POAC'13
Espoo, Finland

Proceedings of the 22nd International Conference on
Port and Ocean Engineering under Arctic Conditions
June 9-13, 2013
Espoo, Finland

RUBBLE ICE TRANSPORT ON ARCTIC OFFSHORE STRUCTURES (RITAS), PART III: ANALYSIS OF MODEL SCALE RUBBLE ICE STABILITY

Sergey Kulyakhtin [1], Knut V. Høyland [1], Oda S. Astrup [1, 2]
Karl-Ulrich Evers [3]

[1] Sustainable Arctic Marine and Coastal Technology (SAMCoT), Centre for Research-based Innovation (CRI), Norwegian University of Science and Technology, Trondheim, Norway

[2] Multiconsult, Tromsø, Norway,

[3] Hamburg Ship Model Basin (HSVA), Hamburg, Germany

ABSTRACT

A series of tests on model ice rubble were conducted at the Hamburg Ship Model Basin (HSVA) in Hamburg, Germany. This paper is the third out of four papers from the RITAS experiments. The three others are "*Rubble Ice transport on Arctic Offshore Structures (RITAS), Part I: Model scale investigation of level ice action mechanisms*", "*Part II: 2D model scale study of the level ice action*", and "*Part IV: Tactile sensor measurement of the level ice load on inclined plate*". Ice rubble properties were investigated both in water and air. For submerged tests a box with 0.93×0.97×1.1 m dimensions of internal volume was filled with rubble material and tilted afterwards until failure occurred. For dry tests a rectangular board 2×1.3 m with support ledges along the long dimensions was used for rubble ice pile construction and subsequent tilting. During both procedures initial geometry of rubble piles and angles of inclination leading to failure were measured. Considering ice rubble as a bulk material which obeys Coulomb's failure criterion and that the repose angle of the pile equals to the friction angle (initially zero cohesion is assumed) the cohesion component of shearing strength can be estimated.

INTRODUCTION

Ice ridges make human activity in Arctic and Subarctic seas rather challenging. For many cases study of this natural phenomenon is essential, since consideration of ice ridges gives design loads for structures. An ice ridge consists of a sail above the water line and keel below the water line. The keel consists of an upper refrozen part called the consolidated layer, and lower unconsolidated part, often called ice rubble. When action of the ice ridge on structures is evaluated the sail is often neglected as it is small compared to the rest of the ridge. The loads from the keel are often decomposed into a contribution from the consolidated layer and rubble (see e.g. ISO/FDIS/19906 (2010). The consolidated layer may be treated as a thick level ice, whereas the porous ice rubble is often treated as a granular/pressure sensitive material. Ice ridge keel can be more than 30 m thick, but the consolidated layer is only about 2 times the level ice thickness (often less than 4 -6 m). This means that even if the ice rubble is weaker than the consolidated layer it may contribute significantly to the total ice ridge action on structures and vessels. ISO/FDIS/19906 (2010) provides analytical methods to estimate the rubble action. There is a reason to believe that these methods oversimplify the physics and may not be reliable over a wide range of boundary conditions (Serré & Liferov 2010). This necessitates sophisticated numerical tools like Discrete Element Method (DEM) and Finite Element Method (FEM) which are commonly used. These methods require parameters describing material behavior under applied loads and in particularly FEM simulations are not possible without an appropriate constitutive relation for certain material. Rubble ice can be considered as a bulk material to certain extend. Strength of this kind of materials is usually considered by its resistance to shear and is often described by Coulomb's criterion. That is done by two material parameters, namely cohesion and friction angle. The present paper analyses scale-model experiments with ice rubble and discusses how material properties can be evaluated. The experimental part of the RITAS project (*Rubble Ice transport on Arctic Offshore Structures*) was conducted in April 2012 at the Hamburg Ship Model Basin (HSVA) in Hamburg. This paper is the third out of four papers from the RITAS experiments. The four others are "*Rubble Ice transport on Arctic Offshore Structures (RITAS), Part I: Model scale investigation of level ice action mechanisms" (Serré et al., 2013a), "Part II: 2D model scale study of the level ice action" (Serré et al., 2013b) and "Part IV: Tactile sensor measurement of the level ice load on inclined plate" (Lu et al. ,2013a)*

TEST PROCEDURES

Probably the oldest way of testing bulk properties of granular materials is by measuring the repose angle. It is defined as the angle between a horizontal line and sloping of the freely formed pile. In addition to the repose angle, the critical angle was estimated, as an angle between a horizontal line and slope of the pile at which failure occurs. In following by term "failure" we assume conditions under which existing geometry of the pile could not be retained and sliding of the rubble material occurs. In order to investigate rubble ice properties two types of pile test were performed. In one case piling was performed in air and another test was carried out under water. Underwater and in the air tests are named submerged stability test and dry stability test correspondingly. It should be noted that dry stability test (referred as pile up test) on model ice rubble was previously performed by Serré (2011), where he used the repose angle value obtained from this test as a friction angle of ice rubble for FE-simulations.

