SCALE-MODEL RIDGES AND INTERACTION WITH NARROW STRUCTURES

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An experimental campaign to investigate sea ice ridge interaction with bottom-fixed structures has been designed. We aim to investigate a) the scaled ridge properties, b) the processes during testing and c) the scaling of ridge forces with respect to a cylindrical and conical structures at the water line. Full-scale ridge structure interaction data is available for the Norstrtrömsgrund lighthouse so we will use its size in scaling the tests. We will assume that gravity/buoyancy forces contribute and combine Froude and Strength scaling with a geometric scale-factor of 15. The initial ice temperature and accumulated air temperatures during consolidation (FDD) will be varied to investigate how reasonably scaled ridge properties can be achieved. Finally, structures with cylindrical an conical different waterlines will be used.

1. INTRODUCTION

Ice action from first-year ice ridges remains one of the key challenges in design of structures (offshore wind, aids for navigation and oil/gas), mooring systems and ships in a warming Arctic and sub-Arctic marine and coastal environment. There is a relatively high uncertainty in the prediction of ridge loads, in the most recent review the world-wide expert estimation of ridge loads ranged from 120 to 605 MN (Timco and Croasdale, 2006). In shallow water without tide such as the Baltic conical structures are often used. But, the effect of cones, and in particularly narrow cones, on ice ridge interaction is not well known or documented. Basin tests are often carried out in relation to design of structures, but the validation of these experiments is lacking, and there is no general agreement on how to scale and produce first-year ridges in ice basins (Repetto-Llamazares, 2010).

Due to climate change the Arctic sea ice cover is changing, it becomes thinner (Kwok et al., 2009; Kwok and Rothrock, 2009; Haas et al., 2008; Giles et al., 2008) and younger (Maslanik et al., 2007, 2011; Wadhams et al., 2011). It gives longer ice-free summers, lighter ice condition and a larger fraction of the Arctic sea ice cover becomes *First-year ice*. This will probably cause increased Arctic sea transport, both through Arctic waters (e.g. Northeast passage), and to and from Arctic settlements. It will also increase the exploitation of mineral resources. Much of this increased activity will take place in areas with predominantly first-year ice, such as all sub-Arctic seas (the Baltic Sea, the Sea of Okhotsk, the Caspian Sea and the Sea of Bohai), and many shallow Arctic areas where *First-year ice ridges* give the Ultimate Limit State quasi-static design ice load. Even though the ice conditions get lighter it is not obvious that the extreme events are reduced. Cammaert et al. (2008) used a probabilistic approach and included a warming climate, but found negligible effect on a 100 year ice load. One important application is the development of European offshore wind power in the Baltic Sea, where one promising way to decrease the costs in the sub-structure part is to use a slightly conical structures. However, this will lead the ice load design outside the guidelines (*e.g*. ISO 19906).

2. BACKGROUND AND THEORY

We wish to examine

- The scaled ridge properties
- The processes during testing

- The scaling of ridge forces with respect to a cylindrical and conical structures at the water line.

The scaling of measured ridge forces can be done by assuming that the gravity/buoyancy give vital contributions to the force, or by assuming that these can be neglected. We assume that during the ridge interaction with the structure the effects of inertia, gravity/buoyancy and ice breaking are the three essential force contributions. The geometric and strength variables are both scaled - according to the Froude scaling law - with the same factor λ, the velocity is scaled with $\lambda^{1/2}$, and the forces with λ^3. However, there is considerable disagreement in the ice community about scaling of ice-structure interaction dominated by crushing, see Määttänen (1979) for derivation of scaling without gravity/buoyancy effects. The most important ridge properties are the thickness and the strength of the consolidated layer. It may easily become too thick and strong and seems to be very sensitive to the temperature of the ice used to produce the ridge (Høyland, 2010). Thermo-dynamics play an essential role and we wish to quantify the effect of initial ice temperature and FDD on the thickness and strength of consolidated layer. This will enable a controlled way to scale the consolidated layer.

