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Soil mechanics measurement methods applied in model brash ice

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ABSTRACT

In ship building, vessel performance can be verified before prototype building by ice model tests, which are conducted according to verified modelling laws. The test methods are calibrated with full scale references. Currently, model tests predict vessel performance reliably, particularly in level ice conditions.

Finnish-Swedish ice class rules (FSICR) define the minimum engine power required for a safe operation in certain conditions. Ice class rules present an equation for required engine power, but a vessel with less engine power can be approved, if the engine power is sufficient according to the model tests. The ship's performance is defined so that an 1A class vessel must be able to proceed at a constant speed of 5 knots in an old brash ice channel, which mid part thickness is 1.0 m.

Recently, channel test result variation has been observed between model test laboratories, especially when new EEDI-type tankers have been tested. Different test results can be achieved from tests, which all fulfill the requirements of the FSICR guidelines. FSICR define the brash ice channel thickness and width, but no other parameters. Different model test results indicate that the channel resistance depends on one or more parameters, which are not defined by the guidelines. To evaluate other parameters relevancy, there was a need to define the potentially important brash ice parameters and develop measurement procedures, which are relatively simple, fast to conduct and repeatable.

As a material, brash ice resembles granular soil. In this paper, potentially applicable soil mechanics test procedures for brash ice are presented. Test equipment were built and tested with three different brash ice types. The difference between the materials was the ice piece target crushing strength.

The measured brash ice properties were porosity, piece size distribution, angle of repose, angle of internal friction (or shear strength) and compressibility.

KEY WORDS: Brash ice channel; Model test; Soil mechanics

BRASH ICE CHANNEL IN FULL SCALE AND IN MODEL SCALE

Sea ice is an anisotropic material, which mechanical properties vary according to location, climate, weather, currents, sun radiation and many other causes. In addition to variation in properties of unbroken level ice, ice appears in many forms, such as brash ice, ice floes, ridges, and ice bergs (Cammaert, 1988). For typical commercial vessel navigation during winter period, brash ice channel is a typical ice condition. Brash ice channel is formed when an icebreaker or other vessel breaks through a uniform ice field. Over time, if multiple vessels use the same track, the ice pieces in channel become rounder and they accumulate in channel evenly in longitudinal direction. The cross-section of broken ice pieces in channel, brash ice, is typically thickest at the channel edge and thinnest in the middle (Kujala and Riska, 2010), see Figure 1. Pictures of ice channels are presented in Figure 2 and Figure 3.

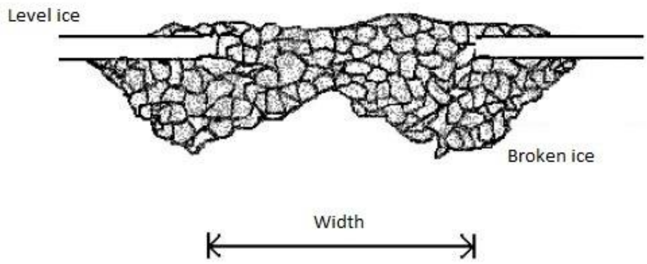

Figure 1. Typical cross-section of an old brash ice channel (Sandvist, 1978)

Figure 2. Newly broken brash ice channel

Figure 3. An old brash ice channel consists of rounded ice pieces. In the Baltic sea, the diameter of ice pieces is typically 10 – 100 cm.

Weeks (2010) defines brash ice to be “an accumulation of floating ice made up of fragments not more than 2 m across (small ice cakes), the wreckage of other forms of ice”. In Baltic sea the piece size seldom exceeds 1 m in fairway channels due to active winter navigation. To understand and predict brash ice behavior, the material must be studied both in nature and in theory.

Before now, soil mechanics has been successfully exploited in measuring mechanical properties of unconsolidated ridge keels by Keinonen and Nyman (1978). Soil mechanics offers a decent basis for material analysis, and therefore the material measuring procedures developed for soil mechanics are applied also in brash ice research.

Model testing is commonly used in ship design. In open water conditions, hydrodynamics can be precisely predicted based on model test results. Nowadays, the vessel performance can be predicted rather well with ice model tests, and the model testing procedures are commonly verified by conducting correlation tests in full scale.