Submerged stability test

Underwater type of tests was performed using a box with approximately one cubic meter internal volume submerged into the water. The box consists of the steel beam frames with the back side, the front side and the lid covered by water resistant plywood and the side walls made from acrylic glass (Plexiglas®) plates. A full description of this testing rig, further called buoyancy box, can be found in (Serré et al., 2013b). The Plexiglas® material was used to enable video recording of the test from both sides of the box by underwater cameras. In addition a 10 x 10 cm grid was drawn on both side walls for estimation of rubble volume and repose angle from video recordings.

The test procedures includes following steps (Figure 1):

- filling buoyancy box with rubble material
- weighting filled buoyancy box
- tilting filled buoyancy box until rubble keel starts to deform

First step was performed by pushing buoyancy box into level ice, using the mobile measuring platform in the ice tank. Two cutters in front part of the box facilitated this process, in order to ensure ice breaking in bending mode a 45° inclined plane was fixed on the back side of buoyancy box at water level. After the box was filled the front wall and lid were put in place so only the bottom of the box remained open. In this configuration the box was submerged by the crane with the load cell attached to record submerged weight of the system. The third step was performed by fixing buoyancy box to the mobile measuring platform with two pins in back side beams in such a way that it can be rotated around these pins but constrained in all others directions. Afterwards it was tilted by the crane with a speed of 7 mm/s, during this process video recording from one of the cameras could be seen in real time, and as blocks movement in the keel was observed the tilting was terminated and the horizontal inclination of the box was measured.

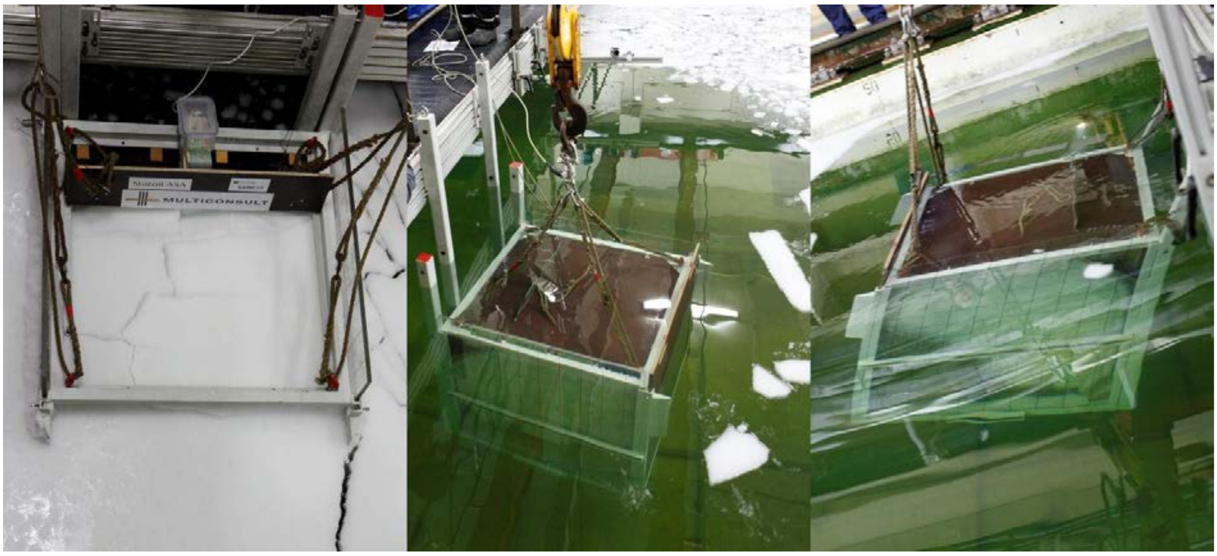

Figure 1 Filling, weighting and tilting of buoyancy box

The second step was required for determination of rubble ice porosity, detailed description and results can be seen in (Serré et al., 2013b). The current paper is mainly devoted to the determination of ice rubble repose and critical angles. The critical angle was calculated as a sum between initial repose angle and inclination of the buoyancy box lid relative to the horizon at which failure occurs. To evaluate horizontal inclination of the box, distances from higher point on the box lid to water level h_1 and from lower point on box lid to water level h_2 were measured, see Figure 2. From these distances, the angle between box lid and horizon can be easily estimated.

