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NUMERICAL MODELLING OF ICE INTERACTION WITH RUBBLE MOUND BERMS IN THE CASPIAN SEA

A. Barker[1] and K. Croasdale[2]

ABSTRACT

Numerical modelling of sea ice is a useful tool in predicting ice rubble formation around offshore and coastal structures. Such models can capably predict rubble height and extent, allowing engineers to pinpoint “problem” scenarios for structures where ice interaction, and its potential for extensive damage, is a concern. This paper describes numerical simulations that were conducted to examine floating ice interaction with a structure located in the Caspian Sea and its planned surrounding protective rubble mounds. Spatial and temporal distributions of ice rubble pile-up height and depth, as well as forces on the mounds, were determined. The numerical model examined a number of different rock mound configurations, the influence of the direction of ice movement and ice sheet thickness. The results are compared with reported pile-up heights, collected from the field site.

INTRODUCTION

This objective of this paper is to summarize the findings of a numerical model that was used in conjunction with field work and laboratory tests to examine design options for a drilling site in the Caspian Sea. The paper also gives an overview of full-scale conditions for comparison purposes. The numerical model examined floating ice interaction with a barge-type structure and the rock mounds that were to be constructed around it, as part of a contract that the Canadian Hydraulics Centre (CHC) of the National Research Council of Canada carried out for the Agip Kazakhstan North Caspian Operating Company NV (AGIP KCO, formerly OKIOC) (Sayed and Barker, 2000). The problem that was to be studied corresponded to design options for an exploration-drilling structure in the Kazakhstan sector of the north Caspian Sea (see Figure 1).

The structure, called the Sunkar, is 85 m by 55.5 m. Rubble mounds, along the long axis, were at one point considered as protection for the Sunkar from moving ice, although this layout was subsequently discarded. Numerical simulations were conducted in order to determine, for each design option, the expected ice pileup geometries, ice

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rubble grounding, and forces on the rock mounds and structure. Several options for the layout and dimensions of the mounds were examined. The data from these simulations were then compared with ice measurements taken the following season by K.R. Croasdale and Associates, in response to a tender issued by AGIP KCO for an ice research and measurement programme for the North Caspian Sea (Croasdale, 2001).

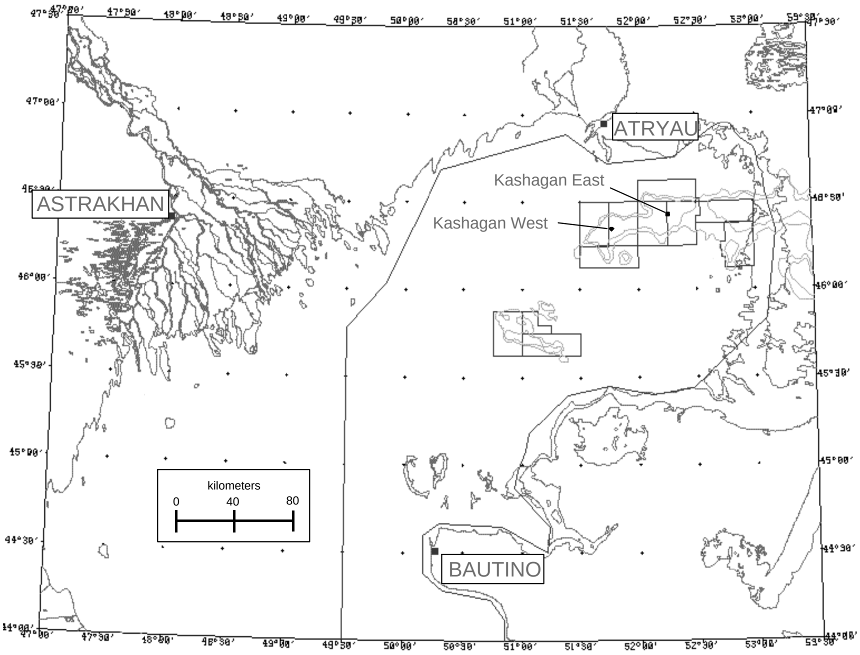

Fig. 1. Regional map of Caspian Sea (from Croasdale, 2001)

