# Experimental study on the deformation and breakup of an ice sheet induced by wave, wind and current

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**Highlight:** An experimental simulation facility considering the coupling of wave, wind, current and ice was established. On this basis, some preliminary experiments of ice deformation and breakup under the action of wave, wind, and current was conducted.

**Abstract:** Sea ice is a typical floating body, and the movement and deformation of ice under the excitation from environmental loads, such as waves, currents and wind, are known as its hydro elastic response. By retrofitting the existing outdoor ice tank with a flap-type wave maker, an internal-circulation current generation system and a suction-based wind generation setup, a testing system to simulate the complex wave-wind-current-ice interaction was established. The responses of ice under different cases were investigated, including only waves, wave-current coupling, wave-wind coupling, and wave-wind-current coupling. Compared with only waves cases, the current in the same direction as wave weakens the hydro elastic deformation of ice, while in the opposite direction promotes the ice deformation, and the presence of wind has a positive effect on the ice deformation.

**Keywords**： experiment; ice sheet; wave; current; wind; fluid-ice coupling

## 1 Introduction

Waves, wind and currents are typical loads in polar environments and are the main driving force for the hydro elastic response of ice. Under these forces, sea ice exhibits dynamic behaviors like drifting, growth, decay, fracture, overlap, and accumulation. Understanding the interaction between fluids and sea ice is crucial for the design and safe operation of polar structures.

According to the differences in research focus, the interaction between wind, wave and current loads and sea ice can be divided into two main categories. One is to consider only the deformation of ice and ignore its dynamic damage, focusing on the movement, drift and accumulation of broken ice under the driving force of fluid, as well as the deformation of complete ice cover and its attenuation effect on hydro elastic waves. Guo et al. (2017)[错误!未找到引用源。] used paraffin wax to simulate ice fragments and carry out the interaction of waves with single and groups of broken ice in a water tank. The drift motion of broken ice under the action of waves was investigated. Dolatshah et al. (2019)[错误!未找到引用源。] utilize experiments in a small ice tank to study the pancake ice rafting due to the combination of wave and wind. Five different wind velocities were tested and results showed that rafting ice thickness dramatically increased along with the wind speed. Huang et al. (2019)[错误!未找到引用源。] carried out a numerical simulation of hydro-elastic waves along a semi-infinite ice floe. The wave-induced ice deformation and the attenuation of hydro-elastic waves along the ice floe were investigated. Parra et al. (2020)[错误!未找到引用源。] conducted experiments on the interaction between waves and ice covers, broken floating ice and grease ice in a wave flume installed in a low-temperature laboratory. The experiments monitored the phase velocity and wave amplitude attenuation laws of wave propagation in different types of frozen model ice.

The other part of the study mainly focuses on the cracks, fracture and erosion of ice under wind, wave and current loads. In 2015, the Hamburg Ship Model Basin in Germany carried out experiments on the interaction between waves and level ice in an ice tank using a wave generator. The continuous fracturing process of level ice under wave action was meticulously observed. The size of the broken ice progressively increased with the distance of wave incidence into the ice cover area. Related experimental results were successively published by Reimer (2016)[错误!未找到引用源。] and Herman et al. (2017)[错误!未找到引用源。], which analyzed the probability density function of the size of broken ice after the fracturing of level ice by using the probability analysis method. He et al. (2022)[错误!未找到引用源。] simulated the interaction of waves and ice sheet by using CFD-DEM coupling method and compared with experimental data of Hamburg Ship Model Basin[5-6]. He et al. (2023)[错误!未找到引用源。] initiated model experiments on the interaction between waves, currents and single floating ice indoors and explored the corrosion effect of currents on ice, etc.

It can be seen that present experimental studies considered the interaction of wave and ice more. The full coupling effects of wave, current, wind on the deformation and breakup of ice sheet were rarely studied. This paper studies the interaction between environmental loads (wave, wind and current) and sea ice experimentally, which tries to explore the deformation and fracture of the ice sheet under the combined action of waves, wind and currents.