Dry stability test (pile up test)

Testing of rubble ice in the air was conducted by construction of elongated ice rubble pile on a rectangular board (2×1.3m) with support ledges along the long side of the board. One of support ledges was adjustable for constraining piles to have a certain width. Pile forming was conducted using a rectangular box with perforated bottom, so floating ice blocks could be scooped out from the tank and dumped on the board with as little disturbance as possible. After the pile was formed the height was measured in three points along the pile and an averaged value was reported. The repose angle was calculated from measured distances between several points on the pile slope and the reference vertical pole. One side of the board was lifted by a crane subsequently with a speed of 7 mm/s until failure occurred. At this stage values of the board inclination and angle of failure plane were calculated. The failure angle is the angle between a horizontal line and the slope of the pile after failure (Figure 3). This quantity characterizes the amount of material which slid of the pile. The critical angle was calculated as a sum of the repose angle and inclination of the board at failure. For testing series 3000 and 5000 ice rubble densities were estimated by weighting a bucket of known volume filled with rubble.

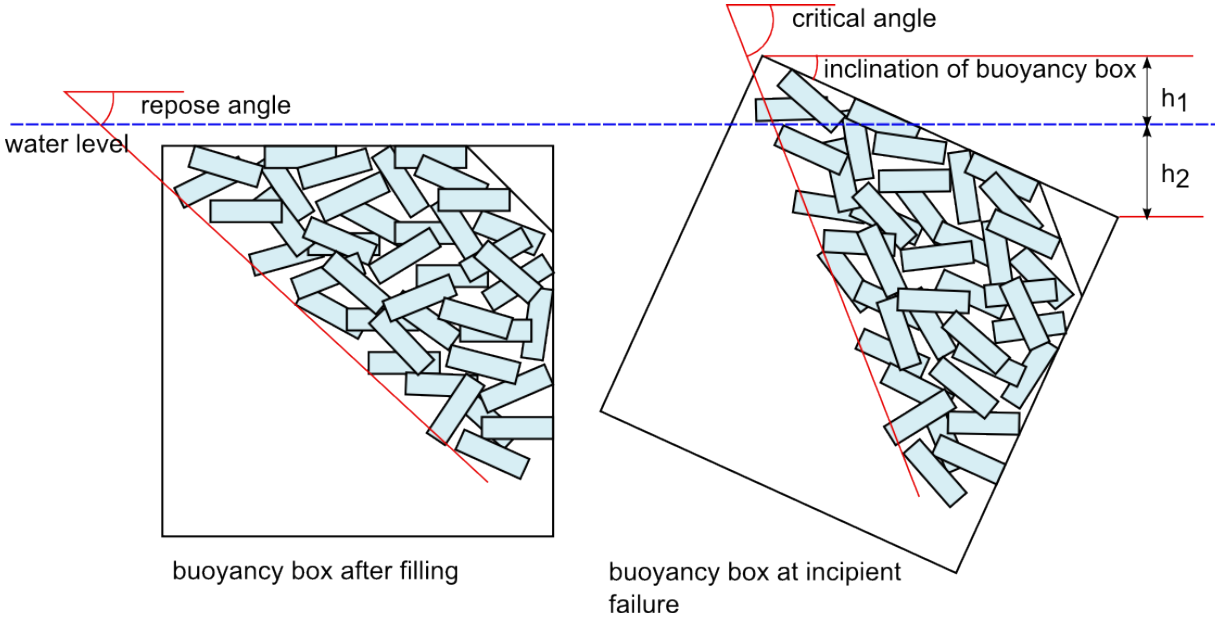

Figure 2 Definition of repose angle and critical angle for the submerged tests

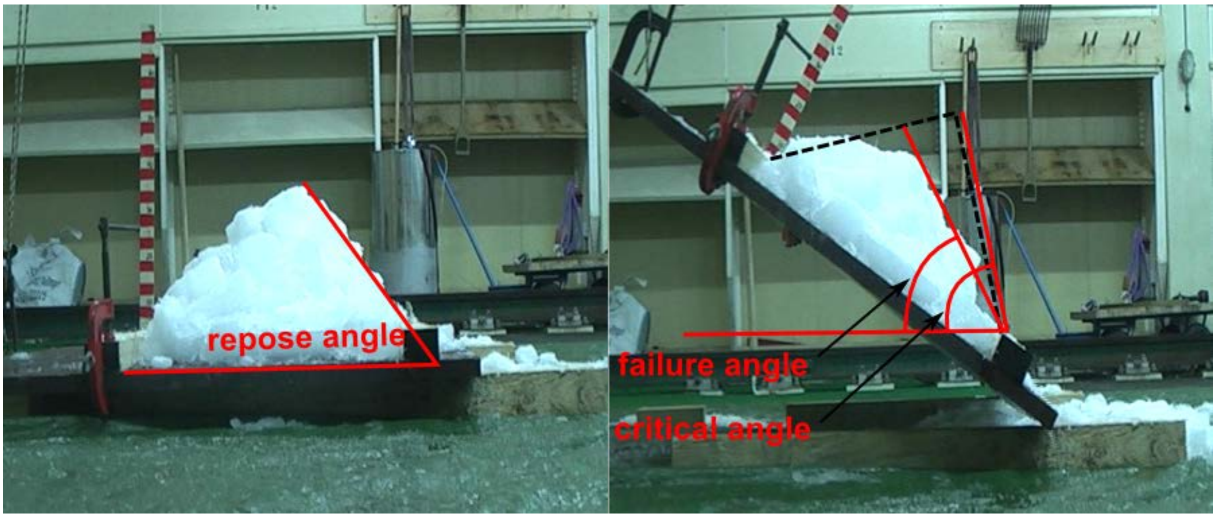

Figure 3 Measured quantities in the dry stability test

RESULTS

Five submerged stability tests and eight dry stability tests were conducted in HSVA during five testing series. For each series properties of level ice used to produce rubble were varied see Table 1, extensive data on ice properties from different test series can be found in (Serré et al., 2013a). It should be noted that results from dry stability test were previously reported by Astrup (2012) as a part of her Master Thesis.

Table 1 Level ice properties (model scale values)

Test series	1000	2000	3000	4000	5000
Ice thickness [m]	0.043	0.043	0.047	0.061	0.041
Ice density [kg/m^3]	906	902	806	928	809

Submerged stability test

For the submerged test two characteristics were determined, i.e. the angle of the repose and the critical angle (Table 2). The values given in Table 2 are model scale values. Repose angles were obtained manually from video recordings by Plot Digitizer program (released under GNU General Public License) using a side wall grid as a reference scale. Repose angles were estimated after the front wall was put in place, except for