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Physical model and theoretical model study of level ice and wide sloping structure interactions

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ABSTRACT

Wide sloping structures have many applications in ice-infested waters because of their ability to fail the incoming ice in a bending failure mode. However, the poor ice clearing ability of such structures could lead to ice rubble accumulation in front of the structure, which subsequently alters the interaction mechanism. In this paper, the mechanism of level ice interacting with wide downward sloping structures was explored through a theoretical model and a series of physical model tests. Emphasis has been placed on the effects of the rubble accumulation. Based on the observations and previous theoretical ice load calculation models, a new theoretical model that couples the rubble accumulation's effects with all of the other interaction processes was proposed in this paper. In addition, this model enables us to effectively construct the ice load's spatial and temporal variations with respect to level ice interacting with downward wide sloping structures. Afterward, the theoretical model was validated by two sets of physical model tests. One of the physical model tests featured a tactile sensor that was installed on a sloping plate, which was pushed through the model level ice. The ice load's spatial and temporal variations were measured and compared to the theoretical predictions. Another physical model test set-up was a wide sloping structure that was equipped with load cells to measure the global ice load. Based on both the experimental results and theoretical model, it was concluded that the rubble accumulation in front of the sloping structure introduces additional pressure on both the incoming ice sheet and the structure itself; this pressure greatly influences the intact level ice's failing mechanism and consequently the ice load. Furthermore, the common results from both the experimental measurements and theoretical model elucidate several important aspects of the interaction mechanisms. For instance, the maximum ice load is detected slightly below the waterline within the undeformed level ice's thickness region; the ice rotating process together with the rubble effects further transmit the ice load downward to a distance of more than three times the ice thickness; and the rubble effects together with possible secondary ice breakings during the ice rotating process were theoretically demonstrated to reduce the eventual ice breaking length.

1. Introduction

Wide sloping structures have many applications in ice-infested waters. Compared to narrow structures, this rather intuitive word ‘wide’ reflects many different mechanisms that occur during the level ice and sloping structure interactions. Some example mechanisms are a circumferential crack before radial cracks (Løset et al., 2006), rubble accumulation, and scaling effects (Sanderson, 1988). Based on the waterline diameter, Timco et al. (2000) set an order of 100 m and 10 m to separate the wide structures from the narrow structures, respectively, whereas Yue et al. (2007) refer to a narrow cone as a structure without rubble accumulation. However, insufficient data are available for a precise structure classification (Løset et al., 2006). In the current paper, the term ‘wide structure’ is used to highlight the rubble-accumulation effects. In addition, the sloping surface of the structure can be conical, multifaceted, or flat (ISO/FDIS/19906, 2010), and the structure can have either downward or upward sloping surfaces. As fundamental research to investigate the rubble accumulation's effect on the overall interaction mechanism, the current study is simply confined to a fixed two-dimensional wide structure with downward, flat sloping surfaces.

In the development of theoretical models regarding the interaction between level ice and a sloping structure, it has long been recognised that the ice load comprises at least two components, namely, the ice-breaking component and the ice ride-up/down component (termed as rubble accumulation in this paper) (Ralston, 1981). The maximum load that a sloping structure encounters could even be due to the rubble-accumulation part rather than the ice breaking part (Määttänen and Hoikkanen, 1990; Paavilainen and Tuhkuri, 2013). Because of the relatively limited clearing capability of a wide sloping structure, the presence of rubble greatly influences the entire interaction mechanism. However, in the current ISO standard (ISO/FDIS/19906, 2010), such an influence is merely mentioned, whereas the recommended principal methods (Croasdale and Cammaert, 1994; Ralston, 1980) treat the rubble accumulation load and ice breaking load separately without explicitly

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accounting for their possible coupling in the bending failure. To account for the fact that the piled rubble rests on both the sloping structure and intact incoming ice, Määttänen and Hoikkanen (1990) introduced additional rubble pressure in their elastic-foundation beam formulation, which was solved with the finite element method (FEM). Mayne (2007) derived analytical formulas to consider the rubble pressure's influence on the ice breaking process for two basic cases, namely, the triangle-shaped rubble pressure distribution and the uniform rubble pressure distribution. The presence of rubble alters the location of the maximum bending moment and thus changes the ice breaking load and ice breaking length. Most of these efforts have been dedicated to identifying the maximum ice load that the relevant structure would encounter.

From a different approach, sophisticated numerical theories and tools have been developed to study the interaction in a procedural manner. These tools include the combined finite element and discrete element method (DEM) (Paavilainen et al., 2009), the cohesive element method (CEM) (Gürtner et al., 2008; Lu et al., 2012a), continuum damage mechanic (CDM) based method (Kolari et al., 2009), etc. In contrast to the abovementioned theoretical methods, these numerical methods allow the progressive failure of the ice to be simulated. The major interaction processes are simulated with the ice load history calculated in the time domain. The rubble accumulation and its effects become a natural output from the simulations. In these simulations, different processes are typically difficult to quantify separately. Furthermore, these tools are computationally exhaustive compared to simplified theoretical models.