## 2 Experimental Setup

In order to explore the deformation and damage mechanism of ice under the action of wind, wave and current loads, a series of experiments were carried out in the outdoor water tank. The ice tank is 20 m long, 2 m wide and 1.2 m deep. As shown in Fig.1, a flap-type wave maker was installed on one side of the ice tank. The wave period was 1-5 seconds and the maximum wave height was 0.1 meters. The internal circulation current generation system was structured with a current-generating pump, a nozzle furnished with a diversion trough, as well as a false bottom. This system could achieve a maximum current velocity of 0.2 m/s. In order to guarantee the stability of the wind field, a suction-type wind generator was utilized, with a maximum wind speed of 10 m/s.

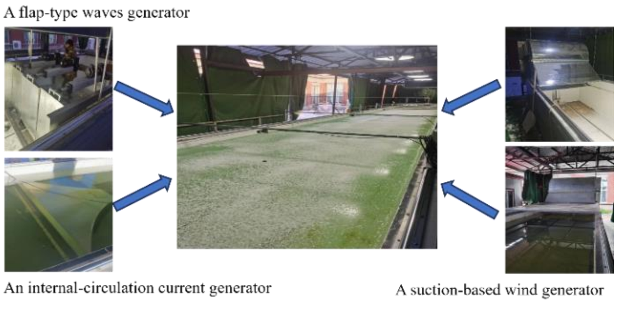


Figure 1 Experimental setup

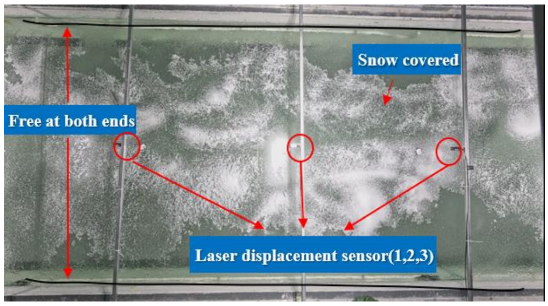


Figure 2 Ice boundary conditions and equipment layout

As depicted in the Fig.2, multiple Panasonic HG-C1400 laser displacement sensors were employed to measure the deflection of the ice sheet. The distance between adjacent sensors was maintained at 1 meter. The boundary conditions of the level ice were set to be free, i.e., the ice was disengaged from the side walls of the tank on both sides, to reduce potential boundary effects and interference. To enhance the observability of experimental phenomena, a uniformly fine layer of snow was artificially deposited on the surface of the level ice.

## 3 Some initial results

### 3.1 The interaction of wave and ice

Firstly, we investigated the effects of single waves on the deformation and fracture of ice sheets. In Fig.2, following the wave propagation direction, the laser displacement sensors were numbered 1, 2, and 3 in sequence. In the experiments, the ice thickness and wave period parameters were kept unchanged, and the wave height gradually increased from 6.08mm until the ice broke. Fig.3 showed the ice plate deflection recorded by the laser displacement sensors where the ice thickness was 6mm, the wave period was 1.5s, and the wave height was 19.37mm. Wave energy decayed rapidly as it passed through the ice, resulting in a gradual reduction in the deflection deformation of the ice in the direction of wave propagation. It can also be seen that the attenuation degree increased significantly with the increase of the wave propagation distance. Under the parameters shown in Fig.3, the ice sheet began to break when the wave height reached 19.37mm. Fig.4 showed the ice damage under this circumstance. The ice sheet broke with multiple cracks generated in a direction nearly perpendicular to the tank wall. The fracture modes were similar to the experimental results of Hamburg Ship Model Basin[5-6].

