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Transmission of Loads Through Grounded Ice Rubble

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Résumé

Dans cette étude de synthèse, l'auteur étudie le rôle que jouent les champs de fragments ancrés au sol dans le transfert des charges de glace flottante sur les structures se trouvant en mer. Les études sur le terrain et en laboratoire fournissent de l'information concernant la géométrie et la composition des champs de fragments, ainsi que certaines mesures des contraintes. L'auteur examine les méthodes employées pour estimer la résistance à l'ancrage au sol, ainsi que d'autres analyses portant sur la stabilité des champs de fragments.

TRANSMISSION OF LOADS THROUGH GROUNDED ICE RUBBLE

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ABSTRACT: This review examines the role of grounded rubble fields in transferring floating ice loads to offshore structures. Field and laboratory studies provide information concerning rubble fields geometry, composition, and some stress measurements. Methods of estimating grounding resistance and other analyses that deal with stability of rubble fields are discussed.

1. INTRODUCTION

The processes of ice rubble formation, grounding, freezing, and response to applied forces remain poorly understood. Early observations of rubble fields in the Beaufort Sea identified two possible scenarios:

(a) Grounded rubble can transfer part of floating ice forces to the berm, and thus reduce loads on the structure.

(b) Because a rubble field's width is larger than that of the structure, floating ice forces would act against a larger area and thus exert a larger total force on the rubble field. Therefore, a frozen rubble field would increase the forces on the structure that it surrounds.

In certain offshore areas, the assessment of a structure's stability requires knowledge of the likelihood of a rubble field to form and its geometry, the ability of grounded rubble to transfer horizontal forces through its keel to the berm, spatial stress distributions in the rubble, and integrity of the field under the action of floating ice. Available literature, however, provides only sparse information concerning these problems. A survey of field observations of grounded rubble geometry, morphology and stress measurements; a discussion of relevant laboratory studies, rubble mechanical properties, and available analytical methods will be covered in this review.

2. FIELD STUDIES

2.1 Geometry and morphology:

Kry (1977) gave a description of the rubble field that formed on the shallow sloped beach around the artificial island at the Netserk location during the winter of 1975-76. The observations were concerned with the geometry of the rubble field, sail profiles and rubble settlements over the season. The measurements of Frederking and Wright (1982) concentrated on a radial line in the rubble field at the Issungnak location. They obtained profiles of sail and keel dimensions, temperature, porosity, salinity, and snow depth. Strength of small ice samples were also measured.

The preceding two references present the most complete published description of rubble fields to date. McGonigal (1983) also reported on a detailed program of rubble field investigations at Issungnak. Other studies, although primarily focussed on stability of islands, give some information regarding rubble field geometry (for example, Strilchuk 1977, and Semeniuk 1977). Geometry data are available, as well, from the rubble fields at Amerk (Croasdale, 1985) and Kaubvik (Frederking, 1988). These are caisson structures sitting on submarine berms 10 m or more beneath water level. The typical features common to most rubble fields are summarized below.

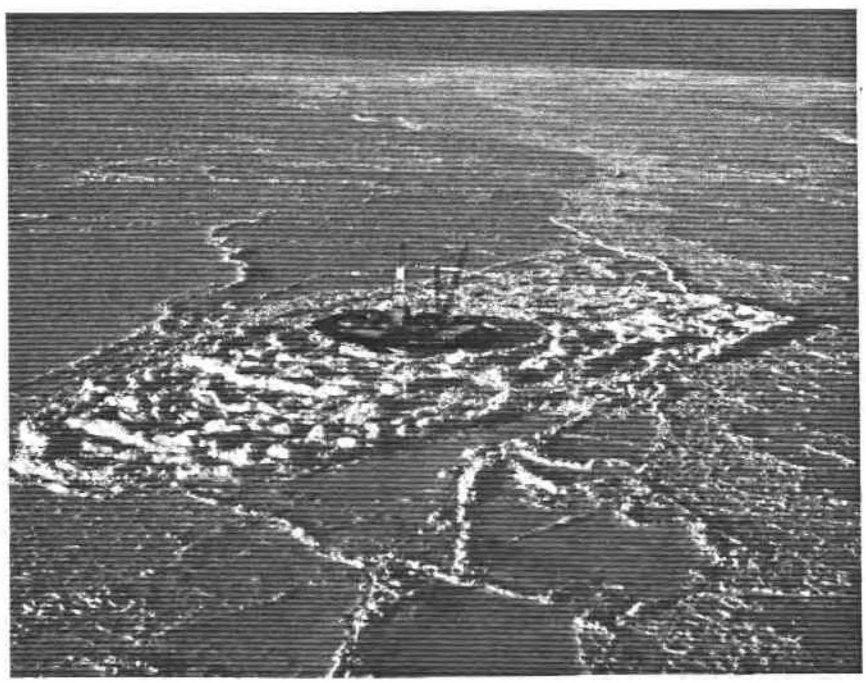

Figure 1: Rubble field at Kaubvik, 1987.