In parallel to studying the interaction mechanism with the presence of rubble accumulation, the current paper also seeks to tender a theoretical model that is situated between the above two approaches (i.e., the conventional theoretical models that focus on the single design ice load and the sophisticated numerical methods that simulate the process as a whole to account for the ice load history). This theoretical model is capable of predicting both the spatial and temporal variation of the ice load in a two-dimensional setting. It is also efficient because of its theoretical simplifications. However, the interaction between the level ice and sloping structures is rather complicated because of the presence of rubble accumulation. Different assumptions and formulas are applicable only at certain interaction stages. For example, Croasdale (2012) identified three different stages and proposed different ice load prediction formulas for different interaction scenarios. Thus, one of the goals for the current paper is to adapt the new theoretical model to different interaction stages that has been observed in the physical model tests.

The current paper is composed of three major parts. In the first part, the theoretical model is proposed and derived in detail. In the second part, physical model studies to validate this theoretical model are introduced and the results are compared to the theoretical predictions. Finally, in the third part, the important findings based on both the theoretical model and physical model are discussed and conclusions are drawn.

2. A theoretical model for level ice interacting with wide sloping structures

The developed theoretical model is presented in this section. First, the interaction mechanism is developed based on previous knowledge and observations. Then, the derivation of the theoretical model within each of the interaction processes is described. Lastly, how different interaction processes are linked to construct the ice load's spatial and temporal variations are elucidated.

2.1. The interaction mechanism

Frederking and Timco (1985) discerned three different ice load components for level ice interacting with sloping structures (i.e., breaking, rotating, and sliding) and proposed formulas to calculate them. These components were conservatively added up to obtain the maximum design ice load.

With respect to the interaction process, Croasdale (2011, 2012) identified three stages. In the first two stages, the incoming level ice fails against the sloping structure, and in the third stage, the incoming ice fails against the accumulated ice rubble. The ISO 19906 (2010) recommended formulas (Croasdale and Cammaert, 1994) are valid only for the first two stages. The third stage is analogous to the ridge building process; and the ice load on the structure can be calculated with the recommended ridging load (Croasdale, 2009; Palmer and Croasdale, 2013). Based on the physical model test observations, the above mentioned two different cases (i.e., incoming ice, case 1: fails against the inclined structure; and case 2: fails against the accumulated rubble) are included in the current theoretical model. However, the possibility of grounding the accumulated ice rubble is excluded from the initial assumption.

With similar definitions for the above-mentioned load components and interaction processes, and in analogy to the research on ship and level ice interactions (Kotras, 1983; Lindqvist, 1989; Valanto, 2001), in the current paper, the interaction processes are categorised into the ice breaking process (i.e., the process in which the intact level ice breaks in bending failure mode), ice rotating process (i.e., the already-broken ice block is further rotated until it becomes parallel to the sloping surface), and rubble accumulation process (i.e., instead of being cleared, part of the ice rubble accumulates in front of the structure, leading to an additional ice load).

Based on the ice basin and field[1] observations and the above classification, the interaction process can be simplified, as shown in Fig. 1. The interaction sequence is assumed to be the following: ❶, ❷, ❸ and ❹, as shown in an anticlockwise sequence in Fig. 1.

The incoming level ice first failed against the sloping structure in a bending failure mode under the influence of rubble pressure (i.e., buoyancy) from beneath, as shown in Fig. 1❶.

Then, in the ice rotating process, the ice started to be gradually rotated downwards. The recorded ice load slides down along the sloping plate. This process is illustrated in Fig. 1❷. Note here that the rotating ice block is 'jumping' out of the water during the rotating process. This phenomenon has been observed both in the current physical model test (see the left figure in Fig. 2) and in the field (see the right figure in Fig. 2). A similar field observation has also been stated by Valanto (2001).

Previous studies have noted that elastic-foundation beam or plate theory tends to over-predict the ice breaking length than the lengths that have actually been observed (Michel, 1978). Some investigators attribute the shorter ice breaking length to a dynamic effect (Lubbad et al., 2008), and others propose that other failure modes play a role, such as shearing failure with thicker ice (Lau et al., 1999; Määttänen et al., 1996). In the current paper, another possibility is introduced: the rubble pressure influence and possible secondary breaking of an ice block in the ice rotating phase, as shown in Fig. 1❸. First, as will be shown later, the presence of rubble accumulation would lead to a shorter ice breaking length. Moreover, depending

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[1] Mainly based on observations on the icebreaker ODEN, which has a rather flat downward sloping bow (with a 31 m beam width) interacting with ice at a rather low speed (e.g., 1–2 knots).