Froude and Cauchy similitude principles are generally applied in ice model testing, basically because of the tradition of open water model tests. None of present model ice materials can model all mechanical properties of sea ice simultaneously (ITTC, 2014). Typically, model ice is produced of water with a dopant in order to adjust the macroscopic strength properties (von Bock und Polach, 2015).

In this study, three different model brash ice materials were produced, and their mechanical properties were measured with measurement devises, which are described in this paper. The target properties were chosen so that the target parameters remained the same in all materials except the ice compressive strength. Two of the materials were fine-grained, salt-doped model ice (FGX-ice) with different target crushing strengths (29 kPa and 57 kPa), which was manually cut into small pieces, and one brash ice consisted of fresh water ice cubes (crushing strength about 3 MPa). This study presents the measuring and analysis procedures and discusses the functionality of each measurement.

MECHANICAL PROPERTIES OF INTEREST

Parental Ice Mechanical Properties

To be able to compare the brash ice types, some basic parameters were measured from the parental ice. In this study, flexural strength, compressive strength, ice density, and friction between ice and model were measured.

Flexural strength is not a basic material parameter, but it is generally considered as an index test in ice technology. This is due to two reasons: firstly, many real sea ice failures occur in flexure, and for example icebreakers are traditionally designed to break ice by bending. Secondly, the flexural strength test is simple to conduct in situ in field conditions, and therefore there is a wide range of existing research on ice flexural strength both in full scale and model scale (Timco, 2010). Flexural strength is not relevant in broken ice, but it is useful in comparing different model ice materials. It is also traditionally one of the few ice mechanical properties, which are properly scaled in model tests.

The compressive strength is a fundamental property of sea ice and it is very relevant in interaction of brash ice particles.

When the ice is displaced down into the sea water, the ice buoyancy force is proportional to the difference in density between the ice and sea water (Timco, 2010). Small changes in density can make a large difference in buoyancy force, which essentially affect e.g. ice accumulation at vessel side and frictional resistance of vessel.

Significant percentage of vessel resistance consists of frictional resistance, which is proportional to dynamic friction coefficient between vessel surface and ice at advance speeds of interest (Malmberg, 1983).

Brash Ice Mechanical Properties

The following parameters were measured from each brash ice material: brash ice porosity, piece size distribution, angle of repose, angle of internal friction (or shear strength) and compressibility.

Amount of void has a significant effect on granular material mechanical properties. Brash ice porosity means the amount of water and air compared to whole volume of brash ice sample. Therefore, porosity affects for example on brash ice buoyancy and the contact area size between the structure and ice. The contact area affects directly to the vessel frictional resistance.

In soil mechanics, grain size is useful as a distinguishing property of material. Soil grain size vary in a wide range, and it is also used as basis of simple subdivision of different types of soil. However, piece size does not define mechanical properties of material, and same grain-sized materials can have different mechanical properties. Contrary to piece size, piece shape affects the mechanical properties. For example, material consisting of round particles has lower shear strength than material consisting of particles with sharp edges. Nevertheless, piece size is an interesting property as geometrical scaling is applied. Brash ice piece size is typically between 10 cm – 100 cm, meaning 0.5 – 5.0 cm in typical ice model test (scale 1:20).

The angle of repose is defined as the steepest slope of the unconfined material measured from the horizontal plane, on which material can be heaped without collapsing (Mehta and Barker, 1994). Angle of repose is affected by water content, and thus it is different for brash ice above and below water. Therefore, it must be measured in both conditions. Angle of repose influences the height of friction in the vessel side.

Generally, Mohr-Coulomb-method assumes shear strength of coarse-grained soils to be function of normal load and internal friction angle. According to the model, shear strength of fine-grained soil is not affected by normal load, but only by cohesion. For intermediate soil materials, shear strength is supposed to be the sum of cohesion and normal load multiplied with tangent of internal friction angle (Helenelund, 1967).

Shear strength of soil along a failure plain could be described by equation [1]:

$$\tau_f = c + \sigma \cdot \tan\varphi \qquad [1]$$

where τ_f is absolute value of shear strength, σ is effective normal stress, φ is the effective angle of friction of the soil and c is a constant, which is often called effective cohesion, independent of the normal stress (Aysen, 2002). In nature, brash ice is a granular material. In model scale tests, the brash ice becomes easily a non-granular (fine-grained) material if Froude scaling is applied, and the model ice has therefore a low strength. As this difference has a principal impact on the physics behind the studied process, there is a need to evaluate the material type and categorize different model ice materials in granular and fine-grained materials. Consequently, the shear stress is interesting for two reasons: firstly, because it affects the vessel resistance in brash ice, and secondly because it is relevant when evaluating the model ice physical behavior.