PARTICLE-IN-CELL NUMERICAL MODEL

Model Description

A Particle-In-Cell (PIC) numerical model developed at the CHC has been used successfully to deal with a number of ice-structure interaction issues (Sayed et al., 2000; Barker et al., 2000; 2001a; 2001b). The numerical model uses a continuum rheology that follows a Mohr-Coulomb plastic yield criterion. An assembly of discrete particles represents the ice cover. The governing equations consist of the continuum equations for the balance of linear momentum and the plastic yield criterion. Those equations are solved using a fixed grid. Advection and continuity, on the other hand, are handled in a Lagrangian manner. An implicit finite difference method is used, based on uncoupling the velocity components and a relaxation iterative scheme. Each particle has a fixed volume, and is assigned an area and a thickness. At each time step the velocities are interpolated from the grid to the particles. Thus, particles can be individually advected. From the new positions, values of particle area and mass are mapped to the grid. The resulting ice mass and area for each grid cell are then used to update ice thickness and concentration. Solution of the governing equations can then be carried out using the fixed grid. Updated velocities and stresses on the fixed grid are obtained from the solution. Both three dimensional and depth-averaged implementations of the model were used in this paper; the latter averages the values of stresses and velocities over the thickness. Thickness variations, however, are accounted for. As stresses exceed a threshold, representing a ridging stress, each particle undergoes ridging; i.e. the thickness increases and area decreases, while conserving ice volume. Further details about the model may be found in Sayed and Carrieres, 1999.

Test Set-Up

The numerical model was used to investigate floating ice interacting with the Sunkar, and its surrounding protective rubble mounds. The simulations that were performed for AGIP KCO consisted of two base cases each with sensitivity and three-dimensional runs. The first base case looked at one rubble mound along the east side of the structure, and another mound along the west side of the structure. For the second base case, two mounds (separated by a gap) were placed along the east and west sides of the structure. Figure 2 shows the general layout. Runs were conducted using different values for the direction of ice movement, distances between the structure and mounds, and gap between the mounds. The effects of changing the freeboard and width of the mounds were also examined. The output of each run gave the extent and spatial distribution of rubble pileup sail height and keel depth in front of the mounds and the structure. The spatial distribution of grounding was also given. The forces on the mounds and the structure were determined. Overall, thirty-three runs were completed.

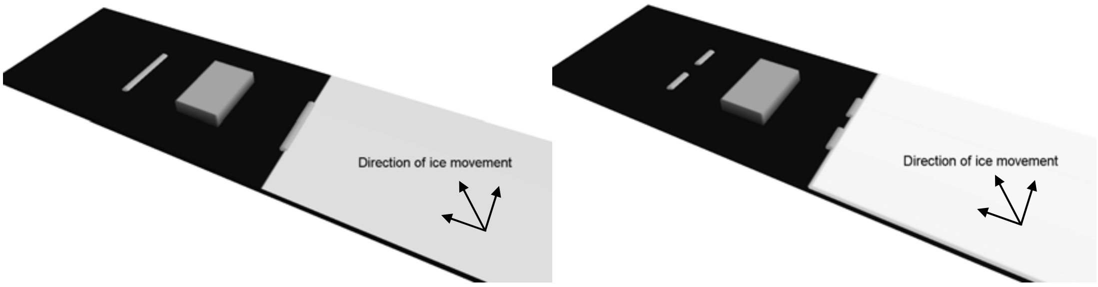

Fig. 2. General test layout for the test cases. The second case (right) had two mounds on either side of the barge, with a gap of various widths, rather than the single berm of the first case (left)

