Is the Wave-induced Impact Load from Pancake Ice Important for Offshore Structures

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Due to the reduction of sea ice in the Arctic, future offshore exploration activities are expected to increase. The increase of open water area, particularly in the summer season, will likely create unprecedented wave conditions in this region. It is known that ice covers produced in a wave field, unlike that formed from a pure thermal growth under a quiescent condition, usually consist of an assembly of floes with strikingly uniform shape and size. This type of ice is approximately circular in shape, thus called pancake ice. In this study we report the results of a numerical simulation using the Discrete Element Method (DEM). With the model described previously for different applications, we examine the impact load of a field of pancake ice under various wave conditions on a fixed circular cylinder built into the sea bed. The dependence of this load on wave conditions, the ice concentration, and the cylinder size is investigated. These loads are compared with the pure wave loads. It is found that under the conditions studied, the mean values of the ice loads are much lower than the corresponding wave loads, even though the peak loads are substantial. Also significant is the frequency content of the ice loads. It appears that all significant frequencies are integral multiples of the wave frequency. Since the dynamics of offshore structures is dependent on the frequency of the loading pattern, these findings are worthy of further study. Particularly, laboratory tests are strongly desirable to verify these computational results.
1. Introduction

As the Arctic ice cover continues to deplete (Kwok et al., 2009), the wave climate is observed to intensify (Francis et al., 2011). The expected increase of resource exploration in this region will have to consider not only wave loads on offshore structures but also the wave induced ice impact loads. Extensive studies of ice loads on various types of offshore structures have been conducted (Gerwick, 1990; Timco, 2011). These studies focused on the severe ice types common to the former Arctic region, including consolidated ice sheets, rubble fields, and icebergs. In future Arctic conditions, it is plausible that lighter structures will be built for a different type of ice environment.

In this study we present a numerical simulation of pancake ice impact on a circular cylinder fixed at the sea bed. The ice impact force and bending moment about the foot of the cylinder are compared with the pure wave loads. The physical parameters used in this simulation are selected as close to realistic cases as possible. Due to the oscillatory nature of the wave induced loads, the power spectrum of the impact loads are also analyzed.

2. The Numerical Model

The pancake ice floes are constructed using the "dilated particle" model described in Hopkins (2004). Each three-dimensional floe is represented by attaching a sphere of radius $r_1$ onto a generating two-dimensional disk of radius $r_2$. Contact between two floes generates force and moment. In addition, hydrodynamic force and moment due to buoyancy, drag, and added mass effects also contribute to the floe dynamics.

The contact forces in the normal and tangential directions of the contact are calculated as

$$\vec{F}_n^n = (k_{ne} \delta - k_{te} \vec{V}_{rel} \cdot \vec{n}) \vec{n}$$
$$\vec{F}_t^n = \vec{F}_t^{n-1} - k_{ne} \Delta t (\vec{V}_{rel} \cdot \vec{t}) \vec{t}$$

[1]

The subscripts $n$, $t$ denote the normal and tangential direction, respectively, the superscript $\tau_t$ denotes the current time step; $k_{ne}$, $k_{te}$ are the normal and tangential contact stiffness, respectively; $\delta$ is the depth of overlap between the contacting pancakes; $k_{nv}$ is the normal viscous damping coefficient; $\vec{V}_{rel}$ is the relative velocity of the contacting pancakes; $\vec{F}_t$ is the tangent force limited by the Coulomb friction $\mu$, $\mu$ is the friction coefficient; $\Delta t$ is the time step. The moment resulting from the above forces are obtained by multiplying these forces with the appropriate force arm about the center of mass of the floe.

