Cold Regions Science and Technology 85 (2013) 191–205

Contents lists available at SciVerse ScienceDirect

Cold Regions Science and Technology

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

On modeling cohesive ridge keel punch through tests with a combined finite-discrete element method

Arttu Polojärvi *, Jukka Tuhkuri

Aalto University, School of Engineering, Department of Applied Mechanics, P.O. Box 14300, FI-00076 Aalto, Finland

ARTICLE INFO

Article history:
Received 3 July 2012
Accepted 17 September 2012

Keywords:
Ice rubble
Punch through tests
Freeze bonds
Numerical modeling
Combined finite-discrete element method
Cohesive elements

ABSTRACT

This paper introduces a technique for modeling partly consolidated ice rubble using a two-dimensional combined finite-discrete element method and an application of the technique on ice rubble punch through experiments. In the technique, each ice block within the rubble, the contact forces between the blocks, the block deformation, and the rubble freeze bonds are modelled. Simulations with various freeze bond strengths and block to block friction coefficients were performed. As a main simulation result, the close relationship between rubble deformation patterns and load records is demonstrated in detail. It is shown that the buoyant load component due to the rubble becoming detached from the surrounding rubble field and displaced during an experiment is of crucial importance when interpreting punch through experiment results. The consequences of simulation results on ice rubble material modeling are discussed.

1. Introduction

Ice ridges are common features in northern seas. Two of the most important parts of ice ridges are the consolidated layer, which is comprised of frozen water and ice blocks, and the keel, which consists of ice rubble. The rubble can be a collection of loose blocks, but it is often partly consolidated, that is, it consists of ice blocks bonded together by freeze bonds, which resist the relative movement of the blocks. The freeze bonds are formed due to freezing or sintering (Ettema and Schaefer, 1986; Kuroiwa, 1961).

Punch through experiments are commonly used to test the properties of ice rubble. In a punch through experiment, a flat indentor platen penetrates the rubble mass while the force applied by the rubble on the indentor is measured. The indentor force-displacement records, together with the dimensions of the experimental set up, are then used to derive some of the material properties of the rubble.

The first punch through experiments were performed by Leppäranta and Hakala (1989, 1992) using a loading platform and concrete blocks. Since then, the experimental equipment has been improved and the method has been used in full scale as reported by, for example, Bruneau et al. (1998), Heinonen and Määttänen (2000, 2001a,b), Croasdale et al. (2001) and Heinonen (2004). For more detailed analysis of the behavior and failure mechanism of rubble in punch through tests, experiments in laboratory scale have been performed by, for example, Leppäranta and Hakala (1992), Bruneau et al. (1998), Azarnejad et al. (1999), Azarnejad and Brown (2001), Jensen et al. (2001), Lemee and Brown (2002), Serré (2011) and Polojärvi and Tuhkuri (2012). Liferov and Bonnemaire (2005) have reviewed the experimental work and modeling.

The modeling of punch through experiments using continuum models has been performed by a number of authors. These models have been successful in replicating full scale (Heinonen, 2004) and laboratory (Liferov et al., 2003; Serré, 2011) experiments, but have the disadvantage that the details about the rubble behavior have been smoothed out from the modeling results due to the continuum description of the rubble. One such detail has to do with the relation of rubble mass transfer to indentor load records as addressed in Polojärvi et al. (2012) in the case of non-cohesive rubble.

Hence, even if the ice rubble usually consists of multitude of ice blocks, it remains unclear whether or not there are enough blocks to describe the rubble as a continuum, and thus, if the continuum models can always reliably be used for rubble. This motivates the discontinuous approach, in which rubble is modelled block by block, used here. We believe, that this approach helps in gaining more understanding on the phenomena behind ice rubble behavior. This understanding can then be used not only in the estimation of ice loads or in the planning of future experiments, but also in making further improvements to the more commonly used continuum models.

This paper presents a technique for modeling partly consolidated ice rubble using a discontinuous approach, and modeling of punch through experiments using the technique. The traditional way of modeling discontinuum is the discrete element method (DEM), which dates back to Cundall and Strack (1979). In DEM, the individual particles are usually assumed rigid, and their deformation is taken into account in the inter-particle contact models. In the present study, however, the blocks within the keel are deformable and the combined finite-discrete element method (FEM-DEM) is used (Munjiza, 2004; Munjiza and Andrews,

* Corresponding author. Tel.: +358 9 470 23438.
E-mail address: arttu.polojarvi@aalto.fi (A. Polojärvi).

0165-232X/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.coldregions.2012.09.013

2000; Munjiza et al., 1995). Cohesive elements were used to model freeze bonds binding the blocks within the rubble together (Block et al., 2007; Camacho and Ortiz, 1996; Morris et al., 2006; Ortiz and Pandolfi, 1999; Sam et al., 2005).

The numerical modeling of ice rubble related problems using DEM and FEM-DEM has previously been used in studies on ice ridging (Hopkins, 1992, 1998; Hopkins et al., 1999), ice pile-up against structures (Haase et al., 2010; Paavilainen and Tuhkuri, 2012; Paavilainen et al., 2006, 2009, 2011) and punch through experiments on unconsolidated rubble (Polojärvi and Tuhkuri, 2009; Polojärvi et al., 2012; Tuhkuri and Polojärvi, 2005). Different types of cohesive models have been previously used in modeling sea ice fracture by, for example, Mulmule and Dempsey (1997a,b, 1999), Bazant (2002), Schreyer et al. (2006), Gürtner (2009) and Dempsey et al. (2010).