Compressibility of granular soils is caused by variation of their porosity under the action of external forces due to repacking of particles (Tsytovich, 1983). Compressibility can be described as relationship between force and displacement, or further as relationship between stress and strain.

MEASURING PROCEDURES, ANALYSIS PRINCIPLES AND FUNCTIONALITY

Parental ice properties

Parental ice mechanical properties were measured according to ITTC guidelines (ITTC 2014). The FGX-ice flexural strength was measured using in-situ cantilever beam method and FGX-ice crushing strength in-situ with cylindrical indenter. Fresh water ice cube strength characteristics were measured using full-scale methods. Ice density was measured by defining the weight needed to submerge a freely floating ice sample. Friction coefficient between model and ice was defined by pulling ice piece on a wet surface of model with a force transducer and varying the normal load.

Channel Brash Ice Thickness

Channel thickness was measured manually using a measuring stick. About 100 measurements were taken from each different brash ice condition.

The measurement accuracy is limited due to the human factor, because the measurement is taken manually, basically using a ruler. The accuracy is practically no better than 5 mm. However, because the FSICR allow using the thickness correction method, the measured thickness has a significant effect on the channel test results. Ideally, the channel would correspond to the target thickness and would be even in both longitudinal and horizontal directions. As this condition can rarely be completely achieved, the included amount of thickness measurements in analysis can affect the final channel test results. Generally, due to the vessel model mass, it could be a good practice to include thickness measurements from at least one model length in the channel resistance analysis.

So far, the manual measurement is considered as the best option. The interface between water and slush-like ice is hard to detect automatically with current technology, and therefore no automatic device is not utilized in the measurement presently. However, we believe it will soon be possible, and the measurement accuracy can be improved simultaneously with a less time-consuming measuring method.

Piece Size Distribution

Piece size distribution was defined by taking photographs and applying mathematical processing to the pictures. First, a known volume of brash ice was poured on a plate with an indicative grid. The plate was photographed (Figure 4A), and the picture was analyzed using Matlab. The program defined area the of each individual ice piece (Figure 4B) and drew a distribution chart from the observations (Figure 5).

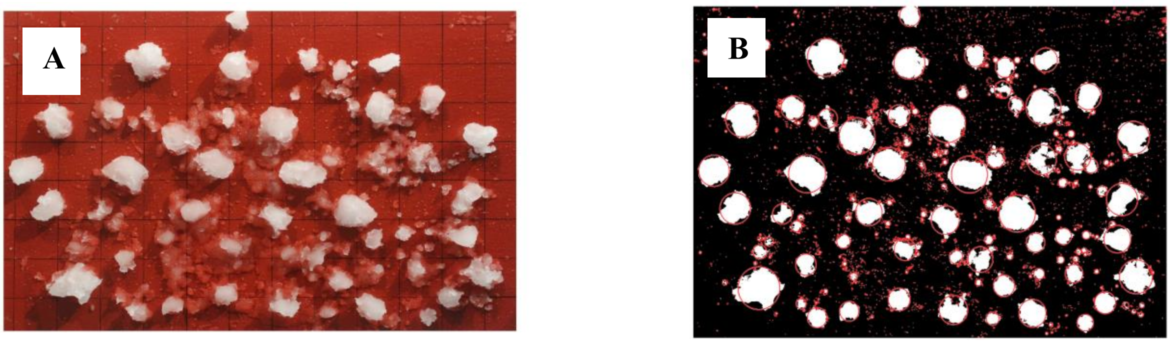

Figure 4 A: Photograph of brash ice. B: The brash ice after processing in Matlab.

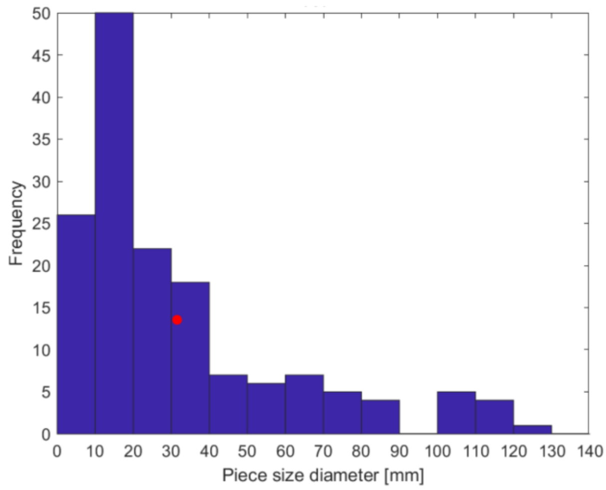

Figure 5. An example of the piece size distribution analysis: the center of gravity is marked in red.