test 4230 where that process considerably changed the keel geometry (so the repose angle was estimated before installation of the front wall). And a critical angle for each test run was calculated by adding the angle of the box inclination at which failure occurred to the corresponding repose angle. For the test 3230 two critical angles were reported. After the inclination of the box reached 25° a few ice blocks slide from the keel bottom, after measurement have been taken tilting testing was proceeded and at inclination angle equal to 39° substantial part of the keel broke down (Figure 4). Worth noting that only during this test significant deformation of keel geometry was observed, in other tests failures occurred close to the keel surface, manifested in sliding up separate ice blocks. The occurrence of these processes was governed by keel geometry and the presence of relatively large ice pieces along the keel surface.

Table 2 Results of submerged stability test (model scale values)

Test	Repose angle	Critical angle	Box inclination	Keel depth [m]
1230	29°	62°	33°	0.38
2230	43°	81°	38°	0.51
3230	36°	61° (75°)	25° (39°)	0.5
4230	44°	80°	36°	0.45
5230	40°	66°	26°	0.38

Figure 4 Submerged stability test 3230 at different inclination angles: 0°; 25°; 39°

Dry stability test

All dry stability tests were conducted with the pile base width equal to 0.6m except test 5060 where base width was 0.4m. Piles were tilted right after formation except for tests 2061 and 3061 when the rubble piles were left undisturbed for about 30 minutes to investigate influence of consolidation time. The deformations did not occur uniformly along the pile and several failures could be observed during single test at different inclination angles. Moreover the number of failures and failure character were different from test to test. To describe results in more or less systematic way following criteria are specified: when one or several local slides occur along the slope of the pile this appearance designated as a first slide; when failure almost instantaneously occurs along the whole pile this is reported as main slide; finally when the rubble pile slides of the board or only a small amount of rubble ice is left, this is called final slide. If several slides occur during one test (first, main and final) when the subsequent critical angle is calculated as a sum of the change in board inclination since last measure and angle of previous failure surface. Results of the dry stability tests are summarized in Table 3. Measured densities of ice rubble for testing series 3000 and 5000 were 560kg/m^3 and 558kg/m^3 correspondingly.