The ice thickness used in the runs was usually either 0.05 m or 0.15 m. These relatively small thickness values were chosen as the predominant thickness during the freeze-up, when it was anticipated that most of the pile-up activities would take place. The ice had a constant ice velocity of 0.5 m/s. The water depth was 4 m, with a 1 m freeboard for the rubble berms. The rubble berms were to have 1:3 slopes (18° from horizontal). An angle of internal friction of 30° was appropriate for modeling the depth-averaged behaviour (as established in previous studies; e.g. Sayed et al. 2000). A number of boundary conditions were used, depending upon the test run configuration. The boundary conditions could include full-slip (ice velocity parallel to the boundary), prescribed velocity (to drive the ice cover) or stress-free (used downstream of a structure) conditions. The environmental driving force on the ice sheets was applied via a water drag coefficient, between 0.5 and 1.5 depending on the ice thickness. The lower value corresponds to a maximum applied shear stress of approximately 1.25 kPa exerted on stationary parts of the ice cover. These values are in accordance with observations of ice jams (Beltaos, 1995). Overtopping of the rubble mound structures was not permitted, although additional tests did examine this scenario. Those simulations showed that ice pileup would not overtop a mound with 1 m freeboard. For a lower freeboard of 0.5 m, a pileup would spill some ice rubble on the top of the mound, but all rubble is stopped in front of the mound. Therefore, the structure remained protected.

Summary of test results

The spatial distribution of ice rubble pileup showed that almost all of the pileup occurs against the East mound (Figure 3). The structure and West mound were sheltered from the ice and forces there were negligible. Pileup against the East mound appeared to form in rings. Once a maximum thickness (height and depth) were reached, the pileup extended outwards, upstream. The pileup grounded on the slopes of the mound and seabed. Forces on the mounds were calculated by integrating the normal stresses acting directly on the mound and grounding shear stresses. The forces on the structure were calculated by integrating the normal stresses at its interface with the ice. The resulting maximum pressure of 2 kN/m is in accordance with observations (Masterson, 2000). The total force on the mound was approximately 90 kN, which was, as expected, relatively low. For a quantitative description of the pileup, the sail height and keel depth were plotted along several cross-sections; an example is shown in Figure 4. The sensitivity runs for Case 1 gave quantitative estimates of the effects of changing ice direction, mound length, and separation distance between the structure and the mound. The direction of ice movement obviously influenced the effectiveness of rubble mounds to protect the structure. The effect of the separation distance became pronounced with increasing angle of ice movement direction. The larger separation exposed the structure to more ice action. Increasing the length of the mound increased the protection of the structure, particularly for oblique angles of ice approach and larger separation distances.

