Cold Regions Science and Technology 87 (2013) 33–46

Contents lists available at SciVerse ScienceDirect

Cold Regions Science and Technology

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

Numerical modeling of ice loads on an icebreaking tanker: Comparing simulations with model tests

Li Zhou [a,*], Kaj Riska [a,b], Torgeir Moan [a], Biao Su [a]

[a] *Centre for Ships and Ocean Structures, Norwegian University of Science and Technology, Trondheim, Norway*
[b] *Total SA (DGEP/DEV/TEC/GEO), Paris la Defence, France*

ARTICLE INFO

Article history:
Received 22 August 2012
Accepted 30 November 2012

Keywords:
Numerical modeling
Level ice
Ice rubble
Tanker
Comparison

ABSTRACT

A numerical model is presented to simulate the dynamic ice loads acting on an icebreaking tanker in level ice, considering the action of ice in the vicinity of the waterline caused by breaking of intact ice and the effect of submersion of broken ice floes. The numerical simulations are also compared with ice tank tests. For these tests, ice rubble accumulation contributes to a high ice load and thus was taken into consideration in the simulations in addition to the ice-breaking forces. In the simulations, an icebreaking tanker fixed by artificial high stiffness mooring lines was towed through an intact ice sheet. The setup of the numerical simulation was as similar to the ice tank setup as possible. The ice loads were compared between model tests and simulations by varying the ice drift speed, the relative ice drift angles and ice properties. The results show that the simulated ice loads are in good agreement with the experimental results in terms of the mean values, standard deviations, and maximum and extreme force distributions, although there are some deviations between the predicted and measured results for certain cases. Some of the possible reasons that may explain the differences have been presented. The numerical model can be applied to predict the ice loads on moored or dynamic structures with station-keeping operations in level ice with a constant drift direction, and it can be extended to variable relative ice drift directions.

1. Introduction

Accurate calculation of the ice load on structures involved in station-keeping operations poses a substantial challenge for the design and safe use of marine structures in ice-covered waters. As a basic component in all ice interactions, level ice load is often studied. Once a drifting, intact ice sheet contacts an inclined structure, fragmentation occurs, and the ice sheet breaks into discrete ice blocks. If the resulting ice blocks clear around the structures, the structures will experience low ice forces, with only rotation and sliding forces occurring in addition to the ice-breaking force of the interaction process. Otherwise, massive broken ice floes may accumulate in front of the hull and contribute to a high ice load on the hull, resulting in possible damage to marine structures. According to Wright (1999), the formation of thick ice rubble created by ice management on the upstream side of the Kulluk amplified load levels significantly. Likewise, based on Explorer 4 drillship station-keeping operations in ice, it is found that the buildup of ice rubble tended to result in unacceptably high forces. Therefore, an understanding of the ice pile buildup process and a method for the accurate calculation of the corresponding ice loads on structures are crucial to the design of marine structures operating in ice.

According to Timco et al. (2000), a number of different methods have been used to calculate the ice loads to which offshore structures are exposed. These methods can generally be categorized into two groups: (1) analytical models and (2) numerical models. A review of these models has been presented by Paavilainen (2011).

The analytical models have mainly considered a combination of different failure modes. In calculating the ice load on sloping structures, Croasdale (1980) separated the failure process into failure of the ice sheet through upward bending and ride-up of the ice along the structure. Croasdale et al. (1994) and Määttänen (1986) included other failure modes and the effects of ice rubble in their calculation models. The main variables in these models include the slope angle of the structure, the thickness and properties of the ice sheet, the properties of the ice rubble, the coefficients of friction of ice–ice and ice–structure interactions, and so on. If all of these variables can be properly measured or evaluated, the ice load for different events during the failure process will be accurately estimated through these models. However, calculation of the total ice load in time domain is difficult because the maximum value of each load component does not necessarily occur at the same time. In most cases, these analytical models provide an upper-bound solution.

The numerical methods commonly used in ice sheet failure and rubble formation simulations are the Finite Element Method (FEM), the Discrete Element Method (DEM) and the combined Finite–

---

[*] Corresponding author. Tel.: +47 41340189; fax: +47 73595528.
E-mail address: li.zhou@ntnu.no (L. Zhou).

0165-232X/$ – see front matter. Crown Copyright © 2012 Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.coldregions.2012.11.006

Discrete Element Method (FEM–DEM). In DEM, each ice block is traditionally considered a rigid body, and its response is obtained by modeling the collisions between the individual rigid ice blocks. Sayed (1995), Hopkins (1997), and Paavilainen et al. (2006) used this method to simulate the ice rubble formation process in two dimensions. In FEM, ice sheet and rubble piles are modeled as a continuum regardless of the presence of individual ice blocks (Heinonen, 2003; Kolari et al., 2009). This approach, which is based on the assumption of continuum and homogeneous material, does not entirely correctly simulate the ice rubble pile build-up process. FEM–DEM, by combining both the discrete and the finite element methods, enables the user to model the ice sheet and its failure with FEM by a continuous approach and the ice rubble pile with DEM by a discontinuous approach. FEM–DEM has been used in ice rubble simulations by Paavilainen et al. (2011), but only the vertical plane was considered, whereas the variation of time history of the ice load at different hull sections was neglected. In addition, in these models, the choice of parameters that describe ice rubble can introduce a potential source of error if not appropriately verified. In contrast to the analytical models described in the previous paragraph, these methods provide a lower-bound solution.

