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The statistical analysis of peak ice loads in a simulated ice-structure interaction process

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ABSTRACT

This paper analyses peak ice load data from 2D combined finite-discrete element method simulations. In these simulations, an initially continuous ice sheet, modeled as a floating beam, breaks into smaller ice blocks as the sheet is pushed against an inclined structure. Multivariate linear regression modeling and the variable elimination method were used in the analysis of the data. The analysis gave valuable insight into the peak ice load data in a simulated ice-structure interaction process. It was found that the peak ice load data can be estimated with good accuracy using only five parameters: the ice thickness, the inclination angle of the structure, the shear strength of ice, the ice-structure, and ice–ice friction coefficients. The ice thickness and the structure's inclination angle had the strongest relative effects, with their importance changing during the process. The results also showed that the stage of the ice-structure interaction process should be taken into account in ice load models. The results of this paper underline the importance of the statistical analysis of ice load data and give valuable suggestions for future work.

1. Introduction

Arctic marine operations are increasing. This includes the use of Northern transportation routes, offshore drilling operations, and the development of offshore wind energy. The Arctic is a sensitive environment and requires a high level of safety in all operations. Understanding the ice loads on structures and the ice-structure interaction processes are key factors in developing safe Arctic operations. The aim of this paper is to increase our understanding of the sea ice loads of inclined marine structures by conducting a statistical study on ice load data created through numerical modeling.

Sea ice loads on structures are caused by the failure of ice against a structure. This ice-structure interaction process is complex and appears to have stochastic properties (Daley et al., 1998; Jordaan, 2001). Throughout the years, different models and approaches have been proposed to study ice-structure interactions. This study is based on data obtained from two-dimensional finite-discrete element method (2D FEM-DEM) simulations conducted by Paavilainen et al. (2009, 2011) and Paavilainen and Tuhkuri (2012, 2013). In these simulations, an initially continuous ice sheet, modeled as a floating beam, breaks into smaller ice blocks as the ice sheet is pushed against an inclined structure. Fig. 1 shows screenshots from the simulations. During the simulation, the discrete ice blocks, broken off the ice sheet, interact with each other and with the structure. The particle interactions are modeled using the discrete element method (Cundall and Strack, 1979). DEM modeling has been used in studies on ice mechanics earlier by, for example, Williams et al. (1986), Hopkins and Hibler III (1991), Hopkins (1992, 1998), Hopkins et al. (1999), Barker and Croasdale (2004), Liferov (2005), Tuhkuri and Polojärvi (2005), Polojärvi and Tuhkuri (2009, 2013a,b), and Polojärvi et al. (2012, 2015).

Fig. 1 shows an example of a simulated ice-structure interaction process and illustrates an important advantage of FEM-DEM modeling. Since the movement and failure of the ice sheet, as well as the development of the ice rubble pile, are simulated as a sequence of individual events in the time domain, there is no need to make assumptions about the geometry and large-scale properties of the ice rubble as they are outputs of the simulations and depend on smaller scale properties, like the strength and friction of individual ice blocks. In analytical or semi-analytical ice load models (Palmer and Croasdale, 2013), in turn, the dimensions of the ice rubble, and the smoothed material properties for the whole rubble mass, are needed. Otherwise the equations used in these models would become too complicated. But this leads to two challenges. First, the rubble dimensions and material properties that lead to high ice loads

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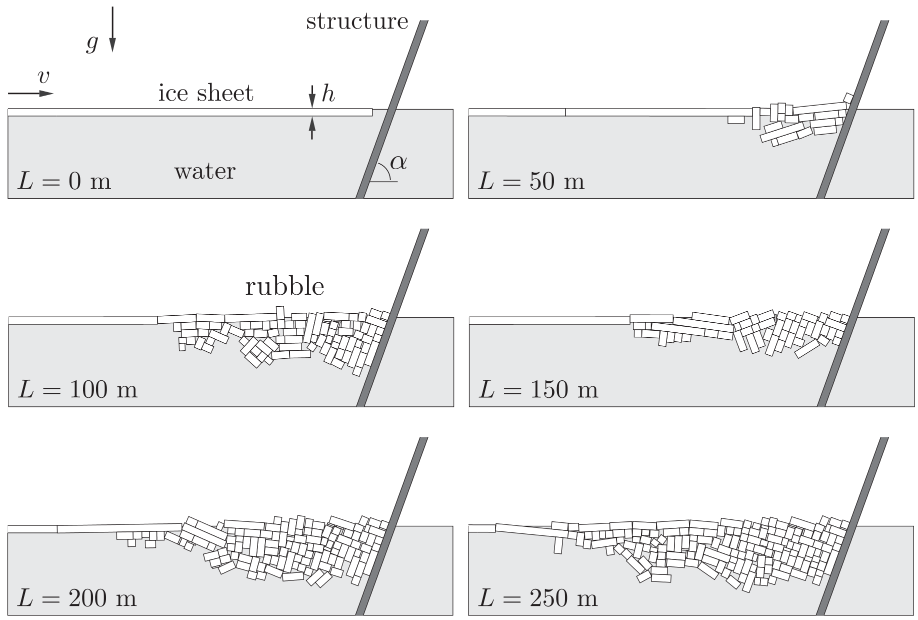