Table 3 Results of dry stability test (model scale values)

Test	Repose angle	First slide		Main slide		Final slide	Height [m]	Rubble density [kg/m^3]
		Critical angle	Failure angle	Critical angle	Failure angle	Critical angle		
1060	46°	-	-	67°	53°	65°	0.31	-
2060	42°	52°	51°	68°	51°	57°	0.27	-
2061	47°	-	-	80°	61°	74°	0.33	560
3060	46°	76°	49°	72°	65°	75°	0.31	560
3061	42°	73°	55°	-	-	67°	0.27	-
4060	41°	64°	50°	63°	54°	62°	0.26	-
5060	42°	71°	29°	-	-	-	0.18	558
5061	36°	68°	42°	75°	53°	67°	0.22	558

DISCUSSION

Values of repose angle for submerged stability test vary from 29° to 44° and seem to be slightly smaller than these for the dry stability test measured in range from 36° to 47°, but it is hard to draw a conclusion due to the large variation in these numbers. A possible explanation of the considerable variance is that an ice thickness and density varied from one testing series to another (see Table 1) which has an effect on ice rubble properties as a material. For the same reason average values of repose and critical angle are not presented because it is logical to expect them be different for rubble materials made from ice sheets of different thicknesses and densities.

The idea of both submerged and dry tests is to define critical configuration under which the pile of rubble ice will not be able to keep it current geometry and fail. Forces causing rubble to fail are gravity and buoyancy in submerged test and only gravity in dry test. To be able to compare these two different test types in similar fashion let us introduce submerged and dry unit weights of ice rubble. Ice rubble is considered here as an assembly of ice blocks, partly refrozen to each other, with voids filled either with water in submerged test or with air in a dry test. The macro-porosity of ice rubble is equal to the ratio of voids volume V_{void} to total volume V_{total}

$$n = \frac{V_{void}}{V_{total}} \tag{1}$$

Using above definition we can define density of rubble ice as weighted sum of densities of the ice ρ_{ice} and void matter ρ_{void} (water or air)

$$\rho_r = (1-n)\rho_{ice} + n\rho_{void} \tag{2}$$

Rigorously speaking this quantity is not constant due to variation of porosity in an ice rubble pile which depends on the degree of confinement. It is reasonable to expect lower porosity in the upper part of rubble keel in the submerged case because of buoyancy of underlying material and lower porosity on the bottom of the pile in the dry test due to self-weight.

Multiplying equation (2) by acceleration due to gravity g one can get the unit weight of rubble ice (the weight per unit volume)

$$\gamma_r = (1-n)\gamma_{ice} + n\gamma_{void} \tag{3}$$

where γ_{ice} and γ_{void} are ice and void matter unit weights correspondingly. For dry stability tests formula (3) gives

$$\gamma_r^{dry} = (1-n)\gamma_{ice} \tag{4}$$

The term with unit weight of voids matter is omitted due to the small value of air density.
For the submerged stability test unit weight of water γ_w should be substituted for γ_{void}. In order to include the buoyancy effect the water unit weight should be subtracted to give submerged unit weight of ice rubble