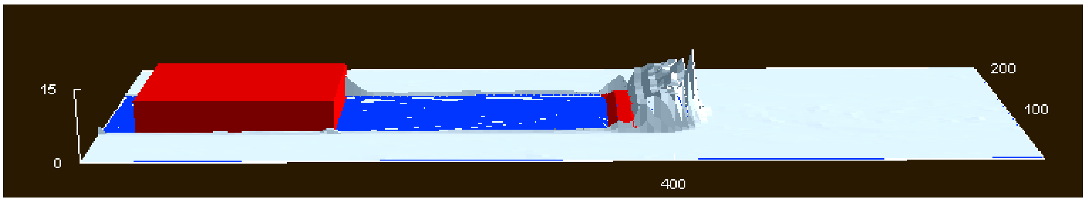

Fig. 3. Ice interacting with a rubble berm. The Sunkar is on the left hand side

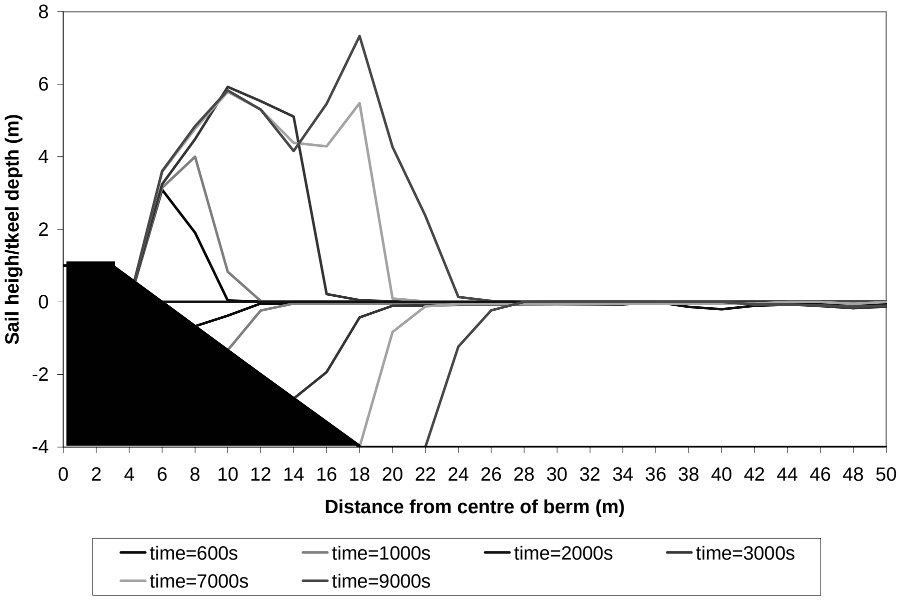

Fig. 4. Cross-sectional view of development of sail and keel thicknesses over time.
Note the grounding and steep angle of repose

For the second case, at the early stages of the run, pileups formed in front of both East mounds. The ice sheet also passed through the gap between the mounds and a pileup developed against the structure. As the pileup against the structure grew, it reached the gap, which eventually filled with grounded ice. Afterwards, a single grounded pileup developed in front of the both the East mounds. Once this occurred, the two adjacent mounds acted as a single large mound, which provided shelter for the structure. With a larger ice sheet thickness, the pileup formed and grounded in the gap between the mounds. For a larger separation distance between the mounds and the Sunkar, the pileup in front of the structure obviously took longer to reach the gap. Increasing the angle of ice movement (from the x-direction to an oblique angle) was shown to expose larger parts of the structure to ice action. Also, the gap between mounds appeared to block earlier. The latter result is expected since the projected gap width normal to ice movement would be smaller. The larger gap and the corresponding smaller mound length produced pileup in front of each mound and the structure. The larger separation distance exposed the structure to increased ice action. In cases where the gap was greatest, the gap did not become blocked. Additionally, a run was done to examine the stability of an existing grounded pileup under the action of a moving ice sheet. The results showed that the grounded pileups did not move under the action of the moving ice sheet. Instead, a new, grounded pileup formed on the South sides of the existing pileup and the structure. Only a small part of the initial pileup, west of the mounds, that was not firmly grounded was cleared by the moving ice sheet.

MEASURED FULL-SCALE FEATURES

The full-scale data was collected in February 2001 (Croasdale, 2001). The main focus of the project was to examine grounded ice rubble and ridge features. The measurements that were collected that pertain to this paper included ridged and rafted ice thickness and geometry, ice pile-up geometry and block size distribution and other measurements concerning sea water and ice properties. Overall, fourteen features were surveyed over the course of the month. General descriptions for each feature are shown in Table 1. With respect to the ice conditions in the area of the drill site, ice is generally present from December to March, with a mean level ice thickness ranging between 0.3 m to 0.5 m. The water depth is quite shallow (the water depth in the study area is 4 m), with a deepest depth of approximately 10 m. Ice ridging and rafting occur frequently in the area, with keels scouring the seabed in the case of the former. A photograph of one of the features is shown in Figure 5. Table 1 lists the sail and keel measurements, water depth and level ice thickness for each feature, as well as some other pertinent details, where available. Feature 14 is omitted, as it was a sounding at various locations. The average sail (pile-up) height of the observed features was 3.3 m, with a maximum height of 6.6 m. The average thickness of the surrounding ice sheet was 0.33 m. The water depth varied from 2.0 to 5.9 m, and most of the features had grounded on the seabed. Croasdale (2001) discussed that it appeared that ice pile ups in the Caspian could be higher than other regions (for the same ice thickness), which he attributed to the shallower water and reduced ice friction between ice blocks due to lack of snow.