Fig. 1. The simulated ice-structure interaction process and six different stages of the process described by the length of the pushed ice L. In this simulation the thickness h of the ice sheet was 1.25 m and the slope angle α was 70°.

are not known very well. Second, it has been observed that force chains develop into the rubble and have an important role in the ice-structure interaction process (Paavilainen and Tuhkuri, 2013). Such force chains cannot be predicted by models that use smoothed material properties for the whole rubble mass.

In this paper the peak ice load data from the 2D FEM-DEM simulations of Paavilainen et al. (2009, 2011) and Paavilainen and Tuhkuri (2012, 2013) is investigated using multivariate regression analysis. Usually the statistical studies of ice loads are based on experimental data from full-scale measurements. Often these studies aim to find a statistical distribution that is suitable for predicting peak ice loads. Studies on the statistics of ice loads have been conducted for ships (Kheisin and Popov, 1973; Kujala, 1994; Kujala et al., 2009) and for fixed structures (Brown et al., 2001; ElSeify and Brown, 2006; Fransson and Lundqvist, 2006; Kärnä et al., 2006; Qu et al., 2006; Timco and Johnston, 2004). However, regression analyses on peak ice loads on fixed structures are rare (ElSeify and Brown, 2006; Timco and Johnston, 2004), and applications of a multivariate regression analysis on ice load data do not yet exist.

While full-scale data on ice loads is very valuable, it also has limitations. Often the range of parameters observed is narrow, and in many cases the ice properties (e.g., thickness, strength, friction) are not well known, if known at all. Therefore, it is not easy to use the full-scale data to analyse the effects of different parameters on ice loads. Numerical simulations on ice-structure interaction provide another kind of data. In a simulation-based statistical study, all the model parameters are known exactly and can be varied as wished. In addition, it is easy to perform simulations wherein the parameters are only given small changes, and thus study the sensitivity of the process to changes in parameters.

The results from full-scale experiments, and also from model-scale experiments, often show wide scatter. This may be due to the above-mentioned challenges in recording the ice parameters, but also due to the complexity of the interaction process itself. If the scatter in the results is large and the number of the experiments is small, the statistical significance of the results on parameter effects may be questionable. However, numerical simulations allow a large number of repeated experiments with full control of parameters, and hence the parameter effects on results can be reliably studied. This is the main purpose of the study in this paper: To investigate the sensitivity of peak ice loads to different parameters during the failure process of a sea ice sheet against an inclined structure.

In the following, first the 2D FEM-DEM simulations are described and the linear regression analysis and variable elimination techniques are introduced. After this, the regression equations obtained and the peak ice loads estimated with the regression model are given. Finally, the relative combined parameter effects from the most sensitive parameters are presented and the potential implications of the findings are discussed.

2. Simulations and statistical analysis

This section introduces the 2D FEM-DEM simulations and the linear regression analysis. A detailed description of the simulations can be found from Paavilainen et al. (2009, 2011) and Paavilainen and Tuhkuri (2012, 2013). The linear regression analysis is described further in Appendix A.1 and comprehensively by Rawlings et al. (1998) and Walpole et al. (2012), for instance.

2.1. FEM-DEM simulations

The data used in this paper is from the 2D FEM-DEM simulations conducted by Paavilainen et al. (2009, 2011) and Paavilainen and Tuhkuri (2012, 2013). The code used in the simulations was developed in Aalto University (see Paavilainen et al. (2009) for the simulation details) and its DEM part is in aligned with the model by Hopkins (1992). Paavilainen et al. (2009) found the model to be able to capture the ice-structure interaction processes, wherein a continuous ice sheet fails against the structure by bending and shearing. The model does not describe continuous crushing nor does it include any rate-dependent ice properties. Additionally in 2D simulations, clearance and non-simultaneous ice failure in ice-structure interface are not modeled. Additionally, the model was validated in Paavilainen et al. (2009, 2011) by performing comparisons with laboratory and full-scale measurements, as reported by Saarinen (2000) and Timco and Johnston (2003) respectively.