The piece size distributions of different brash ice types were compared by determining the center of gravity from each distribution chart and comparing the mean piece size and standard deviation of the observed piece sizes.

The analysis displayed the obvious result that the piece size of ice cubes was the smallest as was also the deviation of piece size distribution. However, with soft FGX-ice the smallest, slush-like material is not presented well in the analysis, because the transparent mass is not visible in the picture and therefore not taken into account in Matlab analysis. Because the analysis is fast to conduct as it requires only taking a picture, the obtained information of piece size distribution might still be useful.

Porosity

Porosity of the brash ice was measured according to ITTC recommendations (ITTC, 2014) by submerging a known amount of brash ice and then measuring the ice mass buoyancy. An instrumented device, a box, was submerged through the brash ice channel completely and held steady until the buoyancy force was constant. The force was measured with the force transducer, which was mounted between the box and a motor, which drove the box in a vertical direction. In addition to the actual porosity test, the box was submerged in open water to measure the buoyancy of the box. The ice channel porosity was calculated according to Archimedes' principle.

The porosity was measured three times from each brash ice material, and the standard deviation of the measurements was defined based on the repeated tests. The measurement turned out to be quite accurate and repeatable. It was observed that the porosity of different brash ice materials in the test channels could vary, even though the brash ice thickness was the same. Therefore, the amount of brash ice and its mass is not equal between the different brash ice materials. This is expected to cause deviation in channel test results between different brash ice materials.

Angle of Repose

The angle of repose was also defined using cameras, both below and above water.

Below water, a container built from plexiglass was set just below the water level, and it was filled with brash ice so that one slope formed freely. Ice brash was pushed gently towards one end with a pushing plate, after which the pushing plate was pulled back. An underwater camera was used to take a picture of the freely-formed slope. The angle was defined later from the picture (Figure 6).

Above water, the angle of repose was defined by piling ice brash gently on a horizontal plane (Figure 7). Angle of repose was defined in a similar way as below water, by taking a picture and measuring the angle from the picture.

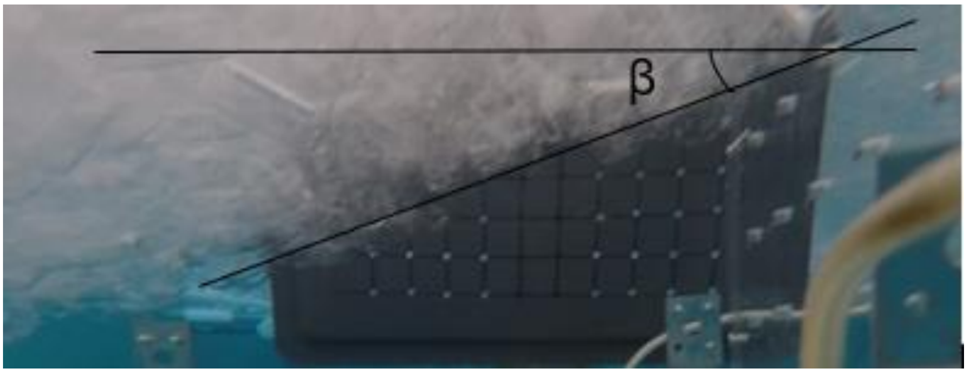

Figure 6. Angle of repose below water

Figure 7. Angle of repose above water

Angle of repose was relatively easy and repeatable measured, although accuracy depends on how carefully the brash ice pile was assembled. It could be seen in the analysis that softer ice forms steeper angles than more coarse-grained ice cubes, which was expected. The slush increases the frictional interaction between the ice pieces.

Brash Ice Angle of Internal Friction and Shear Strength

As discussed earlier, Mohr-Coulomb-method assumes shear strength of coarse-grained soils to be function of normal load and internal friction angle. The shear strength measurement was arranged by building a plexiglass box, which consists of two separate halves. The box was filled with brash ice and a weight was positioned on the top of upper box to cause normal load, and upper part was transferred with a force transducer, see principle picture in Figure 8 and picture of actual device in Figure 9 and Figure 10.