During process of interaction the ice rubble surcharge and effect of level ice confinement behind the ridge affects the force on the structure. The present ISO standard disregards the effect of surcharge, and, tacitly assumes full level ice confinement behind the ridge. However, the study of Serré and Liferov (2010) indicate that the surcharge may significantly affect the ridge action. Further Dalane et al. (2009) suggest a significant reduction of ridge force for unconfined ridges. We will quantify the mechanical (including volumetric) properties of the ice unconsolidated layer (rubble) by critical state theory, and study the rubble surcharge during tests with a scaled version of the Norströmsgrund lighthouse (LOLEIF / STRICE data). We will also quantify the reduction of ridge force with level ice confinement. In this project, we wish to scale, produce and characterize first-year ice ridges and measure their interaction with a scaled model of the Norströmsgrund lighthouse. Full-scale measurements of first-year ice ridge action on the Norströmsgrund lighthouse has been thoroughly measured through the EU projects LOLEIF and STRICE (1997-2003) and gives a rare base for the comparison of measured full-scale ice ridge action and a scale-model test.

3. EXPERIMENTAL PLAN

3.1 Scaling

We assume that during the ridge interaction with the structure the effects of inertia, gravity/buoyancy and ice breaking are the three essential force contributions so that the geometric and strength variables are both scaled with the same factor λ, and the velocity is scaled with $\lambda^{1/2}$. We choose a scale factor λ=15. The deepest measured ice ridge keel in the Baltic ever was 28 m (Palosuo, 1975), but no ridges deeper than 9 m were observed in the LOLEIF/STRICE programs to interact with the Norströmsgrund lighthouse, so we choose a full-scale value of ridge keel depth of 10 m. Palosuo (1975) report that block thickness in the Baltic ridges range from 0.15 to 1.2 m so we choose a full-scale initial level ice thickness of 0.75 m. We will not study ice-induced vibrations so the scaled structure will be as stiff as possible. Further, there is little proof that ice drift velocity affects the ice ridge action, and most high load events on the Norströmsgrund occurred with drift velocities between 0.1 and 0.2 m/s, so we choose a full-scale ice drift velocity of 0.15 m/s. Table 1 gives the geometric properties. The mechanical properties of the ridges is a function of the geometry and the thermodynamic processes and will be measured, not predetermined.

Table 1. Scaling of properties, full-scale and model-scale (scale factor λ=15).

	Ice thickness	Keel depth	Structure diameter	Ice drift velocity
Full-scale	0.75 m	10 m	7.5 m	0.15 m/s
Model-scale	0.05 m	0.67 m	0.50 m	0.04 m/s

3.2 Test matrix and parameter variation

The experimental program consists of four steps (see next paragraph) and we aim at letting the following three variables have two levels (high / low) as detailed in Table 2: a) The initial temperature of the level ice going into the ridge ($T_{i,0}$), b) Degree of consolidation measured by the *Freezing Degree Days (FDD)* and c) the level ice confinement in the interaction experiments. Høyland et al. (2001) showed that $T_{i,0}$ may have considerable effect of the thickness of the consolidated layer, a change of $T_{i,0}$ from -1.3 C to -1.8 C increased the thickness of the consolidated layer from about 0.08 m to 0.12 m. With a low *FDD* the initial phase of consolidation will dominate (Høyland, 2010) but with higher FDDs the main phase becomes more important so our experiments will allow for a quantification of this effect. Finally, Dalane et al. (2009) showed that the ridge load can be reduced considerably if the level ice behind the ridge is broken. This means that ice ridges embedded in a large ice sheet will give higher ridge action than ridges without a surrounding confining level ice sheet. The main features in the experimental program are:

1. Ridge production where the initial temperature ($T_{i,0}$) and the thickness (h_i) of the level ice are the variable parameters. These will be measured manually.
2. Consolidation where the air temperature (T_a) and the consolidation time (Δt_{cons}) give the *Freezing Degree Days (FDD)* that will be the variable parameter. The development of the consolidated layer will be monitored with thermistor-strings installed through the ridges.
3. Measure mechanical properties and geometry prior to interaction experiments. The strength of the ice ridge consolidated layer and ice rubble fragments is measured as explained below. To accurately measure the ice ridge profile, an upward looking sonar will be utilized.
4. Run ridge interaction experiments with a cylindrical and conical structures. The cylindrical will be the base as comparison can be done with full-scale data from the EU projects LOLEIF and STRICE. The cone angle will be 75°.