The hydrodynamic forces are determined as follows. The added mass effect is incorporated by adding $C_m \rho_w V_{sub}$ to the floe mass in its equation of motion, where $C_m$ is the added mass coefficient, $\rho_w$ is the water density and $V_{sub}$ is the submerged volume of the floe. In addition, corrections due to the relative accelerations of the floe and the surrounding water are also considered. The drag force and the corresponding moment on a floe are given by
\[ \vec{F}_d = -\frac{1}{2} C_d^f \rho_w A_{sub} (\vec{V} - \vec{V}_w) \cdot (\vec{V} - \vec{V}_w) \quad \vec{M}_d = -\frac{1}{2} C_M^M r^3 \rho_w A_{sub} \omega \cdot \omega \]  

Where \( C_d^f \) and \( C_M^M \) are the coefficients for the drag force and moment, respectively; \( \vec{V}_w \) is the water velocity; \( \rho_w \) the water density; \( A_{sub} \) the submerged area. Note the drag moment is modeled slightly differently from that in Hopkins and Tukuri (1999) and Hopkins and Shen (2001) so that the resulting drag coefficient \( C_d^f \) is dimensionless. Following the same consideration as in Hopkins and Shen (2001), the form drag in the axial direction is different from that in the radial directions. To account for this difference, the drag coefficient in \( \vec{F}_d \) for the axial direction is set to be ten times that of the radial directions. Similarly, in \( \vec{M}_d \) the rotational drag coefficient about the radial axes is set to be ten times of the axial direction. The components of the water velocity \( V_{wx} \) and \( V_{wz} \) in the \( x \) and \( z \) direction, respectively, at the floe position \((x, z)\) are:

\[ V_{wx} = \frac{1}{2} \sigma H \frac{\cosh(kz)}{\cosh(kh)} \cos (kx - \sigma t) \quad V_{wz} = \frac{1}{2} \sigma H \frac{\sinh(kz)}{\cosh(kh)} \sin (kx - \sigma t) \]  

Where \( H \) is the wave height, \( h \) is the mean water depth, \( k = \frac{2\pi}{L} \), and \( \sigma = \frac{2\pi}{T} \). \( L \) is the wavelength and \( T \) is the wave period. We assume that the pancakes are close to the water surface, hence the approximate water pressure on an infinitesimal area \( dA \) is:

\[ d\vec{P} = -\rho_w g (\eta - z) \bar{n} dA \quad \eta = \frac{1}{2} H \cos (kx - \sigma t) \]  

Where \( \bar{n} \) is the outward normal of \( dA \), \( \eta \) is the water surface elevation, and \( z \) is the elevation of \( dA \). Eq. [4] includes the first order correction of the hydrostatic pressure due to the wave effect (Dean and Dalrymple, 1991).

3. Simulation Results

We model the pancake ice floes and the cylinder size using field observations in the Bohai Bay, as shown in Fig. 1. The ice thickness is not known. Hence we used the diameter to thickness ratio found in a previous laboratory test to provide the simulation thickness (Yuan, 2002). The wave characteristics and the ocean depth are modeled after the Chukchi Sea, as motivated by the recent report of enhanced wave conditions (Francis et al., 2011) and field observations of pancake ice (http://frontierscientists.com/tag/chukchi-sea/). A large range of wave amplitude is included to determine the trend of ice load during normal and stormy conditions. The hydrodynamic coefficients and the material property parameters of the ice floes are fictitious. However, from a previous study comparing the DEM results with a laboratory test, these coefficients and material parameters appear to be reasonable (Hopkins and Tuhkuri, 1999). Table 1 summarizes the set of parameters used in this study. The domain of simulation and the geometric symbols are defined in Fig. 2. The ice concentration is defined as \( C = N \pi (r_1 + r_2)^2 / (\text{Simulation domain area}) \) where \( N \) is the number of floes.
Figure 1. A pancake ice field in the Bohai Bay (courtesy of Shunying Ji).

Figure 2. Schematic diagram of the simulation domain.