To study internal friction angle, the test was conducted with different normal loads. The shear strengths with different normal loads are plotted in a chart, and in the analysis, a line was fitted to the data points. An example of test results is presented in Figure 11; internal friction angle φ represents the slope of the line.

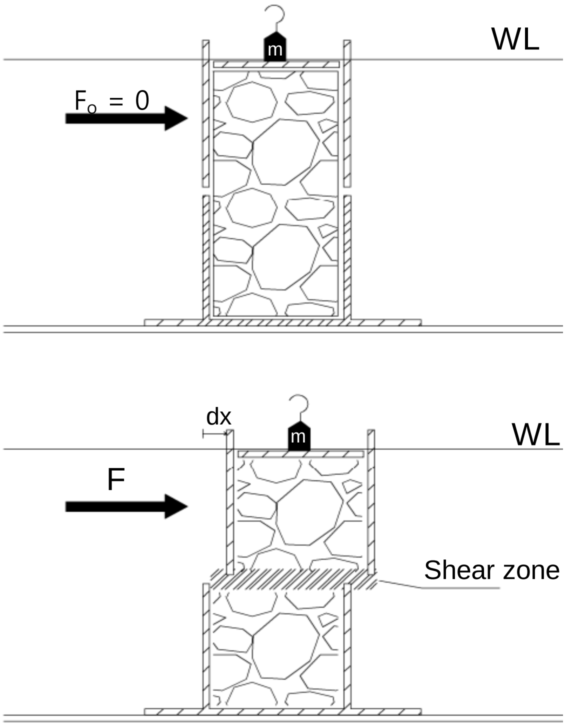

Figure 8. In shear strength tests, a weight is positioned on the top of upper box to cause normal load, and upper part is transferred with a force transducer.

Figure 9. Double-box device was developed for studying shear strength and internal friction angle of brash ice.

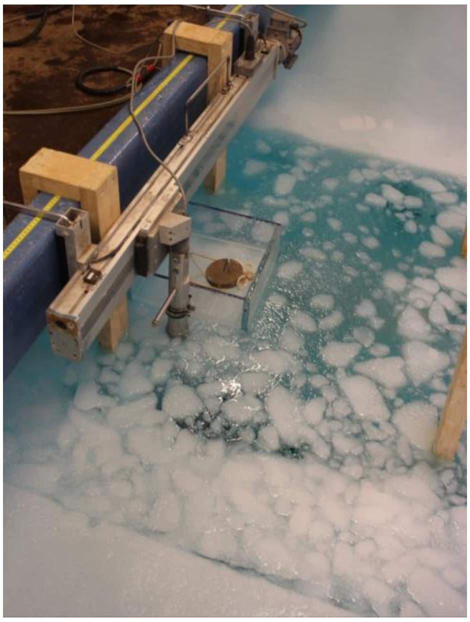

Figure 10. Double-box devise test.