$$\gamma_r^{sub} = (1-n)(\gamma_{ice} - \gamma_w) \tag{5}$$

This expression gives negative values which is just a manifestation of the fact that dry unit weight and submerged unit weight act in opposite directions.
Tests were analyzed considering ice rubble as a bulk material and assuming that it obeys Coulomb's failure, so that friction angle and cohesion are to be determined. For cohesionless materials the repose angle should correspond to the friction angle but if even a small amount of cohesion presents the interpreting of this angle is somewhat ambiguous. Some experimental evidence from in situ tests, see e.g. Timco et al. (2000), such as "pull up" tests show ice rubble ability to sustain tensile stresses. This tensile strength may be attributed to freeze bonds development, which mathematically can be seen as some sort of cohesion. Presume that only freeze bounds compose cohesion and other resistance comes from the internal friction then it can be further assumed that without time to consolidate rubble ice can be treated as purely frictional material. Based on foregoing discussion the calculated angles of repose can be used as a crude approximation for angles of internal friction. This assumption seems reasonable for submerged tests, because the procedure of buoyancy box filling seems to prevent adfreezing of ice blocks, the box was pushed into the level ice and it is seen from video records that broken ice pieces were in constant motion until the box was stopped. Surely this assumption is questionable for a dry stability test, but due to missing data aforementioned presumption is also supposed. After rubble piles were prepared some time passed before the actual testing started and it is assumed that this time is sufficient to create some freeze bounds between ice blocks (20-30 minutes for submerged tests and 5-20 minutes for dry tests). Hence, in following analysis of stability tests the ice rubble strength is considered to have both cohesional and frictional components.
For further detailed investigation submerged test 3230 and dry tests 3060 and 5061 were chosen. Test 3230 was chosen since only during that test failure occurred deep below the keel surface which is a manifestation of non-zero cohesion. For dry stability tests ice rubble densities required for analysis were measured for series 3000 and 5000 but main slides were observed only in tests 3061 and 5061 that is why they were selected for further investigation. Plane strain conditions are assumed for these tests in the vertical cross-section of the piles.
For dry stability tests the forces acting of the failure plain are (a) weight of rubble material above the plane, (b) friction resistance and (c) cohesion.

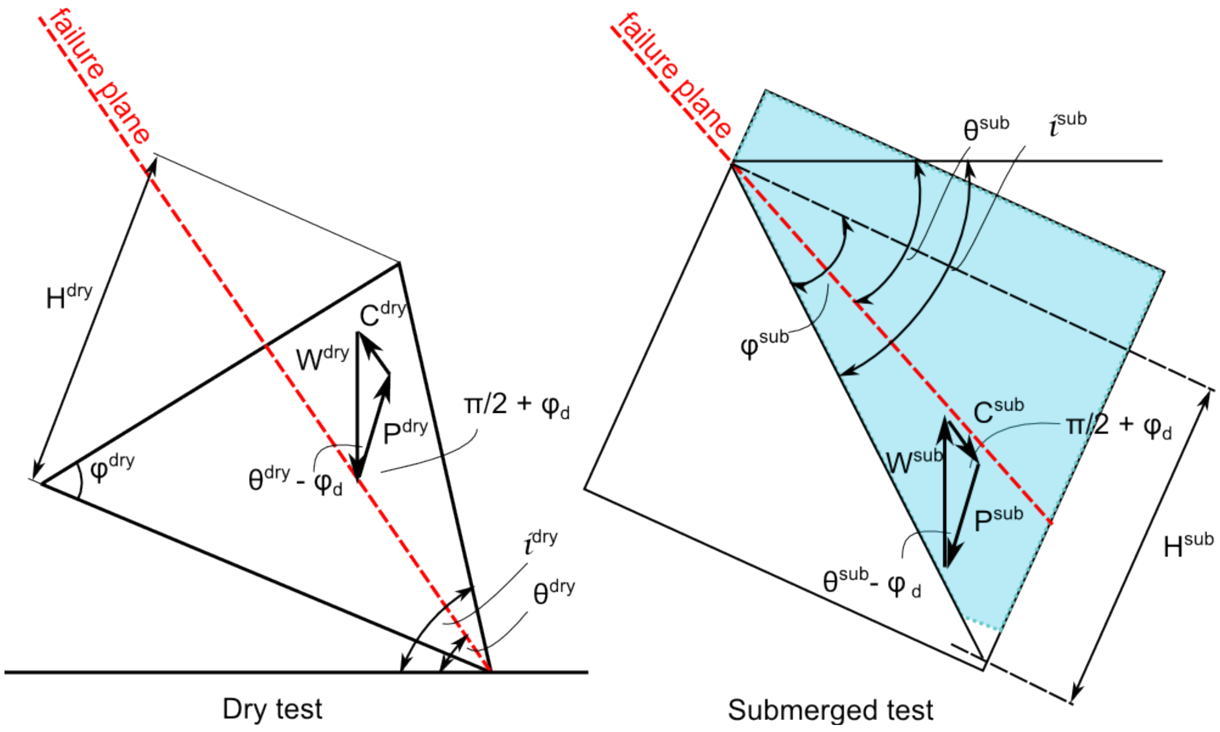

Figure 5 Notations definition in dry and submerged rubble stability tests analyse