Rubble (around artificial islands) may become grounded over submarine berms in the landfast ice zone of the Beaufort Sea, where water depth is usually less than 20 m. A photograph of the rubble field at Kaubvik is shown in Figure 1. The extent of grounded rubble from the island depends on the bathymetry over the berm and ice cover movements. As an example, the boundary of the rubble field at Kaubvik is superimposed on the bathymetry contours in Figure 2. The rubble extends to the 18 m depth contour toward the east and west but ends at shallower depths towards the north and south apparently because ice movements were small from these directions.

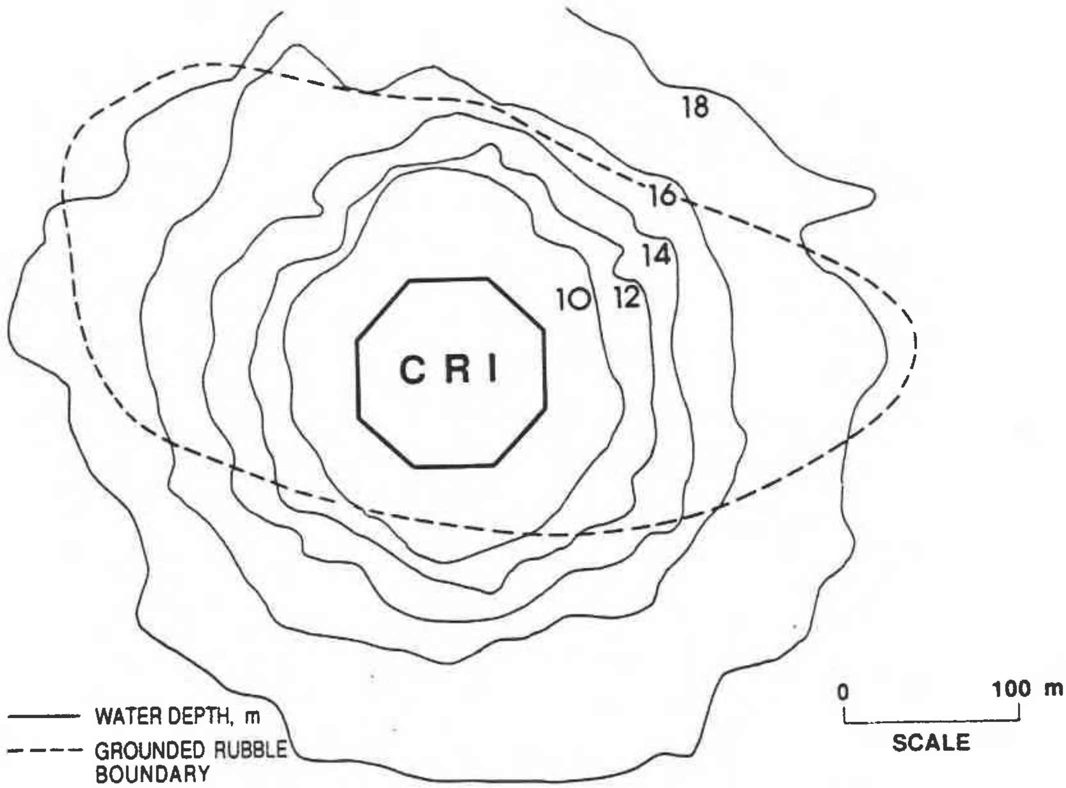

Figure 2: Boundary of the rubble field and water depth contours at Kaubvik, 1987.

A rubble field begins to form in the fall as a result of several separate pileup events. The field gradually grows to reach its maximum extent, usually by February. During the field's growth, parts of the pileups can apparently be dislodged and moved by floating ice. Consequently, steep sail slopes (sometimes near vertical) are often observed. Individual pileups join to form oval rings of "hills" and "valleys" around the island (see Figure 1). At the outer edge of the field, a tidal crack separates the grounded rubble from floating ice.

As an example of sail and keel geometry, the radial line profile at Issungnak (from Frederking and Wright, 1982) is shown in Figure 3. While this profile is typical of most rubble fields, sail heights can be higher, reaching 10 m where large ice movements occur.

Temperature distribution in the rubble usually causes water to freeze in the voids between ice blocks near water level. Thus, a so-called "consolidated layer" forms. Such a layer contains solid ice, without voids, and appears to have larger stiffness and strength than bulk rubble.