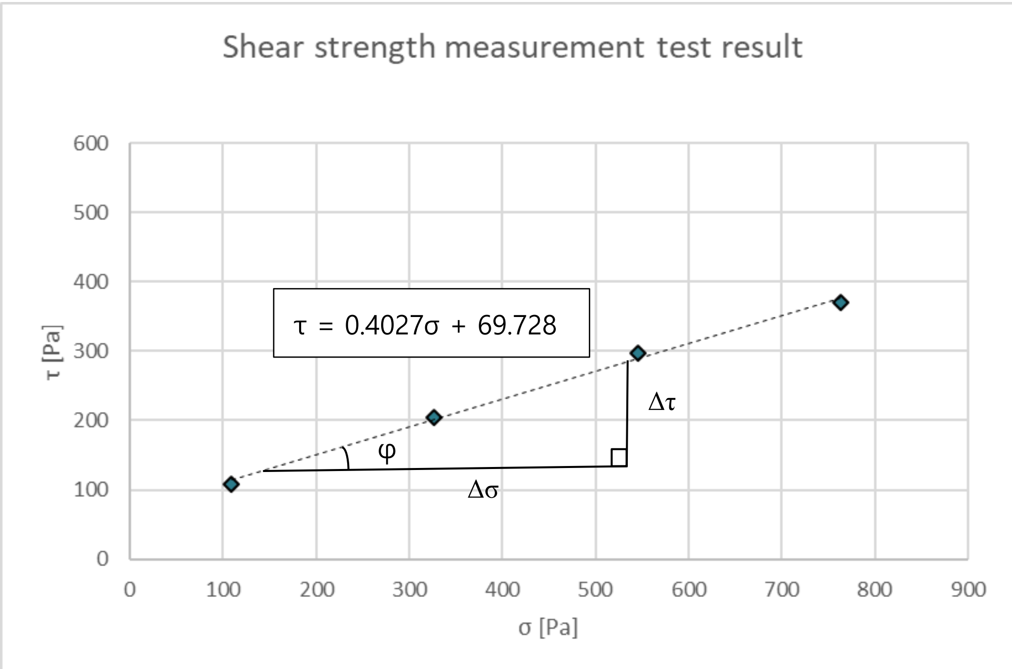

Figure 11. An example of a double-box device test results. According to the Mohr-Coulomb theory, the granular material's shear strength depends on normal load, but non-granular material's does not.

It was assumed that brash ice material consisting of ice cubes would represent granular soil. The interception of the result curve was not close to zero, so we decided to focus on slope of the τ, σ -curve. The measurement was easy to conduct with strong ice, but soft model ice became easily slush-like, non-granular material. According to the Mohr-Coulomb theory, the granular material shear strength depends on normal load, but non-granular material shear strength not. This could be observed when the brash ice was needed to be handled during the measurements. When repeating the test with different normal loads, the normal load did not anymore affect the measured shear strength. This result supports the visual observation that the soft model ice material characteristics change during the processing.

Compressibility

Change of brash ice volume as a function of external pressure was defined using a measuring device made of low-friction plexiglass. The results can be presented as force - displacement diagram, and further as stress - strain chart. The end plate of box is made of perforated plate which allows water escaping. A principle picture of the device is presented in Figure 12 and pictures of actual device is presented in Figure 13 and Figure 14. The front plate is a piston, which moves forward when a weight is added in a wire system. Weights are added one by one and transition of piston is observed. After adding a weight, 30 seconds is waited to let the process to complete before recording the result.

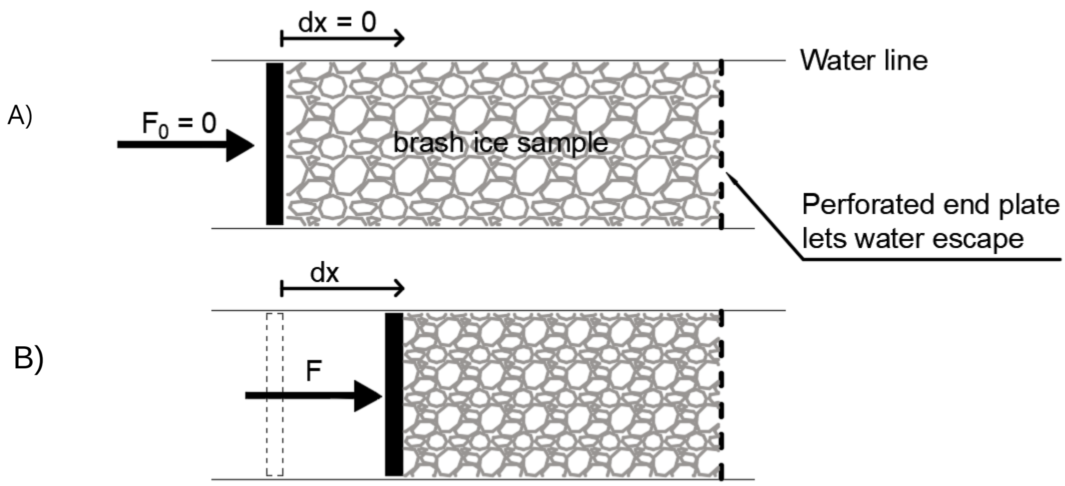

Figure 12. Sample volume decreases as piston moves forward, as it is loaded with weights.

A) Initial situation with no load

B) When an additional weight is applied, the piston moves forward and the volume change can be calculated.

