Ocean Modelling 96 (2015) 85–92

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Virtual Special Issue
Ocean Surface Waves

An idealised experimental model of ocean surface wave transmission by an ice floe

L.G. Bennetts[a], A. Alberello[b], M.H. Meylan[c], C. Cavaliere[d], A.V. Babanin [b], A. Toffoli[b,*]

[a] School of Mathematical Sciences, University of Adelaide, Adelaide 5005, Australia
[b] Centre for Ocean Engineering Science and Technology, Swinburne University of Technology, Hawthorn 3122, Australia
[c] School of Mathematical and Physical Sciences, University of Newcastle, Callaghan 2308, Australia
[d] Polytechnic University of Milan, Milan 20133, Italy

ARTICLE INFO

Article history:
Received 7 October 2014
Revised 27 January 2015
Accepted 4 March 2015
Available online 14 March 2015

Keywords:
Ocean waves
Sea ice
Marine geophysics

ABSTRACT

An experimental model of transmission of ocean waves by an ice floe is presented. Thin plastic plates with different material properties and thicknesses are used to model the floe. Regular incident waves with different periods and steepnesses are used, ranging from gently-sloping to storm-like conditions. A wave gauge is used to measure the water surface elevation in the lee of the floe. The depth of wave overwash on the floe is measured by a gauge in the centre of the floe's upper surface. Results show transmitted waves are regular for gently-sloping incident waves but irregular for storm-like incident waves. The proportion of the incident wave transmitted is shown to decrease as incident wave steepness increases, and to be at its minimum for an incident wavelength equal to the floe length. Further, a trend is noted for transmission to decrease as the mean wave height in the overwash region increases.

1. Introduction

Ocean surface waves penetrate up to hundreds of kilometres into the sea ice-covered ocean (e.g. Squire and Moore, 1980; Kohout et al., 2014). The region occupied by waves is known as the marginal ice zone (MIZ). Waves have a profound impact on the ice cover in the MIZ. They (i) fracture large floes into smaller, more mobile and vulnerable floes (Langhorne et al., 1998), (ii) herd floes (Wadhams, 1983), (iii) introduce warm water and overwash the floes, thus accelerating ice melt (Wadhams et al., 1979; Massom and Stammerjohn, 2010), and (iv) cause the floes to collide, which erodes the floes and influences the large-scale deformation of the ice field via momentum transfer (Shen et al., 1987; Martin and Becker, 1987; Martin and Becker, 1988). Kohout et al., 2014 recently identified a negative correlation between trends in local wave activity and trends in regional ice extent in the Antarctic MIZ, which is conjectured to result from impacts of large-amplitude storm waves on the ice cover.

Interactions between waves and the ice cover cause wave energy to reduce with distance travelled into the MIZ. Moreover, the ice cover reduces the energy of short-period waves more rapidly than longer-period waves (Wadhams et al., 1988; Meylan et al., 2014). Incident wave spectra, therefore, skew towards long periods as they propagate deeper into the MIZ, in addition to a reduction of energy held by each spectral component.

The ice cover in the MIZ is composed of ice floes with diameters on the order of metres to hundreds of metres. The ratio of the prevailing floe diameters to the incident wavelengths determines the form of the wave-ice interactions, and, hence, the mechanisms responsible for reducing wave energy. In particular, waves perceive a field of floes with diameters much smaller than their wavelength, for example, pancake ice, as an effective medium. In this regime, wave energy is reduced with penetration distance due to viscous losses (e.g. Keller, 1998; de Carolis and Desiderio, 2002; Wang and Shen, 2011; Zhao and Shen, 2013).

In contrast, waves distinguish individual floes with diameters comparable to their wavelength, for example, floes produced by wave-induced fracture. The individual floes reflect a proportion of the incident wave energy, dissipate a proportion and transmit the remaining proportion. Theoretical and numerical methods have been developed to predict the rate at which wave energy reduces in a large field of floes by combining transmission properties of individual floes (e.g. Masson and LeBlond, 1989; Meylan et al., 1997; Bennetts et al., 2010; Bennetts and Squire, 2012a,b). The models have recently

* Corresponding author.
E-mail address: toffoli.alessandro@gmail.com (A. Toffoli).

http://dx.doi.org/10.1016/j.ocemod.2015.03.001
1463-5003/

been used to parameterise wave propagation in the MIZ in large-scale ocean wave and sea ice models (Doble and Bidlot, 2013; Williams et al., 2013a,b).

The present investigation focusses on modelling transmission of waves by a solitary ice floe. A sum of processes involved in wave-floe interactions determine the proportion of wave energy transmitted. Floes bend and flex in response to wave motion, in addition to responding in the standard six rigid-body degrees of motion. Waves experience drag (form and skin) travelling around the floe (Kohout et al., 2011). The floes are also susceptible to drift. Further, the small freeboards of floes permit waves of moderate amplitude to overwash the floes, and the shallow draughts permit energetic waves to slam floes against the ocean surface.

A series of mathematical models of wave interactions with an ice floe, and hence transmission, have been developed (e.g. Masson and LeBlond, 1989; Meylan, 2002; Bennetts and Williams, 2010). Thin plates are used to model the floes. The models are conservative, i.e. no energy dissipation, and assume all motions are proportional to the incident wave amplitude, i.e. the proportion of wave energy transmission does not depend on the incident amplitude. They neglect wave overwash of the floes by waves, slamming, drag and drift.

An idealised experimental model of wave transmission by an ice floe is presented here. Consistent with the mathematical models, thin plastic plates were used to model the floe. Regular (monochromatic) incident waves, ranging from gently-sloping to storm-like, were used. The transmitted wave field was measured by a wave gauge.

