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Rubble height prediction based on a rubble mass conservation model

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ABSTRACT

The ice load resulting from level ice moving against a sloping structure can be determined using ISO 19906 (2010). In the design equations, the rubble height has a significant influence on the ice load prediction. In this presentation, a rubble mass conservation model is proposed to provide guidance on the rubble height for upward conical structures. The proposed rubble mass conservation model considers the rubble mass supply and clearance rates into and out of an identified region surrounding the conical structure. Some simplifying assumptions are adopted such that the rubble mass supply and clearance rates can be written in terms of the structure waterline width and ice feature properties. Considering a fully developed rubble at steady state, the balance between rubble mass supply and clearance rates thus enables the determination of the rubble height. The model is finally benchmarked against field data from the Confederation Bridge.

KEY WORDS: Ice rubble; Conical structure; Ice load.

Introduction

Conical shapes at waterline are preferred in many offshore engineering structures. Such geometries induce a bending failure of the ice sheet, to give a corresponding ice load which is lower than that associated with a crushing failure mode encountered with vertical structures. Referring to ISO 19906 (2010), the ice load on a sloping structure can be determined based on the elastic beam theory in Croasdale's model (Croasdale et al 1994), or the plastic limit analysis in Ralston's model (Ralston 1979). In these two models, the rubble height is an input parameter which influences the ice load prediction significantly. However, little guidance on the rubble height determination was provided in ISO 19906 (2010). The direct application of the design equations can pose some difficulties for engineers. This sets the motivation of the current paper.

In this paper, a rubble mass conservation model for rubble height determination is developed for upward conical structures. Considering an identified region surrounding the conical structure, the rubble mass supply rate into the said region is written in terms of the waterline diameter, the ice thickness, and the ice velocity. Separately, the rubble mass clearance rate out of the identified region is approximated in terms of the rubble porosity and rubble height. For a fully developed rubble at steady state, the balance between the rubble mass supply rate and its clearance rate provides an equation to solve for the corresponding rubble height. Finally, the model is benchmarked against field data from the Confederation Bridge.

Rubble mass conservation model

In this section, a rubble mass conservation model is proposed. Based on field observations from the Confederation Bridge and the Bohai sea, as well as the model test observation by Lau (2004), the movements of broken ice blocks generally fall into the following three categories, depending on their positions around the conical structure (Fig. 1):

I. Breaking from the ice sheet → rotation of ice blocks → riding up → turning over to the rubble → clearance from both sides of conical structures.
II. Breaking from the ice sheet → rotation of ice blocks → riding up → clearance from both sides of conical structures.
III. Breaking from the ice sheet → clearance from both sides of conical structures.

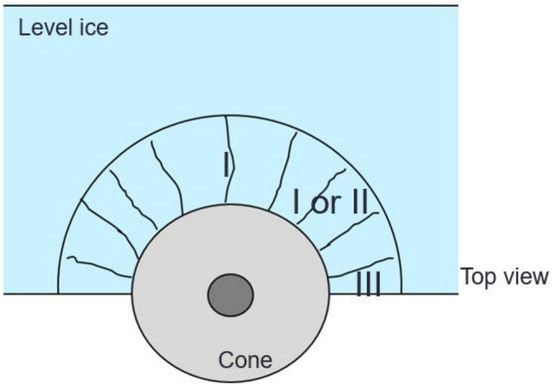

Fig. 1 The general movement of broken ice blocks at different positions around the conical structure, following the description in Section 3

Fig. 2 Study object of the rubble mass conservation model: (a) top view; and (b) perspective view from the Confederation Bridge

Based on this understanding of the rubble movement, we identify the entire rubble region around the cone as our study object, see Fig. 2. For this identified region, the rubble mass supply section is shown in Fig. 3, to give a rubble mass supply sectional area A_s as

$$A_s = tD_c = t(D + 2L_b) \quad (1)$$

where t is the ice thickness, D_c is the width of the broken channel, D is the waterline diameter of the conical structure, and L_b is the breaking length. The corresponding rubble mass supply rate R_s is thus

$$R_s = \rho V A_s = \rho V t(D + 2L_b) \quad (2)$$

where ρ is the ice density and V is the ice velocity.

