RUBBLE-ICE LOADS GENERATED BY CABLE-MOORED CONICAL PLATFORM: ICE-TANK TESTS

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ABSTRACT
Presented herein are ice-tank data concerning ice-rubble loads against a moored conical platform. Of prime interest is how rubble-ice loads are influenced by horizontal stiffness of the platform’s mooring system. An important, yet poorly documented, feature of rubble loading and clearing around the platform is the accumulation of ice rubble as a false bow, or prow, at the platform’s leading perimeter. The ice-tank data show that, under some conditions of ice-rubble loading, the lowest stiffness of mooring tested resulted in prow instability and sloughing, which in turn lead to a cyclic pattern of loading, and to rubble congestion around the platform. An outcome of such rubble congestion was a marked increase in the overall rubble-ice load exerted against the platform.

INTRODUCTION
Cable-moored platforms for offshore work in frigid waters likely encounter ice-rubble fields. The well-known moored platform “Kulluk” is, for example, subject to extensive ice rubble. Prediction of ice loads resulting from platform interaction with ice rubble is complex because load magnitudes are governed by uncertain patterns of ice-rubble accumulation around the platform and by platform motions during impact. In turn, patterns of ice-rubble accumulation, and platform motions, are influenced by rubble field thickness, size distribution of constituent rubble ice, and by speed of rubble-field impact. They also are influenced by the stiffness of the mooring system restraining the platform. To obtain an initial evaluation as to how mooring system stiffness influences rubble clearing and rubble-ice loads, this paper re-visits data obtained from several series of ice-tank tests conducted at the Iowa Institute of Hydraulic Research during the mid/late 1980s. Full details on the ice tank tests are provided by Matsuishi and Ettema (1985a) and Nixon and Ettema (1988). Matsuishi and Ettema (1985b) describe the performance of the platform impacted by level floes of ice.

ICE-TANK SETUP
Experiments were conducted using IIHR’s ice towing tank (21 m long, 5 m wide, and 1.3 m deep). A motorized carriage was used either to push a field of ice rubble against a

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test moored platform connected to a fixed test beam, or to tow the platform through the rubble ice. The test platform is similar to the existing cable-moored platform Kulluk at 1/45 scale. The principal dimensions of the test platform are given in Figure 1. The test platform responded to three linear restoring forces or moments:

1. A horizontal mooring force, modeled in this case by means of a linear leaf spring with stiffness $K_x = 0.5$ kN/m.
2. A vertical foundation reaction force attributable to buoyancy, with stiffness, $K_h = 17.3$ N/m.
3. A foundation reaction moment attributable to buoyancy, with stiffness $K_p = 35.1$ kN/m/degree.

Figure 1: Cross-section and dimensions (mm) of model conical platform.

The same instrumentation was used for both arrangements of platform mooring. The platform was connected to the beam or the carriage by way of a linear mooring harness. The mooring harness comprised a pair of elastic leaf springs, a spline bearing, stroke bearings and universal bearings. Two vertical rods located fore and aft restricted yawing and swaying of the platform. The rods were constrained to slide in slots. Thus, the platform had three degrees of freedom for motion: heave, pitch and surge. Heave and pitch motions were measured by means of two linear voltage displacement transducers, which sensed the vertical motion of the platform at two positions, fore and aft. For the present study, sway, yaw and roll were constrained to be zero. Similarly, though heave and pitch were measured directly, surge was inferred by means of measuring, with a load cell, the restoring force exerted by the leaf spring in the mooring harness.

Model rubble ice was formed by breaking 5-mm-thick sheets of un-tempered urea ice. The process comprised a two-stage process. First, an unseeded sheet was grown from a 0.7 % urea solution to the desired thickness. The sheet then was broken up by an attachment on the push-blade of the towing carriage, and, by use of screens, stored under insulation at one end of the tank. This process was repeated until between 7 and 10 sheets had been grown. The ice rubble (mean plan width of 49.5 mm, and standard deviation of 65.3 mm, for model pieces; overall layer porosity 36 %) was then spread over the tank surface to the required layer thickness. Three thicknesses of ice layer were tested; single layer (5mm), 50 mm layer, and 100 mm layer. Between tests, the layer was carefully groomed to achieve again a uniform thickness.
ICE-TANK RESULTS
On contact between the platform and ice rubble, a “prow” (or false bow) of rubble ice accumulated along the platform’s leading edge. The ice load and platform displacements typically increased until the prow attained an equilibrium size, as illustrated in Figures 2a–c. Thereafter, the ice load would be steady or mildly cyclic for some layer thicknesses and ice speeds. The principal results relating surge-force (main mooring load) and mooring-system stiffness are shown in Figure 3 and discussed subsequently. Example load and displacement data are presented in Figures 4–6. The data are mean values, and mean plus two standard deviations (2σ); the latter value is intended to indicate maximum value of a measured quantity.