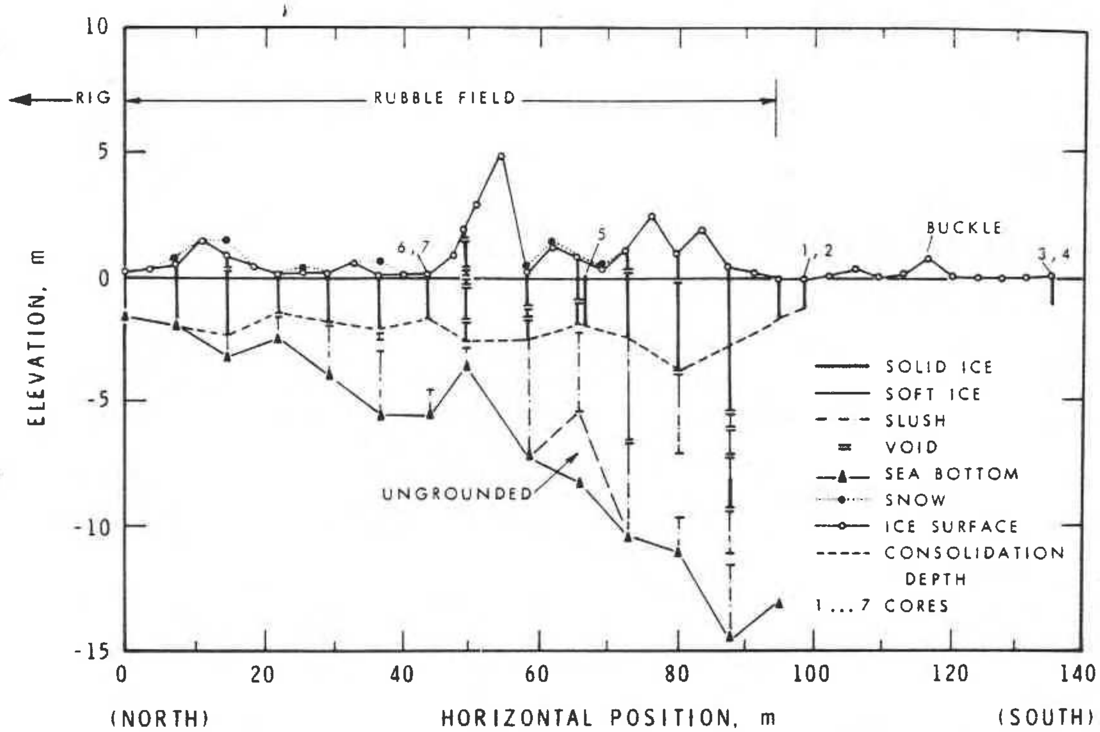

Figure 3: Longitudinal rubble profile at Issungnak, 1980 (from Frederking and Wright, 1982).

A vertical temperature and salinity profile, also from Issungnak, is shown in Figure 4. Estimates of consolidated (or frozen) layer thickness obtained by drilling boreholes usually agree with that of the relatively colder layer of rubble near water level.

The average consolidated layer thickness, by January or February, varies between 2.5 m and 3 m (Frederking and Wright, 1982; and Croasdale, 1985). Below such a layer, temperature is relatively warm (above -5° C) and ice offers weak resistance to drilling. The vertical temperature profile and consolidated layer thickness vary within a rubble field according to sail height, snow depth, and date of rubble pileup. Generally, temperatures near water level are high (and the consolidated layer is thin) under high sails and deep snow covers. Exceptions to this general trend may occur due to the complex three-dimensional geometry of snow and sail as well as wind action.

Rubble settlements over winter were measured at Netserk by Kry (1977). Comparison of stereo-pair photographs showed that settlements of up to 1 m occurred between November and February. Repeated surveys of the rubble at Kaubvik (Frederking, 1988) showed settlements, between January and April,