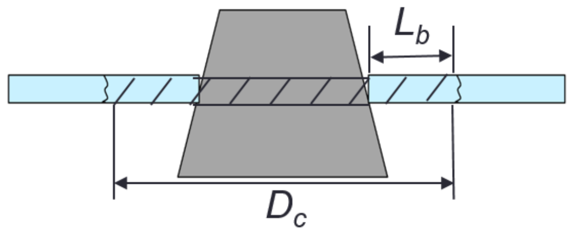

Fig. 3 Rubble mass supply section

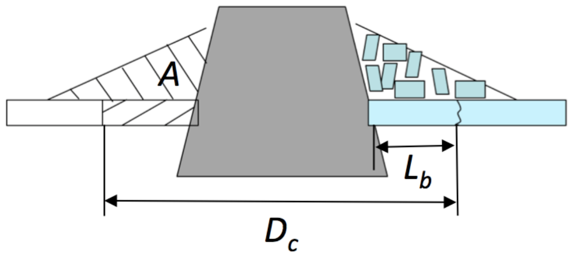

Fig. 4 Rubble mass clearing section

The rubble mass clearing section comprises of the sections of ice rubble on the ice sheet and the sections of the broken ice fragments on both sides of the cone, as shown in Fig. 4, to give a rubble mass clearance sectional area A_c as

$$A_c = 2(1 - P)A + 2tL_b \quad (3)$$

where P is the rubble porosity, A is the area of the ice rubble section which is a function of the rubble profile as shown in Fig. 4. The corresponding rubble mass clearance rate R_c is thus

$$R_c = 2\rho(1 - P)AV_c + 2\rho V t L_b \quad (4)$$

where V_c is the rubble clearance velocity.

During the development of the ice rubble, the rubble mass supply rate is larger than the clearance rate ($R_s > R_c$). A steady state is reached when the rubble is fully developed, to give a rubble mass conservation balance as

$$R_s = R_c \quad (5)$$

Substituting (2) and (4) into (5), we obtain

$$VtD = 2(1 - P)AV_c \quad (6)$$

In the absence of suitable data, we make the following simplifications based on Confederation Bridge observations: a linear rubble profile; rubble porosity $P = 0.15$; a rubble repose angle of 40°. Additionally, we refer to the model test results in Mckenna and Spencer (1994), where the rubble clearance velocity is shown to be larger than the ice velocity V. In the following, $V_c = V$ is adopted for a conservative estimate.

With these simplifications, the side rubble height H_s in Fig. 5 can be obtained by solving (6).

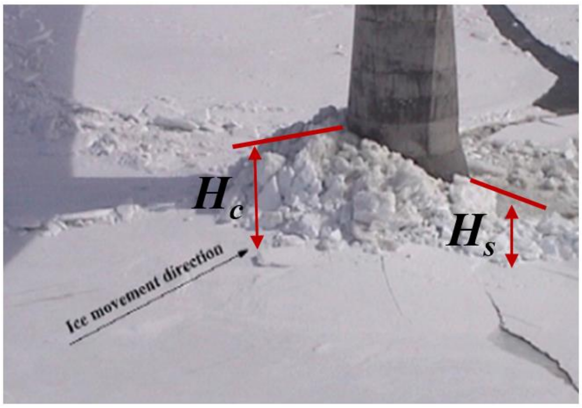

Fig. 5 Central and side rubble heights around the Confederation Bridge (H_c and H_s respectively)

Determination of central rubble height

The ice load design equations given in ISO 19906 (2010) require inputs on the central rubble height H_c, as shown in Fig. 5. To obtain H_c from H_s, we furthermore define a parameter R_h characterizing the ratio of the central rubble height to the side rubble height

$$R_h = H_c/H_s \tag{7}$$

This parameter R_h is calibrated from events with stable rubble from the Confederation Bridge, i.e., Events KRCA 14 and 17 (Croasdale et al, 2016), as given in Table 1. For a conservative estimate, the larger value of $R_h = 1.51$ is adopted in this paper.

Table 1 Events with stable rubble from the Confederation Bridge

Event id	Average ice thickness t_a (m)	Waterline diameter D (m)	Central rubble height H_c (m)	Resultant R_h
KRCA 14	0.73	13.9	6.09	1.51
KRCA 17	0.77	13.4	5.51	1.39

Evaluation and discussion

To evaluate the predictive capability of the rubble height model, we consider the 59 Confederation Bridge events documented in Croasdale et al (2016). Two different approaches for estimating the rubble heights are considered:

- Rubble heights are determined from the proposed rubble mass conservation model with a calibrated R_h value of 1.51.