For dry stability test from force triangle (Figure 5) relation between rubble weight W^{dry} and total cohesion C^{dry} is given by

$$\frac{C^{dry}}{W^{dry}} = \frac{\sin(\theta^{dry} - \phi_d)}{\cos(\phi_d)} \tag{6}$$

where ϕ_d friction angle and θ^{dry} failure angle. From the geometry of the pile ice rubble weight and total cohesion are given by

$$W^{dry} = \frac{1}{2}\frac{\sin(i^{dry} - \theta^{dry})\sin 2\phi^{dry}}{\sin(2\phi^{dry} - i^{dry} + \theta^{dry})\sin^2\phi^{dry}}(H^{dry})^2\gamma_r^{dry} \tag{7}$$

$$C = c_d^{dry}\frac{\sin 2\phi^{dry}}{\sin(2\phi^{dry} - i^{dry} + \theta^{dry})\sin\phi^{dry}}H^{dry} \tag{8}$$

where c_d^{dry} cohesion per unit length. Substituting above equations into (6) gives expression for cohesion

$$c_d^{dry} = \frac{1}{2}\frac{\sin(i^{dry} - \theta^{dry})\sin(\theta^{dry} - \phi_d)}{\cos\phi_d \sin\phi^{dry}}\gamma_r^{dry}H^{dry} \tag{9}$$

Assuming that the repose angle is equal to friction angle $\phi = \phi_d$ the above equation for measured value for ice rubble densities and data from Table 3 (for main slides) gives values of cohesion equal to 68 Pa and 139 Pa for tests 3060 and 5061 correspondingly.

In a similar fashion submerged the stability test can be analyzed. Again, force triangular for submerged test (Figure 5) gives

$$\frac{C^{sub}}{W^{sub}} = \frac{\sin(\theta^{sub} - \phi_d)}{\cos(\phi_d)} \tag{10}$$

where W^{sub} is submerged rubble weight and θ^{sub} is the failure angle. From the geometry of the pile the total submerged rubble weight and cohesion are given by

$$W^{sub} = \frac{1}{2}\frac{\sin(i^{sub} - \theta^{sub})\cos\phi^{sub}}{\cos(i^{sub} + \phi^{sub} - \theta^{sub})\sin^2\phi^{sub}}(H^{sub})^2\gamma_r^{sub} \quad (11)$$

$$C^{sub} = c_d^{sub}\frac{1}{2}\frac{\cos\phi^{sub}}{\cos(i^{sub} + \phi^{sub} - \theta^{sub})\sin\phi^{sub}}H^{sub} \quad (12)$$

where γ_r^{sub} is given by formula (5). The failure angle θ^{sub} in submerged case is unknown, since ice blocks stay inside the box after failure takes place that makes the determination of failure angle from video recordings impossible. It is assumed analogous to Cullman's method used for slope stability problem, see e. g. Taylor (1948), that the failure angle corresponds to maximum developed cohesion for a given friction angle. By setting first derivative of c_d^{sub} with respect to θ^{sub} equals to zero, we find the expression for the failure angle

$$\theta^{sub} = \frac{1}{2}(i^{sub} + \phi_d) \quad (13)$$

Substituting this and formulas (11) and (12) into (10) gives

$$c_r^{sub} = \frac{1 - \cos(i^{sub} - \phi_d)}{4\cos\phi_d \sin\phi^{sub}}\gamma_r^{sub}H^{sub} \quad (14)$$

Assuming that the repose angle is equal to the friction angle $\phi^{sub} = \phi_d$ and using an estimated rubble porosity value of 0.21 (Serré et al., 2013b) and data from Table 2 formula (14) gives a value of submerged cohesion equal to 91 Pa.

Obtained values of cohesion for submerged and dry tests for the testing series 3000 do not show significant differences, but the cohesion value obtained from dry test 5061 is considerably higher. As previously mentioned this could be explained by the fact that ice sheets used to produce rubble piles had different properties for different test series. In addition inaccuracies in measuring initial and deformed ice pile geometries could be the source of the discrepancy in cohesion values. Also it should be mentioned that comparison of ice rubble parameters is rather difficult, because not only the properties of the ice sheet from which rubble is formed are important, but also the time plays significant role. It is reported in the study of Repetto-Llamazares et al. (2011) by investigating the development of adfreeze strength between ice blocks made from model ice that for ice with initial temperature equals to -14°C freeze-bonding was present after 1 minute of consolidation, however for ice blocks with initial temperature -3°C freeze-bonding was not observed before 1 hour of consolidation time. It should also be taken into account that ice rubble properties are not constant through the keel. Timco et al (2000) suggested based on in situ observations that ice rubble shear strength increases from almost zero at keel bottom to its maximum value below the refrozen layer.