This paper first discusses the mechanics of the simulations. The emphasis of this part of the paper is on the modeling of the freeze bonds between the individual rubble blocks. This is followed by a description on the application of the model on the study of ridge keel punch through experiments. After this, we present the results and analyze them in detail, and provide a discussion on them. Finally, the paper concludes with some remarks on and suggestions for future work.

2. Description of the simulations

The virtual punch through experiments were performed using the combined finite-discrete element method (FEM-DEM). In this method, the discrete elements representing the ridge keel blocks are meshed into finite elements. The finite elements are used to compute the block deformation and the contact forces between colliding blocks. In addition to contact forces, the deformation and the motion of the blocks is caused by inertial forces and cohesive forces, and by buoyant force, which is caused by water.

The simulations were explicit and central difference method was used to advance between the time steps. On each time step of a simulation, the following seven tasks are performed: (1) Determination of internal forces according to the displacement field for continuous material, (2) a neighbor search, (3) derivation of contact forces, (4) stress state check at freeze bonds, (5) calculation of the cohesive forces in the material points under failure process, (6) adding external forces, and (7) updating of node positions using Newton's laws for the next time step.

2.1. Contact forces

The contact forces were derived using a penalty function and the potential contact force method (Munjiza, 2004; Munjiza and Andrews, 2000; Munjiza et al., 1995). In the potential contact force method, a potential φ with continuous first partial derivatives with respect to spatial coordinates is defined for every point P of each finite element area Γ. Further, $\varphi=\varphi(P)$ should vanish on finite element edge S for a smooth collision response. Hence,

$$\varphi(P)>0, \quad P\in\Gamma \quad \wedge \quad \varphi(P)=0, \quad P\in S. \tag{1}$$

When triangular finite elements are used, an obvious choice for $\varphi(P)$ is the area coordinates.

The contact force, $d\mathbf{f}_\varphi$, applied to an infinitesimal area element, $d\Gamma_o$, penetrating into φ is determined from the gradient of φ as (Fig. 1a)

$$\frac{d\mathbf{f}_\varphi(P)}{d\Gamma_o}=-s\nabla\varphi(P), \tag{2}$$

where s is a positive constant penalty term. The negative sign is due to the repulsive nature of the contact force. The contact force, $\mathbf{f}_\varphi$, due to $\varphi(P)$ is determined by integration over the overlap area, Γ_o, of two

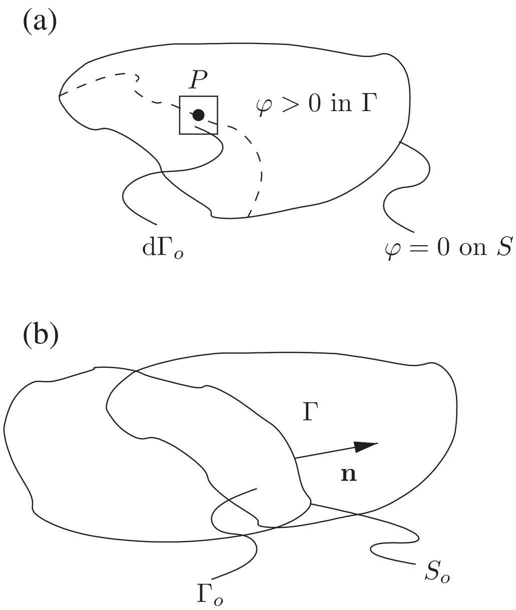

Fig. 1. (a) An infinitesimal area element $d\Gamma$ at point P penetrating a finite element with area Γ and (b) the overlap area $d\Gamma_o$ of two elements.

colliding elements. The integral is reduced to a computationally more efficient integral over the boundary of area $d\Gamma_o$ using a generalized version of Gauss's theorem:

$$\mathbf{f}_\varphi=-s\int_{\Gamma_o}\nabla\varphi(P)d\Omega=-s\int_{S_o}\varphi(P)\mathbf{n}\ d\Gamma, \tag{3}$$

where $\mathbf{n}$ is the unit outer normal of S_o (Fig. 1b). The previous equation shows that the distributed load acting upon overlapping volume elements due to φ is reduced to a force acting upon a single point on S_o.

Dissipation due to sliding friction is modelled using dynamic Coulomb friction. The frictional force, $\mathbf{f}_\mu$, is solved using the following equation:

$$\mathbf{f}_\mu=-\mu|\mathbf{f}_c|\frac{\mathbf{v}_r-\mathbf{v}_r\cdot\mathbf{n}}{|\mathbf{v}_r-\mathbf{v}_r\cdot\mathbf{n}|}, \tag{4}$$

where μ is the friction coefficient and $\mathbf{v}_r-\mathbf{v}_r\cdot\mathbf{n}$ is the tangential component of the relative velocity of contacting blocks at the point of contact.

2.2. Block deformation

Though large displacements of individual ice blocks are allowed in the simulations, the deformation of material elements within the continuous ice blocks was assumed to be small. The material behavior of the continuous ice blocks is thus assumed to be linear elastic. This assumption is justified because, rather than being dominated by the deformation of the individual ice blocks, the deformation of the ice rubble is dominated by inter-particle sliding and the movement of the blocks within the rubble (Heinonen, 2004; Sayed et al., 1992).

Furthermore, the material behavior of the blocks is assumed to be isotropic and plane strain state is assumed. The material damping of the blocks on the elastic regime is viscous. Internal forces due to the deformation of the blocks are solved using constant strain triangle elements with an explicit solution procedure implemented as presented in detail by Munjiza (2004).