- Rubble heights are determined from an available empirical equation (Mayne and Brown, 2000) relating the rubble height to ice thicknesses. An upper bound fit to the data is given as,

$$H = 7.6t^{0.64} \tag{8}$$

The comparison of the rubble height predictions utilizing the two approaches is shown in Fig. 6. It is easily observed from Fig. 6 that the rubble mass conservation model compares well against the empirical equation obtained from numerous field data.

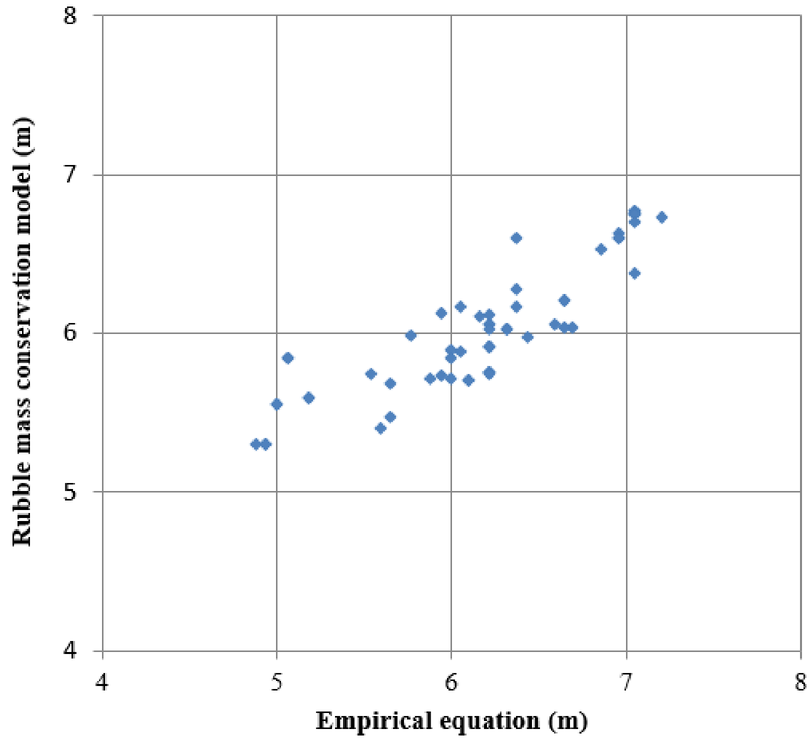

Fig. 6 Comparisons of rubble height predictions

At the initial design stage of an arctic offshore conical structure, in the absence of any empirical equations for the relevant rubble height, engineering judgements and/or model tests are required to estimate the rubble heights as inputs for the design equations. Referring to Fig. 6, the rubble mass conservation approach is able to predict rubble heights comparable to an empirical equation obtained from numerous field data. This provides some confidence that the proposed approach can provide reasonable load predictions when combined with available ice load models, e.g., the improved model documented in Croasdale et al (2016).

A limitation of the current work is that the R_h value is calibrated based on Confederation Bridge data. It is likely that the R_h is dependent on the cone geometry and ice thickness. The determination of R_h values for generic applications will be a focus of future work by the authors.

CONCLUSIONS

In this paper a rubble height model based on a rubble mass conservation concept is established for upward conical structures. Specifically, the rubble mass supply and clearance rates are written in terms of case parameters. Considering a steady state analysis, the balance between the rubble mass supply and clearance rates provides an equation to determine the side rubble height. Assuming a consistent ratio between the central and side rubble heights of a conical structure, this parameter is next calibrated from the Confederation Bridge data.

To benchmark the performance of the proposed model, we consider the 59 Confederation Bridge events documented in Croasdale et al (2016). The rubble heights of these 59 events are predicted using the proposed mass conservation model, compared against those based on an existing empirical equation determined from a collection of Confederation Bridge data. It is shown that the rubble height predictions determined with the proposed mass conservation model compare well with those utilizing the empirical equation. This provides confidence that the proposed approach can complement the design equations by providing a reasonable estimate of the rubble height, particularly when no prior field data / empirical relation is available, thus reducing the burden on design engineers for making the necessary assumptions.

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