Available online at www.sciencedirect.com
SCIENCE DIRECT®
Cold Regions Science and Technology 41 (2005) 135–151
cold regions science and technology
www.elsevier.com/locate/coldregions

Ice rubble behaviour and strength: Part I. Review of testing and interpretation of results

P. Liferov[a,b,*], B. Bonnemaire[a]

[a]*Norwegian University of Science and Technology, Trondheim, Norway*
[b]*Barlindhaug Consult AS, Tromsø, Norway*

Received 4 May 2004; accepted 5 October 2004

Abstract

The deformation behaviour and strength of ice rubble are addressed in this paper. Review of ice rubble testing and strength is given. Pure shear and punch tests on ice rubble are considered with special attention to derivation of material properties. The primary failure mode associated with initial breakage of rubble skeleton is found to dominate overall rubble strength in punch tests. Scaling of ice rubble is touched upon and a summary of scaled rubble properties is presented. The average c/t value was found to be around 20 kPa/m derived both from the laboratory and the in-situ tests. Unreasonably high values of φ (above 50°) seem to come from analyses where cohesive component of rubble strength was neglected when deriving the material properties.

Keywords: Ice ridge; Ice rubble; Strength; Mohr-Coulomb; Scaling

1. Introduction

Ice rubble plays an important role in many engineering problems, ranging from river engineering aspects to ice-cover interaction with offshore structures. Knowledge about the mechanical properties of ice rubble is however rather limited. Several programs on testing these properties have been carried out since the beginning of the seventies. Both laboratory and in-situ tests were conducted.

Most of the laboratory experiments were done with different types of shear boxes. The first shear tests were done in direct shear boxes (Prodanovic, 1979; Keinonen and Nyman, 1978; Weiss et al., 1981; Hellman, 1984; Fransson and Sandkvist, 1985) followed by simple shear tests (Urroz and Ettema, 1987) and constant confining pressure tests (Sayed, 1987) and finally more sophisticated bi-axial tests (Timco et al., 1992; Løset and Sayed, 1993; Cornett and Timco, 1996). Extensive reviews of shear tests and interpretation of results are given by Ettema and Urroz (1989, 1991) and Timco and Cornett (1999). The results showed that ice rubble behaviour could generally be described by an elastic-perfectly plastic

* Corresponding author. Norwegian University of Science and Technology, Trondheim, Norway. Fax: +47 77 62 26 99.
E-mail address: pavel.liferov@barlindhaug.no (P. Liferov).

0165-232X/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.coldregions.2004.10.001

model where the plasticity is defined by the Mohr-Coulomb law. Tri-axial tests on ice rubble as described by Wong et al. (1990) supported the idea of using the Mohr-Coulomb yield criterion. They observed that the cohesion and the friction angle depend on the initial void ratio. Recent direct shear tests done by Yasunaga et al. (2002) agree with the above findings. Several programs on punch testing of ice rubble were also performed in the laboratory as described by Azarnejad and Brown (1998), Jensen et al. (2000, 2001) and Lemée and Brown (2002).

The variation in the reported values of ice rubble strength was very wide. Ice rubble strength appeared to be dependent on the confining pressure, strain rate, size of ice blocks, void ratio, time history, etc. Control of the boundary conditions during testing and interpretation of test results could also have been a potential source of substantial discrepancy in the measured values. Scaling of the ice rubble strength is another issue that has been addressed very little. Altogether this state of knowledge did not give reliable information for assessment of full-scale loads from first-year ice ridges and caused a need for in-situ testing.

The first in-situ testing was undertaken by Leppäranta and Hakala (1992) in the Baltic Sea. They did several punch tests on first-year ice ridges. A number of in-situ test programs has been carried out later as described by Heinonen (1999), Smirnov et al. (1999) and Timco et al. (2000). The majority of in-situ tests were punch tests. Several direct shear tests and pull-up tests were done as well. Recently, one shear-off test on artificially produced ice rubble was done by Liferov et al. (2003a,b).

The derivation of the rubble strength from tests whose boundary conditions are not well controlled as, for example, in punch tests, is a special issue that demands particular attention. Two approaches have been used to interpret the test results, namely analytical and numerical. Among the analytical approaches both the different forms of limit equilibrium method (Leppäranta and Hakala, 1992; Azarnejad and Brown, 1998; Jensen et al., 2000) and the upper bound theorem of plasticity (Heinonen and Määttänen, 2000) were used. Regardless of the general validity of the above methods, the major problem was associated with the use of the two-parametric Mohr-Coulomb failure criterion. Simplifications were done and ice rubble was considered either as a frictionless or as a cohesionless material. In the later case, however, excessively high values of the internal friction angle were obtained.

As the analytical approach does not take the complexity of deformation mode into account, it may yield to unreliable results. Numerical modelling of punch tests turned out to be a useful tool for judgment of the rubble strength. Finite-element modelling of punch tests was conducted by Heinonen (1999, 2002) and Liferov et al. (2002, 2003a,b). In the later work it was found that in laboratory punch tests the bending failure can contribute substantially and that neglecting the cohesive/adhesive strength might lead to unreliable results.

The writers are by no means the first to ponder the complicated topic of ice rubble strength. This paper is rather an attempt to address some of the unresolved questions that arise when trying to summarize and systemize the ice rubble strength based on the existing data with focus on its further application in assessment of loads from ice ridges. A discussion about interpretation of test results is essentially based upon the most comprehensive test programs conducted during the last decade with some references to earlier research.

2. Shear box tests

2.1. General

A thorough discussion about the shear box tests conducted before the 90's was done by Ettema and Urroz (1989, 1991). They addressed the meaning of internal friction angle and cohesion. An important point has been made about whether the peak angle of internal friction φ_p or the critical state friction angle φ_c have been reported in most of the studies. They also argued that unconsolidated ice rubble undergoing continuous shear deformation is essentially cohesionless and an effective angle of internal friction φ' was suggested to describe the material strength. The derivation of the ice rubble strength from the noticeable series of tests in the bi-axial compression apparatus conducted by Sayed et al. (1992), Løset and Sayed (1993) and Cornett and Timco (1995, 1996) has also been based on the assumption that ice rubble has a cohesionless nature. They used the following formulation to derive the