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The action of long multi-year ridges on upward sloping conical structures

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ABSTRACT

In ISO 19906 (2010), there are no algorithms provided for calculating loads on sloping structures due to interaction with multi-year (MY) ridges; only references are provided for a range of methods. A study was undertaken to review and improve the theories for MY ridge breaking and ride-up on a slope.

This article reports on the new methods developed for long ridges which are defined as being long enough to develop both centre and hinge cracks. Short ridges, which are defined as being too short to develop hinge cracks, have also been investigated and new theories for short ridges are reported in an accompanying paper.

The new method for long ridges includes a simplified approach for secondary failures of the hinge pieces which are successively broken as a ridge is pushed higher prior to rotation of the broken pieces around the structure. As well, for wide ridges, a new theory for failure across their width has been developed which leads to lower loads than if this failure mode is not included.

Results using the new methods have been compared to tests conducted at the Imperial Oil outdoor ice basin in Calgary. These are the largest scale tests ever conducted in studying multi-year ridge loads on conical structures.

A recommended methodology which includes closed-form equations for the various load components is presented. The method is considered suitable for inclusion in probabilistic methods and in future code developments. In this paper, examples of deterministic loads on typical Arctic structures are given.

Continuing uncertainties are discussed and recommendations are made to address them.

1. Introduction

1.1. Past work

In many regions of the Arctic, Multi-year (MY) ridges are the thickest solid ice feature controlling the design ice loads. The first recorded work on developing methods for MY ridge loads on sloping structures commenced in about 1972 in Canada when Imperial Oil was beginning to explore its Beaufort Sea leases. Initially this was to be by artificial islands but mobile drilling rigs of both monopod and conical shapes were being considered for deeper water where MY ice was expected. Imperial, in conjunction with Arctec Inc. in the US, pioneered the use of ice basin (or tank) model tests on fixed platforms (prior to that, the use of ice tanks was limited to ship design and performance – in Russia and Finland). In conjunction with ice tank model testing, analytical methods were developed based on theories of beams on elastic foundations. The third approach was to perform tests with real ice on "small prototype" cones, as large as feasible, in an outdoor ice basin in Calgary which was built for that purpose in 1973. These early initiatives were described and reported in Croasdale (1975); Edwards and Croasdale, (1976); Kim and Kotras (1973).

The equations for ridge failure loads based on beams on elastic foundations were already in use at that time (as described by Croasdale (1975, 1980)) and these are given later in this paper. Ralston (1977) showed that theoretically, short ridges when treated as beams on elastic foundations with free ends could require greater loads to fail them in bending than long ridges.

As model testing and basin tests continued; Lewis and Croasdale (1978) reported on model tests on rectangular ridges; Abdelnour (1981) conducted model tests to compare with the theoretical work of Kim and Kotras (1973); Verity (1975) conducted the first MY ridge tests in the Esso basin on a 45 degree cone; Wood (1980) extended these by incorporating a 40 degree cone. A new theoretical approach based on plasticity theory was developed by Wang (1984). Abdelnour (1988) reported on a comprehensive set of model tests for Exxon to look at ridge length effects.

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The issue of ride-up and rotation of short ridges was addressed by Winkler and Nordgren (1986, 1989).

The Esso ice basin tests documented in this paper were initiated in 1988 (Croasdale and Muggeridge (1993)). This series of tests was also part of a collaborative R&D initiative with Canadian government funding such that model tests were also performed at two different scales at two other model tanks (NRC in Ottawa and NRC in St John's): (Wang et al. (1997)). Wang also wrote his PhD dissertation at Memorial University on this topic Wang (1997).

Chao (1992), made a comprehensive comparison of the predictive models with experimental results from basin tests and model tanks. Later Z. Wang (1997) also did this in his dissertation.

The work listed above spans the period from the mid-1970s to the late 1990s. A recent assessment by Masterson (2011) was based on unpublished work by Nevel (using beam on elastic foundation theory but accounting for the development of successive hinge cracks).

1.2. Current practise

In ISO 19906 (2010), there are no specific algorithms provided for multi-year ridges, however references are provided for a range of methods; to quote Clause A.8.2.4.5.2:

> "Multi-year ridge actions against conical structures can be estimated using a variety of methods."
> Croasdale (1980), Nordgren and Winkler (1989), Wang (1984).

1.3. Scope of work

The aim of this work was to fill the gap in ISO 19906, 2010 and develop a methodology with algorithms for ice loads due to MY ridges on upward sloping structures. The emphasis has been on closed-form algorithms (and/or iterative methods) that could be used by engineers and possibly include in the next edition of ISO 19906, 2010.