Rubble accumulation is believed to be one of the events that may cause extreme ice loads on offshore structures and therefore needs to be considered in an appropriate way. Zhou et al. (2012a) reviewed tests of a towed icebreaking tanker in level ice. It was observed that, depending on the test conditions, several phenomena regarding ice rubble accumulation may occur when the ship model is driven through the ice sheet. In the case of straight-line transit, there is no ice accumulation in front of the hull, and the ice block slides laterally or along the hull. In the case of a 45-degree heading, clearing of the ice did not occur due to the large contact length of the ice–structure interface. In this case, much rubble formed and accumulated beneath the upstream boarding ice sheet at the mid-hull and stern areas. In the case of a 90-degree heading, the phenomenon is more complicated and depends on the ice drift speed in addition to the other factors. At low speed, a large rubble pile formed in front of the hull, while almost all ice cusps went beneath the hull at high speed.

To investigate station-keeping problems in level ice, Zhou et al. (2011) presented a two-dimensional method for simulating the level ice–hull interaction process in the horizontal plane. In this basic study for a moored ship, validation was conducted through the standardized scaling-up technique of Wright (1999). As an extension of that study and to validate the simplified numerical model, Zhou et al. (2012b) showed a simulation of direct level ice action on a conical structure called the Kulluk. The effects of turret position, ice drift speed, ice thickness and global mooring stiffness on moored structure dynamics, which have vital roles in predicting level ice–structure interactions, were also studied.

In Zhou et al. (2012b), the moored structure in the simulations was assumed to have good ice-clearing capacity, so that ice neither piled up nor did ice rubble accumulate. However, for model tests of an icebreaking tanker with a constant relative ice drift angle, this is not the case. As stated above, considerable ice rubble may form in front of the hull after ice pieces break away from the intact ice sheet. In this paper, the ice force components due to ice rubble accumulation are modeled and added to the total ice force. The simulated results are analyzed and compared to the model test data of Zhou et al. (2012b).

This paper first presents the numerical method used and describes some assumptions. Next, the simulation set-up, including the main parameters, is presented. The rubble pile formation process is described with some representative cases. Then, simulated loads on the tanker in full scale are compared with the corresponding loads obtained from model tests. Based on these comparisons, the applicability of the method is discussed. Unless otherwise mentioned, all presented numbers are scaled to obtain full-scale magnitudes.

2. Overview of the numerical method

In the developed model, the scope is limited to level ice with uniform ice properties. The action of drifting level ice on a station-kept structure is complex in that several ice failure patterns occur, primarily crushing and bending. The ice floes fragmented from intact ice may rotate, collide, accumulate, slide along the surface of the structure, or be pushed away from the structure. The corresponding physical phenomena during the process are difficult to reproduce in a numerical way. Therefore, some assumptions must be made to simplify the problem. It is assumed that the ice drift speed is low; thus, ventilation and slamming are neglected. The intact ice sheet is assumed to fail with a mixed mode; local crushing between the structure and the ice and the bending failure that occurs at a distance from the crushing region are both involved.

XYZ, the vessel heading ψ, the ice drift direction β_i and the relative ice drift direction β_r.

Two reference frames are used; see Fig. 1.

- The Earth-fixed frame, denoted XEYEZE, is placed so that the XEYE plane coincides with the water surface and the ZE axis is positive downwards.
- The body-fixed frame, denoted XYZ, is fixed to the vessel in such a way that the origin coincides with the center of gravity, the X-axis is directed from aft to fore along the longitudinal axis of the hull, and the Y-axis is directed to the port.

The horizontal position and orientation of the vessel in the Earth-fixed coordinate system are defined by $\boldsymbol{\eta}=[x,y,\psi]'$, where the first two variables describe the position and the last variable describes the angle. Correspondingly, the translational and rotational body-fixed velocities are defined by $\mathbf{v}=[u,v,r]'$. The body-fixed general velocities are transformed to the Earth-fixed frame by

$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta})\mathbf{v}, \tag{1}$$

$$\mathbf{J}(\boldsymbol{\eta}) = \begin{bmatrix} c\psi & -s\psi & 0 \\ s\psi & c\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{2}$$

where *c* and *s* are compact notations for cosine and sine, respectively.

The equation of motion is first expressed in the Earth-fixed coordinate system and then converted to the body-fixed coordinate system. Based on Newton's second law, the linear coupled differential equations

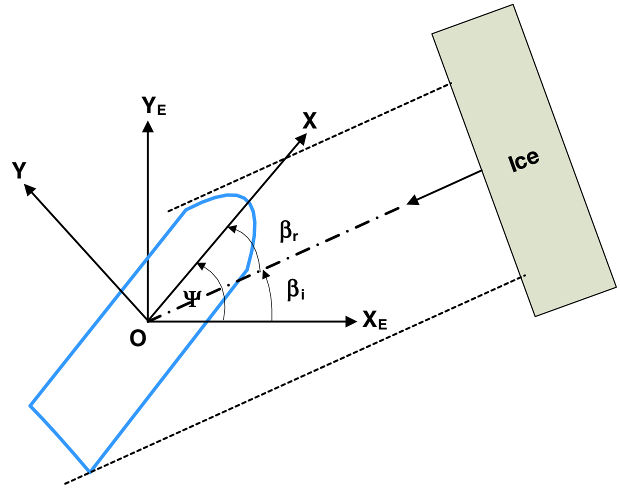

Fig. 1. Definitions of the earth-fixed reference frame $X_EY_EZ_E$, the body-fixed reference frame.