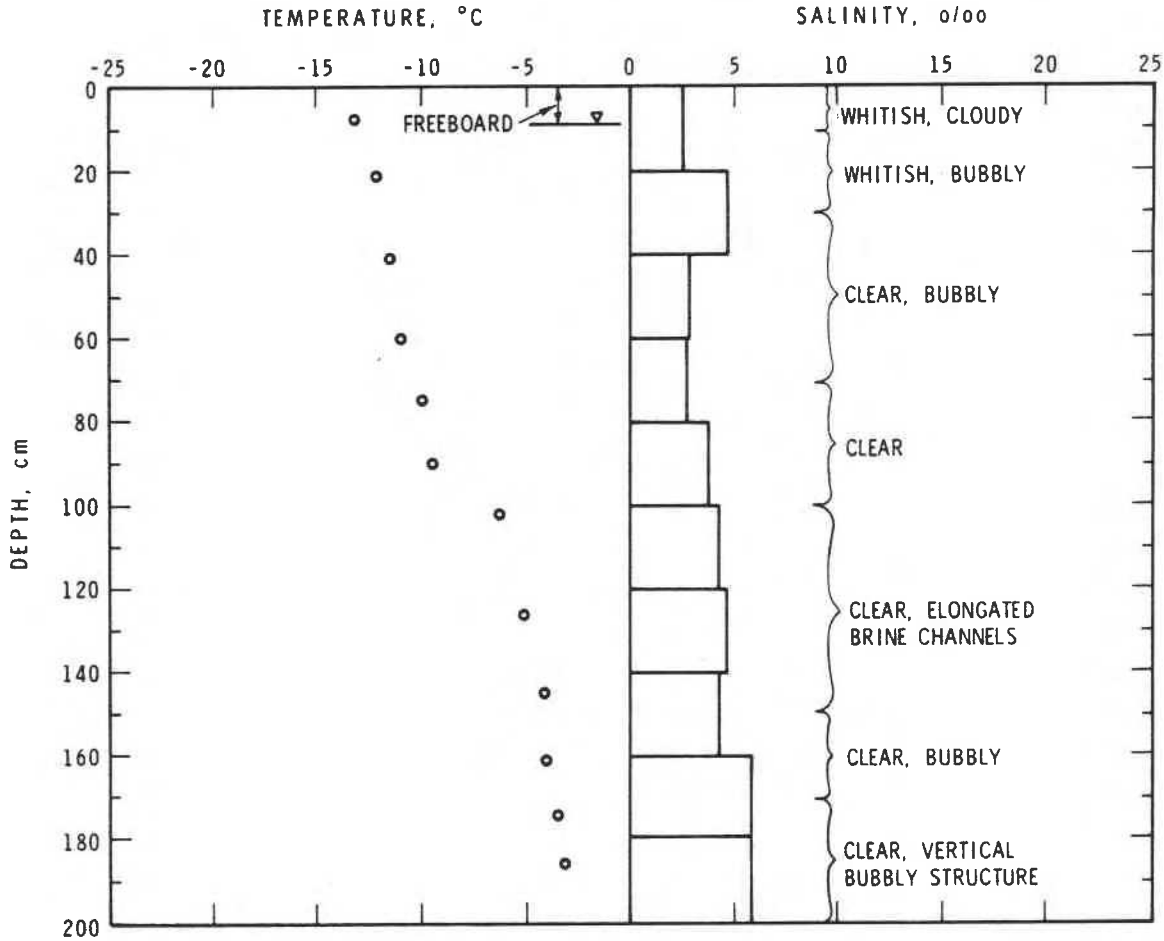

Figure 4: Vertical temperature and salinity profile (at core 5, Fig. 3), Issungnak 1980 (from Frederking and Wright, 1982).

varying from 0.15 m in shallow water areas to a maximum of 0.45 m in deep water areas near the outer edge of the field. Horizontal displacements were relatively small, with a maximum of approximately 0.35 m over the same duration.

2.2 Stresses:

Croasdale (1985) measured normal stresses in the rubble field at Amerk (also see Sayed et al., 1986). Strain gauged panels were installed at a number of locations in the rubble field. Only one panel, located approximately 10 m from the field's outer edge, responded to the action of floating ice. It measured a maximum stress of 200 kPa. The corresponding force per unit length was estimated to be 500 kN/m. Part of the stress-time record (from Croasdale, 1985) is shown in Figure 5. The other panels were installed further inside the field at distances of more than 75 m from the outer edge. Those panels measured negligible stresses. Evidently grounding resistance was sufficient to transmit all of the floating ice forces to the outer part of the berm.