The study was conducted over a period of about 2 years by a team composed of Ken Croasdale (Consultant), Tom Brown (University of Calgary) and George Li and Walt Spring (of Shell Development). In the final stages of the study the algorithms and logic were entered into a probabilistic model by C-CORE. During this process, Mark Fuglem and Jan Thijssen helped with valuable refinements.

The work proceeded by accepting prior idealizations of what can be complex MY ridge shapes as floating solid beams of ice. The prior work in ice basins and model tanks generally confirmed that it is reasonable to examine only the case of ridges moving perpendicular to their main axes and impacting at midpoint ("broadside loading"). Sensitivities with tests done with oblique ridges in the Esso Basin tests (referred to in this Article), have indicated that broadside loading will capture the highest interaction loads.

An examination is first provided of the different mechanics involved with long ridge interactions and the development of simplifying component analytic models. Examples of experimental work done with medium scale ice ridges manufactured at the Esso Basin with observed failure modes and comparisons of loads to the analytic models are presented. A set of algorithms for evaluating loads associated with long ridges, and example calculations, are provided.

In past work (e.g. by Winkler and Nordgren, 1986) short ridges were found to give critical loads when they did not form centre cracks and were driven up the slope as a large ice mass. This study has examined such situations. Changes to the short ridge methods include the relieving mechanisms of failure across the ridge width, and of the ice behind the ridge. When these are introduced, it is found that short ridges will not govern. Using the long ridge methods down to ridge lengths equal to their characteristic length will "capture" the potential range of short ridge loads.

Therefore the scope of this article covers long ridges only. The new theories for short ridges are reported in a separate article (Croasdale et al., 2016a) in which it is also demonstrated that the methods presented in this paper for long ridges will always govern.

A summary of the method with final equations has been published recently in a shortened conference paper (Croasdale et al., 2016b); this Article is more comprehensive, showing the derivation of all equations in the new method with the assumptions, as well as comparisons with physical tests.

2. Mechanics of interaction - long ridges

Long ridges are defined as those with sufficient length to form an initial centre crack and also secondary hinge cracks. These mechanisms are described as follows.

2.1. Theory for long ridges – first cracks

In this approach solid ridges are first considered as infinitely long floating elastic beams. Failure loads can then be calculated using the theory of beams on elastic foundations (Hetényi (1946); Croasdale (1975, 1980). Observations of ridge interaction with sloping structures in model and basin tests indicate that the first failure of the ridge is a centre (radial) crack at the point of contact as the ridge is lifted by the slope. Then the two semi-infinite beams are further broken as the ridge is lifted higher; these are the hinge cracks. This process is shown conceptually in Fig. 1.

As shown in Fig. 1, the calculation proceeds assuming that the ridge has broken out from the adjacent ice sheet early in the process and at load values less that the loads to fail the ridge as a separated beam. Example calculations are provided later to demonstrate that this is the case.

According to beam on elastic foundation theory, the vertical load to cause the centre crack failure is given by,

$$V_1 = \frac{4I\sigma_f}{\delta L_c} \tag{1}$$

where, I is the second moment of area of the beam, σ_f is the bending strength of the ice (upper surface in tension), δ is the distance from the neutral axis of the beam to the upper surface and L_c is the characteristic length for the beam given by,

$$L_c = \left(\frac{4EI}{\rho_w g b}\right)^{0.25} \tag{2}$$

where, b is the width of the beam (ridge) through the water line, E is the ice elastic modulus, ρ_w is the density of water and g is the gravitational constant.

The ridge has now been fractured by the centre crack but it cannot clear until each of the two side pieces have been fractured again, creating what are called hinge cracks (also seen in basin and model tests). It is assumed that these two cracks occur simultaneously and the load is twice the load to fail a semi-infinite beam on an elastic foundation. The load is given by,

$$V_2 = \frac{6.17I\sigma_f}{\delta L_c} \tag{3}$$

In this case δ is the distance from the neutral axis to the bottom of the ridge and σ_f is the bending strength based on tension in the lower surface.

It is seen that V_2 is the controlling load. Note that if the hinge cracks are not simultaneous, V_2 will be reduced and in some cases could potentially be less than V_1. In this work it is always assumed that V_2 controls and is given by Eq. (3).

The corresponding horizontal load (H_2) is given by,

$$H_2 = \xi V_2 \tag{4}$$

where, ξ is the transformation factor relating horizontal and vertical

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