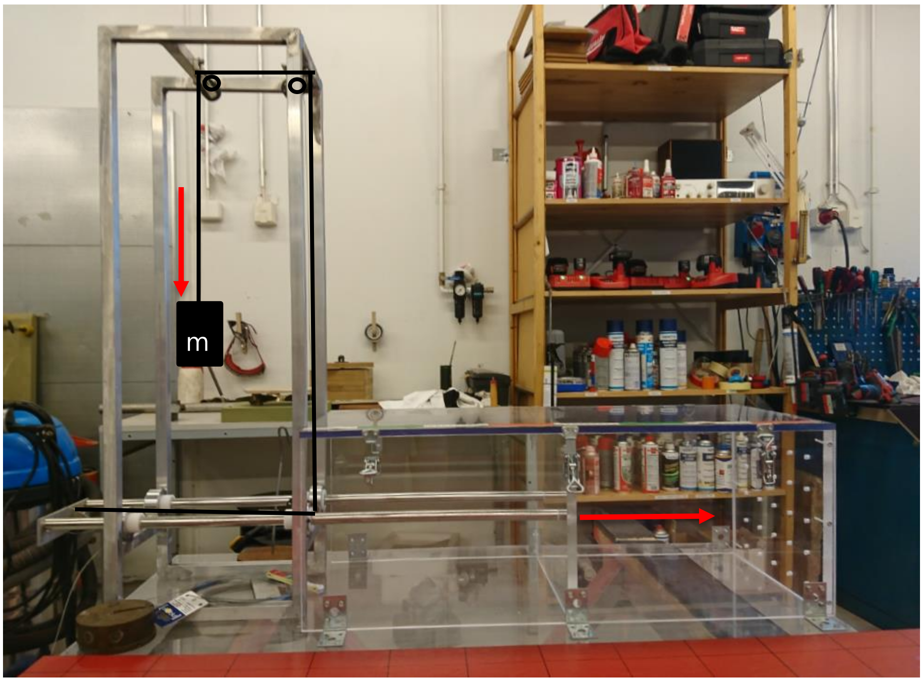

Figure 13. A wire system moves piston inwards the box when the system is loaded with a weight.

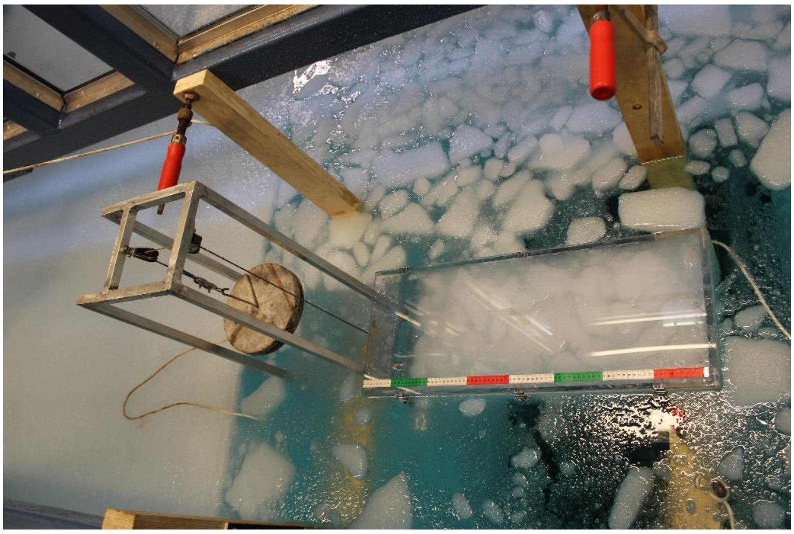

Figure 14. Compressibility measurement

The measurement was conducted with different weights. The small weights did not cause displacement to the piston, but when the load was added enough to overcome the frictional resistance of the system, the piston started moving. The piston stopped moving when the brash ice reached the fully compressed state. The data points were plotted in a chart, and a line was fitted to those points, where piston displacement was observed. The result of the analysis is the slope of that line, which represents the velocity of void escaping from the material, when loaded with a force. An example of the analysis is presented in Figure 15.

It was observed that the change in sample volume was faster with brash ice which consisted of strong ice cubes.

The device will be developed further, so that a force-displacement curve can be drawn fully, including the actual shape and the return path of the curve, when the applied load is removed.

