduled for installation of test set-up, test execution and dismantling of installations in most of the projects, so that extensive systematic experiments were not always possible. Therefore, for experimental test series in the future a time frame of at least 3-4 weeks for a project should be planned.

## WAVE-ICE EXPERIMENTS IN THE LARGE ICE MODEL BASIN

The experiences and results obtained in the various projects mentioned above with “waves in ice” experiments in carried out in the AETB have revealed that a larger basin than the AETB is required to perform complex investigations on the behavior of waves in the ice. Therefore HSVA has decided in 2014 to enhance its testing equipment portfolio in the Large Ice Model Basin (LIMB) facility with a wave generator. The system was successfully installed in December 2014. The generator consists of four flap type wave making modules and covers the entire 10 m width of the basin. The flaps of 1.3 m height can be attached to a basement structure such that the hinge position is set 1.2 m above bottom. All four modules can be installed and removed from the basin within two hours while the basin is filled up with water (Figure 8).
The system is able to produce regular and irregular waves while the maximum wave height is limited to 0.25 m and the maximum deep water wave period is 1.8 seconds with respect to the basin depth of 2.5 m. The system is equipped with an active absorption to reduce reflections. The actual wave signal input is done via user friendly software *AwaSys* which transmits the signal to the control software.

Figure 8. New flap type wave generator in HSVA’s large ice model basin consisting of four removable units

### *Tests in Open Water and Ice*

After the wave generator modules were installed they were calibrated in open water without any ice. For the tests in ice a 30 mm thick ice sheet of 45 kPa flexural strength was produced.
The wave period was kept constant for most test runs while the wave height was increased stepwise. Table 3 shows the complete test matrix.

Table 3. Testing parameters for first series of wave ice tests

| Test ID | Ice Thickness | Wave Period | Wave length | Wave Height | Exposure Time |
|---|---|---|---|---|---|
| 2010 | 29.8mm | 1.27s | 2.52m | 20 mm | 10min |
| 2020 | 29.8mm | 1.27s | 2.52m | 50 mm | 10min |
| 2030 | 29.8mm | 1.27s | 2.52m | 70 mm | 10min |
| 2040 | 29.8mm | 1.27s | 2.52m | 100 mm | 10min |
| 2050 | 29.8mm | 1.50s | 3.51m | 100 mm | 10min |

The main intention of first tests was to observe the interaction behaviour of waves and model ice to obtain practical knowledge on parameter relations, measuring practicability and indication on similarities to phenomena observed in full scale. To reduce wall effects the ice sheet was cut free on both sides. The distance between the wave generator and the ice edge in the basin was about 10 m.

The first important observation during the testing series was that the ice sheet of 30 mm was remaining intact for 20 mm wave height but started to break close to the ice edge at a wave height of 50 mm. The first cracks were orientated close to 90 degree towards the wave propagation direction and only few cracks in longitudinal direction were initially observed. At this point also occasional cracks at some distance from the ice edge could be found such that a large floe was formed which was then broken into smaller fragments (see Figure 9a-d.).

After the exposure time of 10 minutes, the average floe size had reached a certain value and was not further decreasing. The break-up had not yet reached the rear part of the basin in which the ice was still intact. Therefore, the generation of waves was stopped and the wave height was increased to 70 mm for the next test run. At this wave height the floes in the fore part of basin were further broken in to smaller pieces. As the fracture zone was not progressing an area of rafted floes (see Figure 10) was forming at the intersection of broken ice and intact ice. In this area several layers of floes were compacted and slush ice was produced by periodically colliding floes.