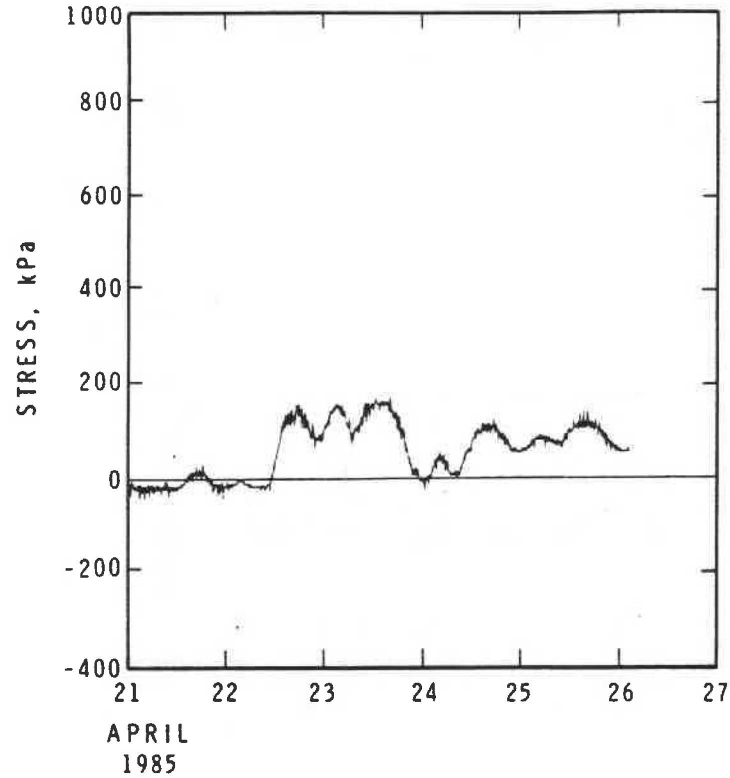

Figure 5: Normal stress near the edge of the rubble field at Amerk, 1985 (from Croasdale, 1985).

Several stress panels were also installed in the rubble field at Kaubvik during 1986-87 winter (Frederking, 1988). The maximum normal stress measured near the field's outer edge was 600 kPa. Stresses at other locations inside the field were negligible.

The low stresses inside the rubble field (at both Amerk and Kaubvik locations) were too scattered to show any pattern of spatial stress distribution. The sizes of all stress sensors used so far are small compared to ice block dimensions. This can further complicate attempts to correlate the stresses measured at various parts of a field.

Other relevant stress measurements were conducted in the floating ice surrounding a number of rubble fields. A comprehensive review of this subject was given by Sanderson (1984). Measurements at Kadluk were also reported by Johnson et al. (1985).

3. PHYSICAL MODELS

3.1 Horizontal loading of grounded rubble:

Experiments concerning grounded rubble stability were conducted by Wards (1984) (other tests were also reported by Wards in APOA report #186). Horizontal forces were applied to pre-constructed rubble pileups in an ice basin. Two pileups were used; the first consisted of a triangular sail and keel with an average sail height of 0.79 m, keel depth of 0.84 m and width of 1.82 m. The second pileup also had a triangular sail and keel cross-section with an average height of 0.43m, depth of 0.87 m and width of 2.42 m. Two types of tests were conducted as illustrated in Figure 6 (a). A barrier supported the pileup during the "constrained" tests. The "unconstrained" tests were conducted without a lateral support to determine the maximum grounding shear resistance.

Unconstrained tests gave friction coefficient values (taken as the ratio of shear to normal forces on the berm) of 0.63 and 1.58. Constrained test results are expressed as the ratio of the horizontal force acting on the berm to that acting on the barrier. This ratio decreased with time during each test. For tests performed using the first pileup, the ratio varied from 0.29 to 0.09 during one test and from 0.26 to 0.24 during another test. A test performed using the second pileup resulted in ratios starting at 1.44 and decreasing to 0.31 by the end of the test.

Information regarding rubble deformation and rubble/bed contact conditions is not available, which limits possible interpretation of the measurements. Deformation of the pileup may have improved the rubble contact with the barrier as a test progressed and thus reduced the portion of the horizontal force transmitted to the berm. The larger grounding resistance of the second pileup (in spite of its lower sail) was probably caused by its larger width which might have produced a larger contact area with the berm.

One significant conclusion that can be inferred from the results is that a grounded rubble pileup does not behave as a rigid block. A "rigid block" assumption considers the horizontal force on the bed to be equal to