Table 1. Parameters used in the simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
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<tbody>
<tr>
<td>Normal contact stiffness</td>
<td>$k_{nc}$</td>
<td>167 kN/m</td>
</tr>
<tr>
<td>Tangential contact stiffness</td>
<td>$k_{tc}$</td>
<td>0.6$k_{nc}$</td>
</tr>
<tr>
<td>Normal viscous damping coefficient</td>
<td>$k_{nv}$</td>
<td>3.4 kN s/m</td>
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<tr>
<td>Floe surface friction</td>
<td>$\mu$</td>
<td>0.35</td>
</tr>
<tr>
<td>Force drag coefficient in the radial directions</td>
<td>$C_d^F$</td>
<td>0.06</td>
</tr>
<tr>
<td>Moment drag coefficient in the axial directions</td>
<td>$C_d^M$</td>
<td>0.14</td>
</tr>
<tr>
<td>Added mass coefficient</td>
<td>$C_m$</td>
<td>0.15</td>
</tr>
<tr>
<td>Ice density</td>
<td>$\rho$</td>
<td>900 kg/m$^3$</td>
</tr>
<tr>
<td>Water density</td>
<td>$\rho_w$</td>
<td>1010 kg/m$^3$</td>
</tr>
<tr>
<td>Water depth</td>
<td>$h$</td>
<td>50 m</td>
</tr>
<tr>
<td>Wavelength</td>
<td>$L$</td>
<td>76.5 m</td>
</tr>
<tr>
<td>Wave height</td>
<td>$H$</td>
<td>0.5, 1~10 m</td>
</tr>
<tr>
<td>Wave period</td>
<td>$2\pi/\omega$</td>
<td>7 sec</td>
</tr>
<tr>
<td>Domain length</td>
<td>$L_x$</td>
<td>153 m</td>
</tr>
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</table>
The time series of the impact force on the cylinder is shown in Fig. 3. The sampling rate shown is at 22.7Hz. Due to the back and forth motion of the floes caused by the wave action, the force on the cylinder is not a sustained load. Many of the data points in Fig. 3 are zero. Even though the peak force shown could be substantial, the average force is much lower. Figure 4 shows the average force and bending moment with respect to the sea floor from the ice impacts for various wave amplitudes. These curves show a near exponential increase of the impact force with wave amplitude when $H < 7$ m, but becomes linear beyond. Dividing the ice load with $D$ (not shown here), the unit diameter force is found to be higher for the small cylinder when $H < 8$ m, but this trend reverses when $H > 8$ m. Note that even though appreciable wave amplitudes are used, linear wave theory is still assumed.

** http://polar.ncep.noaa.gov/waves/viewer.shtml?-multi_1-latest-tp-alaska-

![Figure 3. Instantaneous impact force.](image)

![Figure 4. Ice loads with different wave height. (a) Average forces; (b) Average moments.](image)
Fig. 5 shows a comparison of the ice load with pure wave load. The wave load, including both force and bending moment about the sea floor, is calculated using the Morison equation (Morison et al., 1950; Dean and Dalrymple, 1991) shown below.

\[
F = C_D D n E \cos(k x_1 - \sigma t) \left[ \cos(k x_1 - \sigma t) \right] + C_m \pi D E \frac{D}{H} \tanh k h \sin(k x_1 - \sigma t)
\]

\[
M = C_D D n E \cos(k x_1 - \sigma t) \left[ \cos(k x_1 - \sigma t) \right] \left\{ \frac{h}{2} - \frac{1}{2} \left( \frac{\cosh 2 k h - 1 + 2 (k h)^2}{2 k h \sin 2 k h} \right) \right\}
\]

\[
+ C_m \pi D E \frac{D}{H} \tanh k h \sin(k x_1 - \sigma t) \left\{ \frac{h}{2} - \frac{\cosh k h - 1}{k h \sin 2 k h} \right\}
\]