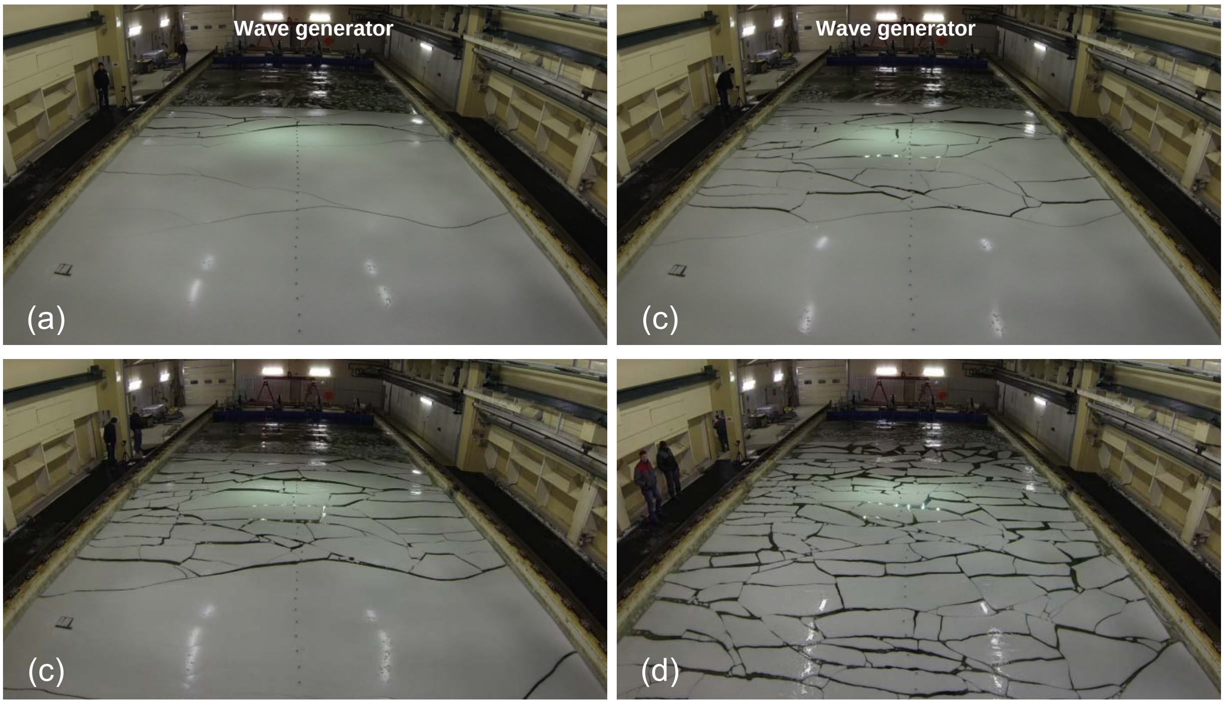


Figure 9. Break-up of 30 mm thick ice sheet by 50 mm high waves with a length of 2.5 m


Figure 10. Rafted zone with grease ice between broken ice floes

Finally, the wave height was increased to 100 mm to break up the remaining ice and in one additional test run, the wave length was also increased to propagate further into the intact ice sheet. After 10 minutes of wave impact, the whole ice sheet was broken up. Photographs were taken from a crane to document the final stage of floe sizes. The resulting floe size image is presented in Figure 11. A zone of smaller floes in loose configuration has formed in the forepart close to the former ice edge. This area is followed by the zone of rafted ice with slush. In this area floes have been compacted as waves approached from one side and intact ice or large floes were supporting on the opposite side. In the rear part very large ice floes remain and form a nearly 100 per cent coverage of the basin. The resulting ice floe distribution is very typical for the marginal ice zone.

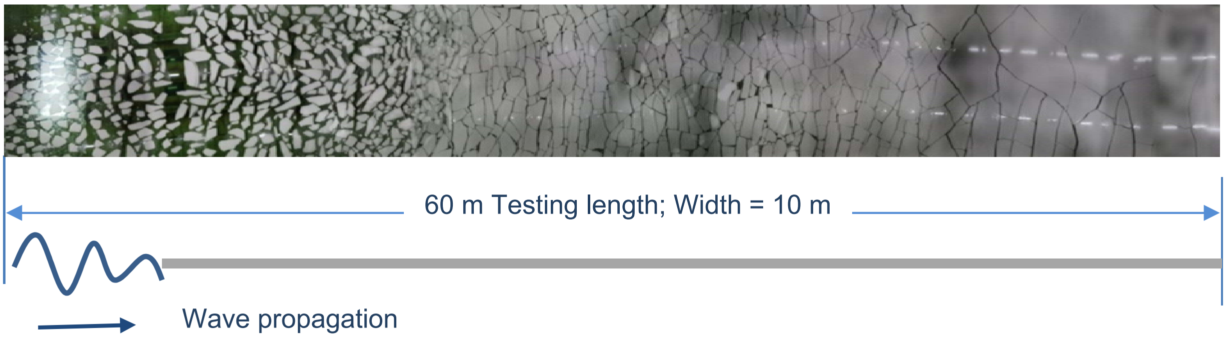


Figure 11. Floe size distribution along the entire ice basin after the last test run #2050

**SUMMARY AND CONCLUSION**

Numerous experiments with waves in the ice were carried out in the past 18 years in various EU-funded projects with international participation in the AETB. In particular, the formation processes of frazil ice and pancake ice were examined. The results show that it is difficult to determine the mechanical properties and viscosity of frazil ice sufficiently. In order to preserve reliable results in terms of wave propagation and wave attenuation, the ice basin dimensions, in particular the length, are of great importance. It has been shown that the dimensions of the AETB for the performance of wave experiments of longer duration are not sufficiently large enough, since due to the short measuring distance waves reflected from the beach have an effect on the propagating waves and thus the wave attenuation in the ice. For this reason, a "removable" wave generator was recently installed in the Large Ice Model Basin (LIMB), allowing tests with waves in ice over a measuring range of 60 metres length.

With this new experimental device, it is possible to perform comprehensive “waves in ice” experiments with respect to efficiency and risk of marine activities in above mentioned conditions. Physical modelling can be used to provide results on wave propagation in ice as well as wave – ice interaction. Model testing can provide valuable knowledge on the actual energy dissipation and fracture process, ice formation under waves, the relation between wave parameters and broken ice floe size and the simultaneous impact of waves and ice on ships and offshore structures.

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