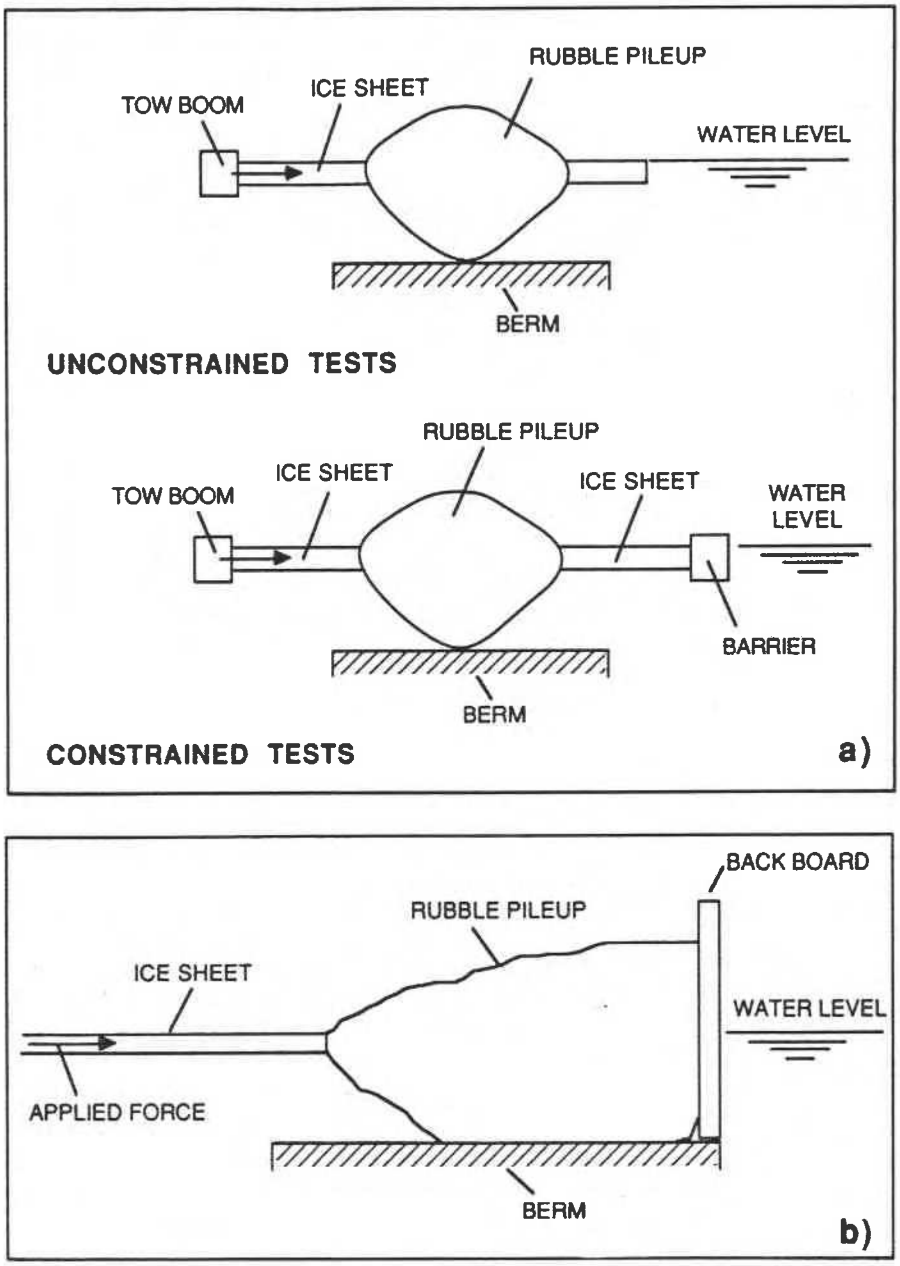

Figure 6: Schematics of ice basin experiments (a) Ward (1984), (b) Timco et al. (1989)

the normal force (on the bed) multiplied by a friction coefficient. Such an approach cannot explain the variations of grounding resistance during each test and between various tests.

Another program was recently conducted by Timco et al. (1989) to measure grounding forces during active rubble pileup, and during loading of an existing consolidated rubble pileup. A two-dimensional chute, instrumented to measure forces on a berm and a vertical back board, was used in a model ice basin as illustrated in Figure 6 (b).

Results indicate that the ratio of horizontal to vertical forces acting on the berm, η, depends on water depth, pileup size, and length of the pileup between the vertical structure and floating ice. As an example, the load apportioning ratio (η) is plotted versus the ratio of vertical force on the berm (V_B) to the horizontal force (H_T), in Figure 7. The shown curves represent various test runs that correspond to two values of rubble length (L) to water depth (d) ratio. The tests were also conducted using rough and smooth berms.