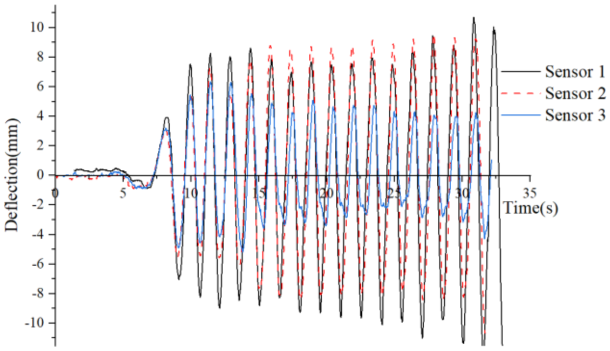

Figure 3 Ice deflection under wave loads

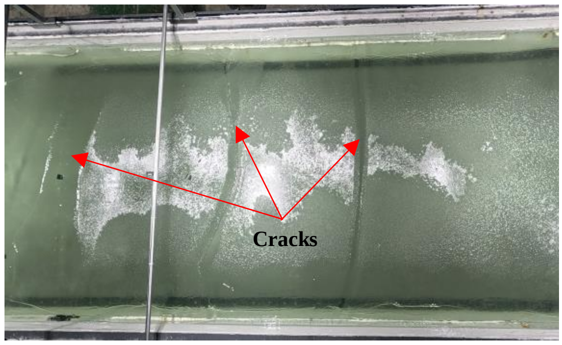

Figure 4 Ice cracks initiation and propagation

### 3.2 The interaction of wave, current and ice

Fig.5 showed the relationship between amplitude of ice deflection at Sensor 1 and current velocities under the combined action of waves and current at different wave heights, in which amplitude of ice deflection was taken as the average value of peaks of deflection in Fig.3. In this context, a positive current velocity signified that the wave and current propagated in the same direction, whereas a negative current velocity implied an opposing directional relationship. As one can expect, the ice deflection amplitude increased along with the wave height, which indicated that the increase of the input energy of the system enhanced the ice deformation. On the other hand, compared with the single wave condition, the deflection of the ice cover exhibited a decreasing trend with the increase of the co-directional current velocity; conversely, the deflection of the ice cover rose along with the increasing current velocity in the opposite direction of wave. The tendency was similar to the interaction between wave and current in open water[9], which indicated that the change law of deflection of flexural-gravitational wave in the ice agreed with that of gravitational wave at free surface.

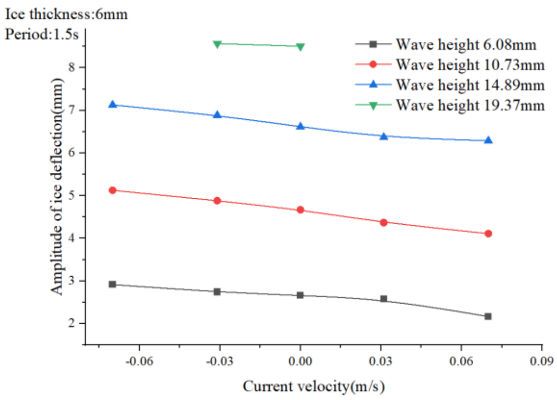


Figure 5 Experimental results of the interaction of wave, current and ice

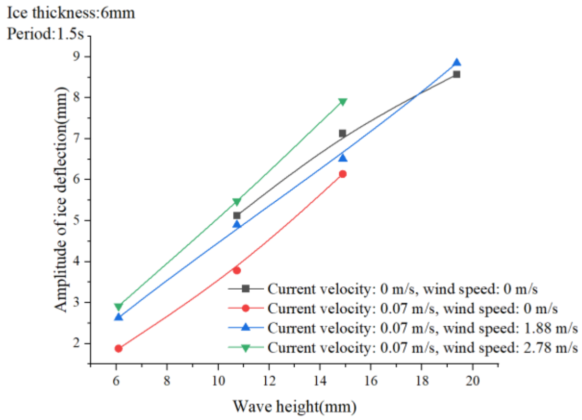


Figure 6 Experimental results of the interaction of wave, wind, current and ice

## 3.3 The interaction of wave, wind, current and ice

Finally, as shown in Fig.6, the deformation amplitude characteristics of ice sheet at Sensor 1 under the coupling of waves, wind, current and ice were studied. The wind and current in this operating condition were both in the same direction as that of waves. According to the red, blue and green curves in Fig.6, one can see that the wind promoted the ice deflection. This may attribute to the lower air pressure on the upper surface of the ice owing to the Bernoulli effect. When the wind speed reached a sufficient magnitude, it can counteract the adverse effect of the co-directional current. Compare with blue and black curve in Fig.6, one can see as the wave height rose, the contribution of the combined loads changed. Therefore, under the combined effect of multiple loads, the kinematic and fracture processes of the ice sheet manifested a high degree of complexity and variability.

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