COMPARISON WITH FULL-SCALE DATA

A direct comparison between the full-scale data and the numerical results is difficult, given that most of the full-scale features were not generated due to interaction with a structure such as the Sunkar. Nevertheless, it is possible to compare the results by examining the relationship between the surrounding level ice thickness and the generated pile-up height. Figure 6 shows two views of ice that did, however, interact with the protective piles that were used at one point to shield the Sunkar. As can be seen in this figure and Figure 5, the pile-ups could be quite steep. This was also observed in the numerical results, as shown in Figure 4.

Fig. 5. Photo of typical feature surveyed in the Caspian Sea (Croasdale, 2001)

Table 1. Details of full-scale features surveyed in Caspian Sea (after Croasdale, 2001)

Feature Number	**Feature Length**	**Feature Width**	$\mathbf{h_{sail}}$	$\mathbf{h_{keel}}$	$\mathbf{h_{water}}$	$\mathbf{h_{level\ ice}}$	**Dominant ice thickness at pile-up**	**Comments**
	m	**m**	**m**	**m**	**m**	**m**	**m**	
1	na	na	3.0	na	2.0	0.23		Rubble pile
2	150	50	6.6	2.6	2.6	0.35	0.30	Grounded ridge/rubble pile
3	30	25	3.0	2.5	2.5	0.32		Rubble pile within 1 km of Feature 2
4a	80	20	3.2	2.0	2.0	0.35		Series of ridges
4b	50	20	3.6	2.0	2.0	0.35		Series of ridges
5	na	na	3.2	3.5	3.5		0.13	Series of ridges
6	na	na	3.7	3.5	3.5		0.19	Series of ridges
7	na	na	1.6	3.7	3.8	0.40	0.16	Series of ridges
8	na	na	na	na	na	0.38		Sonar survey south of (east) piles
9	90	60	5.5	4.3	4.3		0.20	Exposed rock berm
10	30	10	2.1	2.0	2.0		0.07	Rubble pile near Aktote
11	10	10	0.5	2.0	2.0	0.3		Rafted ice/floating ridge area
12	>1000	50-200	5.6	5.9	5.9		0.17	Newly formed grounded ridge and rafted ice ~ 8km from Sunkar
13	65	50	0.5	5.8	5.8	2-3 (rafted)		Rafted ice floes in front of ridge
14								Ice thicknesses and soundings on line from Aktote to shore

Croasdale (2001) plotted the relationship between the ice thickness and the pile-up height for a number of the surveyed features (Figure 7). The plot shows good correlation between dominant ice thickness and pile-up height. A similar chart was created that included data points from a large number of geographic areas, as well as the Caspian full-scale and numerical results. This plot is shown in Figure 8. The Caspian data is on the low-end of the measured ice thickness data. In this region, it can be seen that there is a moderate amount of scatter in the pile-up heights encountered with thin ice. However, both the full-scale and the numerical results fall in with data from other geographic regions. Note that there are numerous pile-up thicknesses for the numerical results for each ice thickness, due to multiple test runs with different configurations in the parametric study.

SUMMARY

The preceding paper describes ice rubble pileup geometries and forces due to an ice sheet impinging on a structure protected by arrangements of rock mounds, and the associated full-scale data for comparison purposes. The chosen driving force and material parameters produced the expected pileup thickness. The maximum grounded thickness was approximately 10 m, with a corresponding pileup height of 6 m in 4 m of water. This result is in agreement with the range observed in the Caspian (Spring, 2000, Croasdale, 2001), and other locations in the Arctic under relevant conditions.