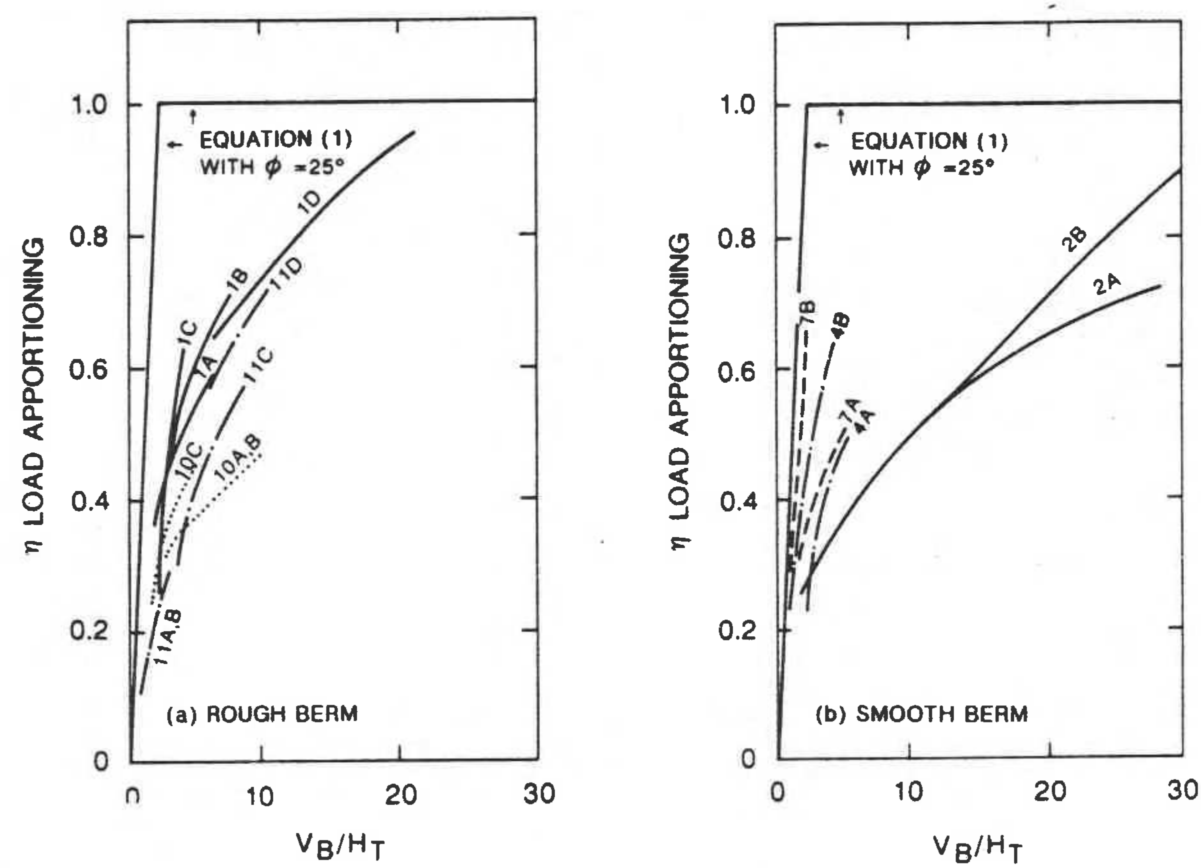

Figure 7: Force apportioning η versus vertical to horizontal force ratio (V_B/H_T) for (a) rough berm, L/d = 4.5 and (b) smooth berm, L/d = 4.5 for test #2 and #4, L/d = 9 for test #7 (from Timco et al., 1989)

Again, these tests indicate that grounded rubble behaviour is more complex than that of a rigid block. The measurements show that grounding resistance can be overestimated if simply taken as the vertical force on the berm mutiplied by a friction coefficient.

3.2 Growth of the consolidated layer:

Definition and description of the consolidated layer were given earlier in this review (section 2.1). Timco and Goodrich (1988) measured the rate of consolidation (or freezing) of ice rubble. Experiments were conducted in a model ice basin to examine the influence of block size, air temperature, and wind chill on freezing rate. The results showed that freezing rate of ice rubble is approximately twice as high as that of level ice.

4. MECHANICAL PROPERTIES OF ICE RUBBLE

Knowledge of the mechanical properties of bulk rubble is a prerequisite for analysis of rubble field behaviour. The main features of these properties are briefly reviewed. More detailed information can be found in the cited references.

Prodanovic (1979) tested submerged rubble samples in a direct shear box. His results indicated that the bulk rubble obeys the Mohr-Coulomb criterion, under a certain range of stresses and displacement rates. Other experiments by Tatinclaux and Cheng (1978), Keinonen and Nyman (1978), Hellman (1984), and Fransson and Sandkvist (1985) were in agreement with this conclusion. Gale et al. (1985) used both direct shear and a small triaxial cell to test small rubble samples.

Urroz and Ettema (1987) used a "true" simple shear apparatus to test floating rubble. Their set-up overcame many of the problems associated with direct shear tests. Sayed (1987) tested dry rubble in a plane strain apparatus, and examined strain rate and temperature influence on the strength. In another related study, Ettema and Schaefer (1986) measured freeze-bonding strength between ice blocks. The shear force at the contact was found to depend on freezing time, temperature and normal stress.

The main outcome of the above experiments is that bulk rubble obeys the Mohr-Coulomb criterion. Values of the angle of internal friction vary from 30° to 50°, and cohesion is negligible. Strength decreases with increasing strain rates (Urroz and Ettema, 1987, and Sayed, 1987), and with decreasing temperature (Sayed, 1987). These results are true for a range of stresses and deformation modes that appear to be relevant to field conditions, i.e. deformation consists of block re-arrangement, block fracture and slight ice crushing. It should be noted that, under certain conditions (e.g. high confining stresses), the bulk rubble may freeze and deform as a single block of solid ice, which is not in accordance with field observations.