Obtained cohesion values can be compared with work of Serré & Liferov (2010) where both numerical model of rubble with constant cohesion and linearly varied cohesion through the keel are used to simulate a model interaction test of the wide ridge with a conical structure. For a model with constant parameters they used a cohesion value for the Drucker-Prager criterion equal to 122Pa which corresponds to 58Pa and 81Pa cohesion for the Mohr-Coulomb model matched along compressive and tensile meridians correspondingly. These values are close to what was obtained from submerged and dry stability tests.

CONCLUSIONS

A new testing procedure for investigating ice rubble properties in a submerged state was proposed. In the submerged tests ice was accumulated by running a buoyancy box through a level ice sheet until a stable geometry was reached. In the dry tests ice rubble was taken out of the basin and piled-up on a board until a stable pile was formed. The depth of the submerged pile ranged from 0.38 m to 0.51 m (model scale) and the height of the dry pile ranged from 0.18 m to 0.33 m (model scale). In both cases the box/board was tilted until failure occurred, and the relevant angles were measured. The pile angle prior to tilting is called *the angle of repose*, and the pile angle at failure we call *the critical angle*. Values of repose angles in the ranges from 29° to 44° (submerged tests) and from 36° to 47° (dry tests) and critical angels from 61° to 81° (submerged tests) and from 52° to 80° (dry tests) were obtained. Assuming Coulomb's failure criterion and that the repose angle corresponds to friction angle (initially zero cohesion) the peak cohesion (at failure) can be derived analytically. One submerged and two dry tests were analyzed and the cohesions became 91 Pa for the submerged test and 68 Pa, 139 Pa for the dry tests.

ACKNOWLEDGEMENT

The work described in this paper was supported by the the European Community's 7th framework Programme through the grant to the budget of the Integrated Infrastructure Initiative HYDRALAB-IV, Contract no. 261520. We would also like to thank Wenjun Lu, Basile Bonnemaire, Henning Helgøy and HSVA (especially the tank crew) for the hospitality, technical and scientific support and the professional execution of the test programme in the Research Infrastructure ARCTECLAB at HSVA. We also wish to acknowledge the support from the Research Council of Norway through the PetroRisk project, the Centre for Research-based Innovation SAMCoT and the support from all SAMCoT partners.

REFERENCE

Astrup, O. (2012) Experimental Investigations of Ice Rubble: Shear Box and Pile Testing. Master Thesis, Norwegian University of Science and Technology, Trondheim.

ISO/FDIS/19906 (2010) Petroleum and natural gas industries - Arctic offshore structures, ISO TC 67/SC 7. Final Draft, International Standard, International Standardization organization, Geneva, Switzerland, 434 p.

Lu, W., Serré, N., Høyland, K.V. and Evers, K.-U., 2013. Rubble Ice transport on Arctic Offshore Structures (RITAS), part IV: Tactile sensor measurement of the level ice load on inclined plate, Proceedings of the 22nd International Conference Port adn Ocean Engineering Underr Arctic Conditions, Espoo, Finland.

Repetto-Llamazares, A. H. V., Høyland, K. V., & Evers, K.-U. (2011). Experimental studies on shear failure of freeze-bonds in saline ice: Part I. Set-up, failure mode and freeze-bond strength. Cold Regions Science and Technology, 65(3), 286–297.

Serré, N. and Liferov, P. (2010) Loads from ice ridge keels - experimental vs. numerical vs. analytical, Proc. of the 20 Int. Symp. on Ice (IAHR), Lahti, Finland, paper #92.

Serré, N. (2011). Mechanical properties of model ice ridge keels. Cold Regions Science and Technology, 67(3), 89–106.

Serré, N., Høyland, K., Lundamo, T., Bonnemaire, B., Evers, K-U. and Gürtner, A. Rubble Ice transport on Arctic Offshore Structures (RITAS), part I: Scale-model investigations of level ice action mechanisms. Proceedings of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions, Espoo, Finland, 2013.

Serré, N., Lu, W., Høyland, K., Bonnemaire. B., Borge, J. and Evers, K-U. Rubble Ice Transport on Arctic Offshore Structures (RITAS), part II: 2D model scale study of the level ice action. Proceedings of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions, Espoo, Finland, 2013.

Taylor, D. W. (1948). Fundamentals of Soil Mechanics (p. 700). New York: J. Wiley.

Timco, G., Croasdale, K., & Wright, B. (2000). An overview of first-year sea ice ridges. Technical Report HYD-TR-047, PERD/CHC Report 5-112, August.