ACKNOWLEDGMENTS

The authors wish to acknowledge Michel Metge, of AGIP-KCO, for obtaining permission to use the full-scale data as well as the assistance of Walt Spring, Exxon Mobil Upstream Research and Dr. Mohamed Sayed, Canadian Hydraulics Centre.

Fig.6. Two views of pile-up occurring at piles used to shelter the Sunkar drilling barge (Croasdale, 2001)

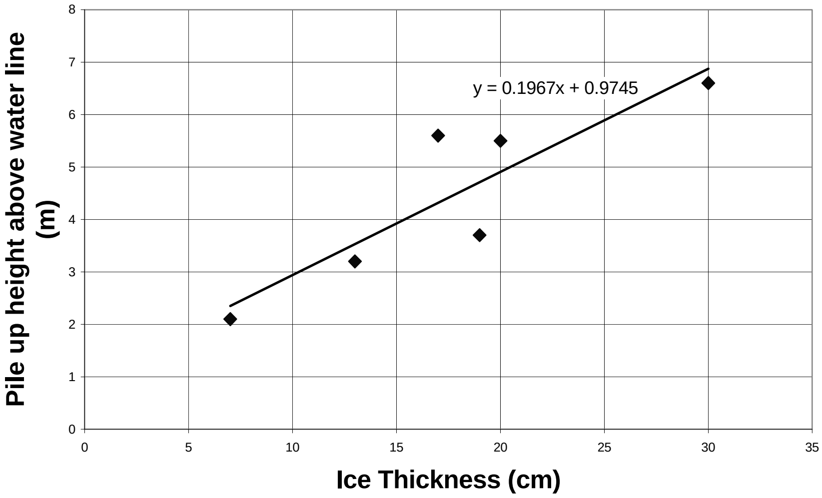

Fig. 7. Pile up height versus ice thickness (Croasdale, 2001)

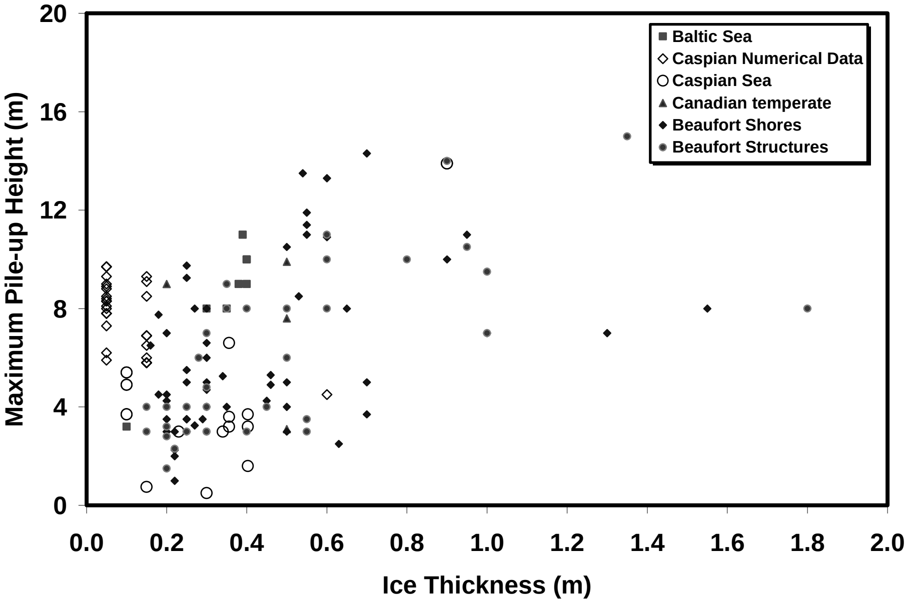

Fig. 8. Maximum pileup height versus thickness for full-scale and model data

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