Kohout et al. (2007), Huang et al. (2011), Montiel et al. (2013b,a) and McGovern and Bai (2014) recently used closely related experimental models to investigate wave-induced motions of ice floes. However, the present investigation is the first to study transmission of waves by an ice floe.

Field measurements of wave energy at discrete points in the MIZ exist (e.g. Squire and Moore, 1980; Wadhams et al., 1988; Meylan et al., 2014). Wave transmission by a large collection of floes can be inferred from these measurements. However, the measurements are not accompanied by detailed information of floe properties. Field measurements of transmission of waves by an individual floe of known properties do not exist.

The experimental model is used to gain understanding of how a floe affects wave propagation, with respect to floe and incident wave properties. The study focusses on the proportion of wave energy transmitted by the floe, i.e. the transmission coefficient. The effect of the floes on the full wave spectrum is also analysed for a subset of the tests conducted. Further, the transmission is related to the properties of the overwash, which were measured by a specifically designed wave gauge mounted on the model floe.

2. Experimental model

The experimental model was implemented in the wave basin at the Coastal Ocean And Sediment Transport (COAST) laboratories of Plymouth University, U.K. Fig. 1 shows a schematic plan view of the wave basin and experimental set-up. The basin is 10 m wide, 15.5 m long and was filled with fresh water $d = 0.5$ m in depth. The room and water temperatures were approximately 20 °C and 16 °C, respectively.

At the left-hand end of the basin, a wave maker, consisting of twenty individually controlled active pistons, generated incident waves. The pistons automatically adjusted their velocities to absorb waves reflected by the basin walls or the floe. At the right-hand end of the basin, wave energy was dissipated by a beach with a linear profile of slope 1:10.

The use of active pistons and a beach could not eliminate the presence of reflected waves in the basin perfectly. However, a reflection analysis in the centre of the basin, from control tests conducted without a floe, showed the reflected energy to be less than 1% of the incident wave energy. (Reflection is largest for low-frequency waves.)

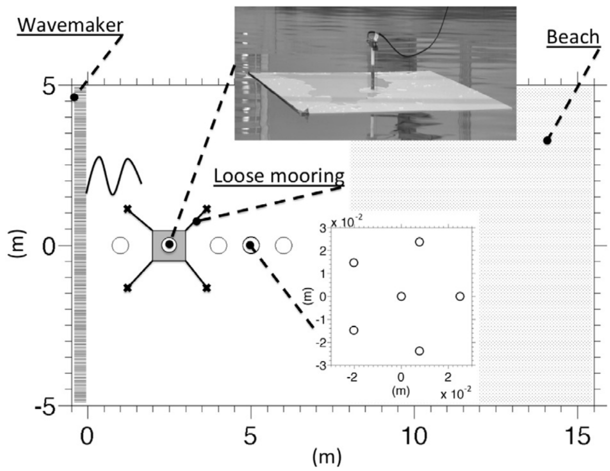

Fig. 1. Schematic of the wave basin and experimental set-up. Circles denote locations of the gauges. Top inset is a photo of the model floe, which shows the gauge used to measure overwash. Bottom inset shows the hexagonal arrangement of gauges in the lee of the floe.

Waves reflected by the beach and wave maker are, therefore, considered to have a negligible impact on the transmission measured in the tests.

A thin plastic plate was deployed 2 m from the wave maker, as a model ice floe. Two different types of plastic were tested: polyvinyl chloride (PVC) with density 500 kg m^{-3} and Young's modulus 500 MPa; and polypropylene with density of 905 kg m^{-3} and Young's modulus 1600 MPa.

A sea ice density of 900 kg m^{-3} and Young's modulus of 6 GPa are commonly assumed for wave-ice interactions. Timco and Weeks (2010) review the mechanical properties of sea ice. They report density measurements from 720 kg m^{-3} to 940 kg m^{-3} with an average of 910 kg m^{-3}, and Young's modulus measurements from approximately 1 GPa to 10 GPa.

For a specified laboratory-to-field geometric scaling factor, the Young's modulus of the laboratory model floe is scaled by this factor to give its equivalent field value, whereas the density is equivalent to its field value without scaling (Timco, 1980). The polypropylene floes, therefore, have a more realistic density than the PVC floes, whereas the PVC floes typically have a more realistic Young's modulus than the polypropylene floes.

PVC plates were provided with thicknesses $h = 5$ mm, 10 mm and 19 mm. Polypropylene plates were provided with thicknesses $h = 5$ mm, 10 mm and 20 mm. The plates were cut into square floes with side lengths $L_{floe} = 1$ m.

Regular incident waves were generated, using three wave periods $T = 0.6$ s, 0.8 s, and 1 s, and corresponding wavelengths $L_{wave} =$ 0.56 m, 1.00 m and 1.51 m, to two decimal places, respectively. The tests, therefore, covered conditions in which incident waves were shorter than, equal to and longer than the floe. The wave amplitude, a, was selected so that the wave steepness (a nondimensional form of wave amplitude), ka, where k is the wavenumber, matched the following values: 0.04, 0.08, 0.1 and 0.15. This range includes gently-sloping waves ($ka = 0.04$ and 0.08) and storm-like waves ($ka = 0.1$ and 0.15), without reaching the breaking limit (Toffoli et al., 2010). The relative water depth, kd, is greater than 2 for all incident waves. Wave interactions with the basin floor are, therefore, marginal, and the waves are considered to be in a deep water regime (Toffoli et al., 2009).

The water surface elevation, η, was monitored with capacitance gauges at a sampling frequency of 128 Hz and an accuracy of approximately 0.1 mm. One gauge was deployed approximately 1 m in front of the floe to capture the incident (and reflected) waves. In the lee of the floe, three gauges were deployed every metre to track the evolution of the transmitted wave field. The