# INFLUENCE OF FRICTION ON ICE FORCES ACTING AGAINST SLOPED SURFACES

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ABSTRACT. On the basis of crushing and flexural failure theories, in conjunction with the assumption that ice–structure interface friction conforms to classical Coulomb friction laws, it is shown that effects of friction can be significant. Generally, the resultant force on the structure will increase very rapidly due to increases in the coefficient of interface friction. This increase in force is attributable to two analytically tractable phenomena; namely, that involving the resistance to sliding caused by the generation of tangential force at the interface, referred to as the primary effect, and that involving propagation of this primary-effect force into the ice failure zone increasing resistance to failure, referred to as the secondary effect.

Next, a non-classical theory of friction is reviewed. It admits the possibility of the coefficient of friction being a function of the normal force, velocity, and temperature for certain materials while still admitting Coulomb-type behaviour for other materials. Effects of replacing the classical theory with the non-classical one are considered, but it is concluded that further work is necessary before they can be realistically evaluated.

Finally, it is concluded that current design practice of neglecting the effects of friction on a certain class of structures is likely to lead to conservative results. Future work necessary to better predict the actual margin of safety resulting from current design practice is identified.

## DISCUSSION

A. FROLOV: What is your opinion about the role of a quasi-liquid layer (film) at the contact zone (friction boundary).

J. V. DANYS: The main goal of the paper is to show that friction has significant influence on ice forces acting against sloped surfaces. Attention is being drawn to the fact that we do not have adequate knowledge of the effective friction coefficients. I do not feel that I can make, at least at the present time, a statement as to which theory of friction applies in this case. Actual laboratory and especially, field tests of friction on sloped surfaces are required. However, our conclusions are based on the "customary" Coulomb theory.

# BREAKAGE OF ICE SHEETS BY UNDERWATER EXPLOSIONS

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ABSTRACT. We have attempted to develop a theoretical understanding of the field experience on the destruction of floating ice sheets by explosives, by performing small-scale laboratory explosions and developing a theory based on the elastic plate. Glass spheres

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$4.5 \times 10^{-2}$ m in diameter and *c.* $4 \times 10^{-4}$ m thick were immersed in water underneath a floating ice sheet *c.* $2 \times 10^{-2}$ m in thickness. The air pressure was raised till the sphere burst at pressures around 15 atmospheres. A high-speed camera (up to several thousand frames per second) recorded the details of the explosion: the growth of the gas bubble and the corresponding deformation and failure of the ice. We observed radial and circumferential cracks develop within 2 ms of the bursting of the sphere.

As a first step in the theoretical development, we have considered the response of an infinite elastic plate to impulsive pressure loading due to an underwater explosion. We have assumed potential, incompressible flow which is a valid approximation for the case of the above experiments and the analogous compressed-gas blasting in the field (Mellor and Kovacs, 1972). However the effects caused by the intense shock wave that is radiated by the detonation of a high explosive are thus not considered. We relate the maxima in the tensile stress with the crack pattern and the eventual damage, and have achieved qualitative agreement with the laboratory observations. The model does reproduce and clarify some aspects of the field data, in particular the role of the thickness (Mellor, unpublished); but it fails to relate the crater diameter to the weight of the explosive. It appears that at *optimum* blasting conditions with high explosives an incompressible-fluid, classical-plate-theory approach is inadequate.

## REFERENCES

Mellor, M., *and* Kovacs, A. 1972. Breakage of floating ice by compressed gas blasting. *U.S. Cold Regions Research and Engineering Laboratory. Special Report* 184.

Mellor, M. Unpublished. Data for ice blasting. [U.S. Cold Regions Research and Engineering Laboratory. Technical Note, 1972.]

## DISCUSSION

J. W. Glen: How close is the analogy with static loads? Is it an analogy with a point load? What does one assume about water reaction, as here it is the water which is applying the stress?

What assumptions do you make after radial cracking? Is circumferential cracking caused by the stress distribution before radial cracking or does it have time to readjust to an essentially wedge-shaped load problem?

E. Vittoratos: An ice sheet is relatively sluggish in responding to forces, as its strong coupling to the water increases its effective inertia. For example, an ice sheet 1 m thick requires at least one second to reach equilibrium deformation upon a sudden loading (or unloading) of it. As the duration of the positive pressure phase due to the bubble expansion is of the order of tens of milliseconds (for some kilograms of explosive), an analogy with static loads will be only of limited value. Furthermore, the pressure on the ice sheet due to the explosion varies approximately as the inverse of the radius, so that it is much less concentrated than a point load.

Your question about the cracking reaches to the heart of the problem. The films up to now indicate that radial cracks begin before the circumferential ones. Therefore, one probably should consider the dynamics of a wedge-shaped plate problem, whereas, up to now, I have assumed that the circumferential cracking is determined by the stress distribution before radial cracking. The wedge problem under static loads has been investigated by Nevel in a number of papers; I have just begun to consider the dynamics.

M. Mellor: Your approach seems well suited to studying ice breakage by compressed gas blasting, but it does not consider the effects of the fast stress wave in pre-cracking and venting the ice. Does this high-explosive effect create problems in your approach?

VITTORATOS: Yes it does. If the depth of the explosion is small, then the strength of the shock wave may be large enough to crack the ice, or even to eject some of it. In that case the present approach is not appropriate. For a cracked surface it is difficult to write an expression for the pressure on the ice surface caused by the incompressible expansion of the bubble. One expedient, if not correct, limit, is to assume that the ice behaves as a free surface; for a heavily damaged sheet this may not be a bad approximation. Venting of the bubble at an early stage will decrease the damage to the ice sheet. It should be noted that the consideration of the interaction of a shock wave with the ice presents considerable difficulties because of diffraction effects and possible cavitation at the ice–water interface.

# AN ACOUSTIC RANGING SYSTEM TO MEASURE MOTION OF SEA ICE

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ABSTRACT. With the present increase of commercial activity in the Arctic Ocean, there is a growing need for advanced engineering techniques and instrumentation. This paper discusses the application, design and testing of an acoustic ranging system used to measure the motion of sea ice at potential ice-platform drilling locations in the Canadian Arctic.

## DISCUSSION

W. F. WEEKS: Roughly how much would this system cost and how much lateral displacement of the ice can you tolerate before your system stops functioning?

R. CLARK: The cost is about \$20 000 with \$2 000 of this being an irrecoverable cost of the pinger. The horizontal range of the system is 1.5–2 km.

K. R. CROASDALE: Doesn't the horizontal range also depend on water depth?

CLARK: Yes. The value decreases with decreased water depth. In the previous case, the value referred to depths of 300–400 m.

W. ST. LAWRENCE: What type of batteries are you using that operate at −50°C?

CLARK: We are using lead-acid batteries that have a concentrated acid and are designed for low discharge. These are very cost-effective and have operated successfully over four months with considerable capacity remaining.

ST. LAWRENCE: Are you telemetering the data?

CLARK: Yes, development of satellite transmission of the data is underway at present and will be available for this winter's field season.

D. T. MELDRUM: Your technique relies on the measurement of the small difference in arrival time of the pulse at the receivers to give the position of the ice. Changes in lateral position are inferred from changes in these small differences. However, vertical tilting of the ice mass could give rise to similar changes; and in fact the system will be much more sensitive to this than to lateral motion since path-length changes are effected more directly. Have you evidence whether vertical motion is involved?