where \( C_D \) and \( C_m \) are the drag and inertia coefficients of the cylinder, respectively; \( x_1 \) the location of the cylinder (conveniently, this can be taken as \( x_1 = 0 \)); \( F \) is the wave energy per unit surface area, and \( R_e \) the ratio of group velocity to wave celerity. In our case \( R_e \) is roughly 1/2. The two coefficients \( C_D \) and \( C_m \) depend, at least, on the Reynolds number \( R_e = U_m D / v \), where \( U_m \) is the maximum water velocity normal to the cylinder axis, and \( v \) is the kinematic viscosity of water (Dean and Aagaard, 1970). In the absence of better guidelines, we choose \( C_D = 0.8, C_m = 1.1 \) (Dean and Aagaard, 1970; Dean and Dalrymple, 1991) regardless of the Reynolds number. This choice is fine at lower wave amplitudes but questionable at high wave amplitudes.

The resulting ice impact load is much lower than that of the pure wave load. For offshore structures, the average amplitude of the load is not the only concern. The frequency content of these loads is equally, if not more, important (Gerwick, 1990). We thus study the frequency content of the impact forces by analyzing their time series. The power spectrum density (PSD) and its 95% confidence interval for the entire time series of the impact force are shown in Fig. 6(a, b). In obtaining the PSD, each dataset is segmented into subsets of 8192 points with 2435 points of overlap, resulting in 50 subsets for each case. The PSD plots show that there is a lot of
noise in the ice force. However, at large wave heights it is clear that there are several dominant
frequencies at the integral multiples of the wave frequency. The root mean square (RMS) of the
energy content about the first ten integral multiples of the wave frequency are calculated, some
of these results are shown in Fig. 6(c). The RMS value about each frequency shown is calculated
as \( A = \sqrt{\frac{\sum_{j=-4}^{4} 2p_j}{M}} \) where \( p_j \) is the power density at an integral multiple of the wave
frequency and \( M \) is the total length of the PSD series. It is clear that the first five integral
multiples are the dominate frequencies. In the following we focus on the first five integral
multiples amplitude.

Figure 6. (a,b) The power spectrum density of the ice load for two different cases. (c) RMS
amplitude of the first ten integral multiples of the wave frequency. Unfilled markers are for
\( C=0.44 \), and filled markers are for \( C=0.88 \).

In Fig. 7 we plot the RMS of the energy content about the first five integral multiples of the wave
frequency. From this figure it is clear that for low wave amplitude and low ice concentration
impact energy is diffused, but for high wave amplitude or high ice concentration the energy is
more focused at lower integral multiples of wave frequencies.
Figure 7. RMS amplitude of the first five integral multiples of the wave frequency.

In each of the cases shown in Fig. 7, the peak RMS values consistently appear at the wave frequency. We examine the time series of the impact event together with the water velocity.

Figure 8 shows this comparison. It is clear that within each wave period, there are concentrated large impact events and a small group of minor impact events. The minor events are swamped by...
the noise. The large events however are responsible for the dominant frequency that shows up in the RMS analysis.

4. Discussion and Conclusions
For the range of ice and wave conditions investigated in the study, the average ice impact load on a fix circular cylinder is much lower than the pure wave load, although its peak load can be substantial. The frequency content of the impact energy is distributed over integral multiples of the wave frequency. At this point there is no published data of pancake ice load on offshore structures. The only field observations we can find are in the Bohai Bay. The ice impact load is found to be below the measurement accuracy (Ji, 2012). There are many assumptions made in this pure numerical study. Most importantly the hydrodynamics is dramatically simplified. Linear wave is assumed and no interactions between the wave and the obstructing cylinder are considered. The same drag and added mass coefficients are used despite the range of Reynolds number simulated. The ice floes are circular in shape, no freezing between floes or breaking of individual floe is possible. In reality complications that violate these simple assumptions do take place. Nevertheless, when validated, this study provides a feasible alternative to laboratory or field experiments to aid offshore structure that will face a new ice condition in the Arctic.

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