All data on mechanical properties are from small scale laboratory tests. Uncertainties remain regarding the extrapolation of small scale data to field conditions. Also, no information is available concerning the properties of frozen (consolidated) rubble.

5. ANALYTICAL METHODS

5.1 Grounding resistance:

Only very limited progress has so far been achieved in modelling load transfer through the keel of a grounded pileup to the berm. A simple method for estimating grounding resistance, however, has been in use. It assumes that the horizontal force at the rubble/berm interface is equal to a friction coefficient multiplied by the normal force (see for example Kry, 1977). The horizontal force per unit area of the berm would be given by

$$F = \mu[\gamma_s H_s - (\gamma_w - \gamma_k) H_k] \qquad (1)$$

where μ is a friction coefficient, γ_s is the sail's bulk unit weight, γ_k is the keel's bulk unit weight, γ_w is water unit weight, H_s is the average sail height, and H_k is the average keel depth. The friction coefficient μ is usually considered to be equal to tan ϕ, where ϕ is the angle of internal friction of bulk rubble. This method has been elucidated in numerous publications. Since the approach is obvious, a listing of that literature is not given here.

In a report by Canada Marine Engineering Ltd. et al. (1986), several calculation methods were given. It includes a finite element analysis of lateral rubble loading. Preliminary results indicated that extensive computing will be required to deal with this problem. Available limited results, however, give values of forces on the berm and the structure that do not appear to exhibit the trends observed in the field (Croasdale, 1985; and Frederking, 1988) or the laboratory (Ward, 1984; and Timco et al. 1989).

Another finite element analysis by Evgin and Morgenstern (1984) examined the stability of offshore caissons. The analysis showed that the relative stiffness of rubble keel, compared to that of the frozen rubble layer, can have significant effect on load transfer through the rubble.

5.2 Stress distribution in rubble fields

Geometry of most rubble fields and loading conditions at their boundaries would give rise to complex stress distributions. In addition to estimates of local grounding resistance, knowledge of spatial stress variations is needed to examine stability of the structure and the rubble field.

The analysis of Sayed and Frederking (1984) treats the bulk rubble as a Mohr-Coulomb material at critical equilibrium. Solutions of the equilibrium equations and yield condition gave stress distributions for a range of boundary geometries and grounding forces.

Another simpler approach considers the equilibrium of a rigid body, representing the rubble. Details of complex geometries can be taken into account, and resulting forces can be checked for failure conditions. Calculations based on this approach were described by Allyn and Wasilewski (1979), Allyn (1982), and Canada Marine Engineering Ltd. et al. (1986).

At present, there are no available data pertaining to the spatial stress distribution from either field observations or laboratory tests. The models and calculations cannot be corroborated.

A category of studies addressed the related problem of forces due to floating rubble. Mellor (1980) considered brash ice to deform as a Mohr-Coulomb material and utilized soil mechanics formulas to estimate the resistance to ships. Krankala and Maattanen (1984) used a similar approach to calculate the forces on structures due to moving rubble fields and ridges. Gurshunov (1987) used a method based on "rigid body equilibrium" to study structure-floating rubble field interaction.

5.3 Rubble consolidation

Kry (1977) discussed the problem of consolidated layer growth. Canada Marine Engineering Ltd. et al. (1986) later developed a model that takes into account the influence of wind velocity, snow depth, and sail height. Predicted consolidated layer thicknesses agreed with field measurements.

6. CONCLUDING REMARKS

Field and laboratory data regarding grounding resistance and stress distribution in rubble fields are very limited, and can only begin to indicate the complexities of rubble behaviour. It can be seen from field measurements, nonetheless, that grounded rubble fields reduce the loads acting on the structures, rather than increase them.

The simple method, currently in use (equation 1), appears to overestimate grounding resistance to applied horizontal loads. More elaborate modelling and measurements are needed in order to obtain realistic predictions.

As for spatial stress distribution, a number of calculation methods are already available. Further refinements of input rubble geometries or parameters are unlikely to substantially improve predictions of the "rigid body models". Field and laboratory data, however, are needed to verify the basic assumptions.

Some limited information from model ice basin tests is now available. Further tests are needed to examine the appropriate scaling laws and the effects of rubble consolidation. Other factors requiring study include: rubble geometry, three-dimensional effects and the type of rubble/berm interface.

An effort to compile and analyze data available in a number of the Arctic Petroleum Operators Association (APOA) reports would produce a manageable and useful reference. Further field and laboratory investigations should include, in addition to stress measurements, rubble characterization and observation of deformation modes in order to gain an understanding of the relevant processes.

7. ACKNOWLEDGEMENTS

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