Moored Platform
Figures 4a–c show the variation of surge force, heave displacement, and pitch angle with speed of rubble-field impact for a 100-mm-thick layer of rubble. Surge force against the moored platform (0.5kN/m) attained a maximum value at ice impact speeds of between 0.02 and 0.05 m/s. Heave also attained a maximum value over that velocity range. Pitch-angle data exhibited some scatter and, while there is a similar maximum for the 100 mm layer, no such maximum is obvious for ice layers 5 and 50 mm thick. By way of comparison, the platform with a simulated mooring stiffness of 1.7kN/m encountered a mean maximum surge (mooring) force of about 30 N, and mean plus 2σ of about 50 N, when impacted by 30-mm-thick sheets of urea ice tempered to a flexural strength of 20 kPa.

Figure 2: Development and sloughing of an ice rubble prow at a moored platform (a) and (b) may result in rubble congestion around platform and a constant surge displacement (c).
Figures 5a–c show the variation of surge force, heave and pitch with rubble-layer thickness when layer speed is 0.02m/s. Surge force and heave increase monotonically with increasing layer thickness. For the pitch data, the increase of peak value with layer thickness is very gradual.

Towed Platform
The series of tests in which the platform was towed through the ice sought to determine rubble-ice loads for a conical platform not congested by flanking ice. Towing did not replicate a moored platform in still water, towing produced significant water currents occurred around the platform. The expectation was that the towed platform would experience a lower surge force (also heave and pitch) than the moored platform. However, the opposite was observed. In all cases heave was greater for the towed platform. Pitch was approximately equal in the two cases, if anything, slightly greater in the towed experiments. Surge force, with open-water towing force subtracted, was greater in the towed experiments for the 5- and 50-mm-thick layers of rubble ice.

Figures 6a–c show the variation of heave, surge force and pitch with ice speed for those tests in which the platform was towed through the 100-mm-thick layer of ice by the carriage. At the three velocities shown (0.04, 0.10, 0.20 m/s) surge force and heave increase monotonically with layer thickness, though no upward curvature is apparent in this case. Scatter in the data obscures any trends relating pitch angle to layer thickness.
However, peak values at 0.10 and 0.20 m/s show clear monotonic increases, while the mean values drop off at the 100 mm thickness. Surge forces on the towed platform rose to a plateau and then remained essentially constant. In contrast, for the stationary moored platform surge force reached an initial plateau (corresponding to formation of a stable ice prow), then rose to much higher values as the prow sloughed off and jammed against the side of the tank. Values for the towed platform are higher than the moored platform values because of added-mass effects associated with acceleration of water around the platform.

Figure 4: Surge force, pitch angle, and heave displacement vs rubble-layer velocity. Layer thickness = 100 mm; Figs (a)–(c) run from top.

Figure 5: Surge force, pitch angle, and heave displacement vs layer thickness. Layer speed = 0.02 m/s. Figs (a)–(c) run from top.
Mooring-System Stiffness, Prow Instability, and Rubble Load

A feature not observed for tests with the two stiffer mooring systems was the instability of the ice prow formed for a certain range of ice speeds (Figure 2). The instabilities,
consequent to the greater flexibility and thereby oscillation of the lesser mooring-system stiffness, occurred when the prow sloughed or slipped to one side of the platform, and congested ice between the sides of the platform and the tank walls. The congestion effectively placed the platform amidst a thickened layer of rubble or brash ice, and thereby increased ice forces exerted against the platform. Prow instability and subsequent ice congestion was greatest for the speed range of 0.02 to 0.10 m/s. At lower speeds, creeping speeds, false-bows remained stable at the leading perimeter of the platform. For speeds higher than this range, false-bows were sufficiently diminished in sizes that their influence on ice forces decreased.

It had been expected that, as the ice moved against the platform, a stable and stationary cone of ice would form as a conical prow at the platform’s leading perimeter. And, as a consequence of this, surge force, heave and pitch would all increase until a stable prow had formed, at which point they would remain essentially constant. However, rather than a prow achieving stability, ice paws would form and grow, then slough to one side. In effect, this sloughing behavior, combined with the confinement of the tank sides, transformed the rubble/brash field to a pressurized rubble/brash field. As the congestion increased, the ice load increased. This finding points to a possible ice-load design concern, insofar that a dynamic rubble field may thicken around a platform and increase ice loads exerted against the platform. Figure 3 shows a trend in surge force variation with layer thickness, for the three values of mooring stiffness tested; the same trend occurred at layer speeds exceeding about 0.02 m/s. The two stiffer mooring systems produced about the same surge force, whereas the more flexible mooring (0.05 KN/m) produced larger surge forces. However, when ice congestion around the platform increased, owing to prow sloughing, the surge force increased monotonically; in fact the surge force did not attain equilibrium and exceeded the values presented in Figure 3. Under this condition, the test setup ceased to be effective and was abandoned, with the intent that it be re-designed and further work subsequently conducted.

**MAIN CONCLUSION**

The reduced stiffness of mooring considered in the present tests led to mild cyclic behavior in the surge force. The cyclic behavior arose because ice rubble would accumulate in a cyclic manner whereby a “prow” of ice rubble would form then slough away to the platform’s side. Prow sloughing leads to congestion of ice around the sides of a platform, and in turn greatly increases ice load if the platform becomes confined in ice congested around it. As rubble ice accumulated, the load it exerted against the moored platform increased and caused the platform to be shoved increasingly from its original moored position.

**REFERENCES**