Table 2. Ridge production and parameter variability. Two ridges will be made from each ice sheet. T_f is the freezing point of the basin-water

	Sheet	Ridge #	$T_{i,0}$	*FDD*	Structure
Week 1 Cylindrical structure , Base case Norströmsgrund to allow for comparison with full-scale data	1	R11	T_f - 1.5˚C	-5˚C·Days	Cylindrical
	1	R12	T_f	-5˚C·Days	Cylindrical
	2	R21	T_f - 1.5˚C	No cooling	Cylindrical
	2	R22	T_f	No cooling	Cylindrical
Week 2 Conical structure	3	R31	T_f - 1.5˚C	-5˚C·Days	Conical
	3	R32	T_f	-5˚C·Days	Conical
	4	R41	T_f - 1.5˚C	No cooling	Conical
	4	R42	T_f	No cooling	Conical

3.3 Testing of mechanical properties

The mechanical properties of the consolidated layer and the ice rubble (unconsolidated part) will be measured separately. In the consolidated layer the uniaxial tensile and compressive strength and bi-axial compressive strength should be measured. The uniaxial tensile strength will be measured through bending tests (Jensen et al., 2001).

The ice rubble mechanical properties will be measured through punch shear tests, in which the ridge keel is penetrated vertically by a cylinder. The punch force and corresponding cylinder displacement is measured. Possible areas for punch tests are indicated in Fig 1a. The force and displacement of the platen is measured with video recordings (above and underwater). Before the keel is loaded, the consolidated layer is cut free from the surrounding ice field along the perimeter of cylinder. This test data is then further analysed to evaluate the material parameters of the ice rubble.

The ice rubble elastic behavior is assumed isotropic so it will be characterized by two elastic constants (K and G). The plastic behavior is modelled by the combination of critical state concept (see e.g. Muir Wood, 1990) which requires a frictional resistance constant (M) and breakage mechanics concept which takes three parameters (p_c, ω, and v) (Einav, 2007).

3.4 Measurements during interaction testing

A schematic drawing of a ridge interaction test is shown in Fig. 1a. The structures, shown in Fig. 1b, are fixed to the main carriage of the ice basin. The carriage is moved with a constant velocity through the ridges. We will measure the forces, displacements and use tactile sensors to measure the contact pressure of ice. The experiments will be filmed above the water level and underwater. In addition, the ridge keel interaction will be continuously scanned with a sonar so that careful studies on the deformation mechanisms in the ridges can be studied.

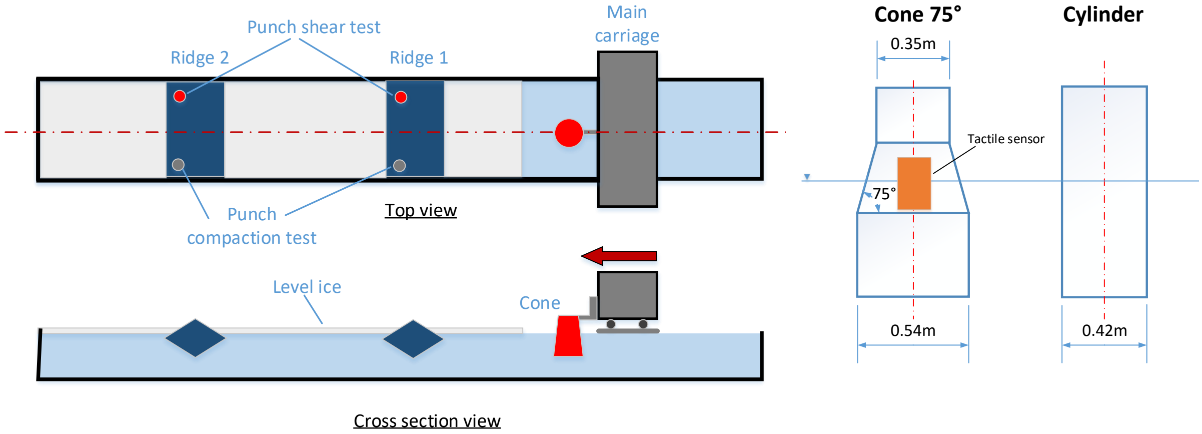

Figure 1. a) Schematic drawing of ridge penetration tests, b) Shape and main dimensions of the test structures in the model scale.

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