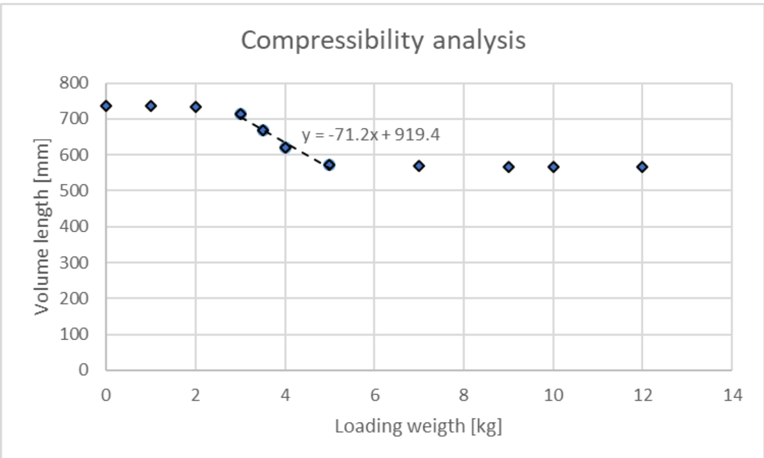

Figure 15. An example of compressibility test analysis. The slope (-71.2 mm/kg) represents the velocity of void escaping from the material, when loaded.

CONCLUSIONS

The objectives of developing new devices and practices for measuring brash ice properties were to enable comparison between different brash ice types. The comparison, in turn, is relevant when studying the brash ice channel behavior in vessel's ice model tests.

The devices functioned generally well enough so that the comparison between the materials could be done, and the results were reasonable. Some weaknesses and limitations of the devices were discovered. However, the most relevant question for channel testing is to understand the physics behind the behavior of the brash ice mass in the ice channel. Based on that, reliable models can be developed to estimate the resistance of ships in channel ice. Furthermore, reliable testing methods in model scale can be developed when the physics of brash ice behavior is well studied.

REFERENCES

Aysen, A. 2002. *Soil mechanics: Basic concepts and engineering applications.* The University of Southern Queensland, Australia. A.A. Balkema publishers, Tokyo. pp.111-152. ISBN 90 5809 358 1.

von Bock und Polach, R.U.F., 2015. *The mechanical behavior or model-scale ice; experiments, numerical modelling and scalability.* Doctoral dissertation: Aalto University, Helsinki, pp. 22-23. ISBN 978-952-60-6822-0.

Cammaert, A.B., 1988. *Ice interaction with offshore structures.* Van Nostrand Reinhold, New York. ISBN 0-442-21652-1.

Helenelund, K.V. 1967. *Pohjarakennus ja maarakennustekniikka I.* Teaching material, Teknillisen korkeakoulun ylioppilaskunta, Otaniemi, pp. 75-81.

ITTC, 2014. *Test methods for model ice properties. ITTC Quality system manual, recommended procedures and guidelines.* [Online] Available at: https://www.ittc.info/media/8061/75-02-04-02.pdf [Accessed 28 June 2018]

Keinonen, A., Nyman, T. 1978. An experimental model-scale study on the compressible, frictional and cohesive behaviour of broken ice mass. IAHR, Proceedings part 2, *IAHR Symposium on ice problems,* Luleo, Sweden. pp. 335-353.

Kujala, P., Riska, K. 2010. *Talvimerenkulku.* Teaching material, Helsinki University of Technology. Faculty of Engineering and Architecture. Department of Applied Mechanics. Series AM. pp. 23.

Malmberg, S.1983. *Om fartygs fastkilning i is.* Master's thesis: Helsinki University of Technology. pp. 22.

Mehta, A., Barker, G.C. 1994. The dynamics of sand. *Reports on Progress in Physics*, 57(4), pp. 385.

Sandkvist, J., 1978. Problems in Keeping Year-Round Navigation in the Luleå Harbour. IAHR, Proceedings part 1, *IAHR Symposium on ice problems,* Luleo, Sweden.

Timco, Q.W., 2010. A review of the engineering properties of sea ice. *Cold Regions Science and Technology*, 60(2), pp. 107-129.

Tsytovich, N.1983. *Soil mechanics*. Mir Publishers, Moscow. pp. 29-31.

Weeks, W.F. 2010. *On sea ice*. Fairbanks, Alaska, University of Alaska Press. pp. 558. ISBN 978-1-60223-079-8.

Wood, D.M.1990. *Soil behaviour and critical state soil mechanics*. Cambridge University Press, USA. pp. 5-7, 175-179. ISBN 0-521-33782-8.